Toward Improved CFD Predictions of Slender Airframe Aerodynamics Using the F-16XL Aircraft (CAWAPI-2)

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A coordinated project has been underway to improve CFD predictions of slender airframe aerodynamics. The work is focused on two flow conditions and leverages a unique flight data set obtained with an F-16XL aircraft. These conditions, a low-speed high angle-of-attack case and a transonic low angle-of-attack case, were selected from a prior prediction campaign wherein the CFD failed to provide acceptable results. In this paper the background, objectives and approach to the current project are presented. The work embodies predictions from multiple numerical formulations that are contributed from multiple organizations, and the context of this campaign to other multi-code, multi-organizational efforts is included. The relevance of this body of work toward future supersonic commercial transport concepts is also briefly addressed.

I. Nomenclature

$C_{f,cfd}$	skin-friction coefficient, computational
$C_{f,exp}$	skin-friction coefficient, experimental
C_p	pressure coefficient
c	wing chord
c_{ref}	reference chord
h	altitude
M	Mach number
R_{cref}	Reynolds number based on c_{ref}, $U\, c_{ref} / \nu$
r_{le}	streamwise leading-edge radius
U	free stream reference velocity
x,y,z	body-axis Cartesian coordinates
α	angle of attack, deg.
β	angle of sideslip, deg.
η	fraction of wing semispan
Λ	wing sweep, deg.
μ	viscosity
ν	kinematic viscosity, μ/ρ
ρ	density

Acronyms

A-D&S	Airbus, Defense and Space, *Germany*
AVT	Applied Vehicle Technology
BL	Airplane butt line, positive starboard
b.l.	Boundary layer
CAWAP	Cranked Arrow Wing Aerodynamics Project
CAWAPI	Cranked Arrow Wing Aerodynamics Project, International (previous)
CAWAPI-2	Cranked Arrow Wing Aerodynamics Project, International (current)
EADS	European Aeronautic Defense and Space Company, *Germany*
FC	Flight Condition
FS	Airplane fuselage station, positive aft
FOI	Swedish Defense Research Agency
KTH	Royal Institute of Technology, *Sweden*
NATO	North Atlantic Treaty Organization
NLR	National Aerospace Laboratory, *Netherlands*
RTO	Research and Technology Organization
STO	Science and Technology Organization
UL	University of Liverpool
UTSIM	University of Tennessee Simulation Center
WL	Airplane water line, positive up

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II. Introduction

Slender airframes are developed to meet the challenges associated with efficient high speed and often supersonic flight. As part of the need to minimize wave drag, such vehicles incorporate slender wings that are designed or even optimized for efficient supersonic cruise. These wings will be thin, highly swept, and incorporate relatively small leading-edge radii. Other design considerations such as area ruling affect the resultant vehicle geometry in ways uncommon to vehicles intended for transonic or low-speed flight. Maneuver aerodynamics can provide other requirements for this airframe class.

These aircraft present many unique aerodynamic challenges across their aggregate performance envelope. The slender wing can produce complex and nonlinear flow fields at other operating conditions such as transonic cruise and/or low-speed take-off and landing. For example, the highly-swept leading edges with small leading-edge radii can produce separation-induced leading-edge vortices at the higher angles of attack often associated with take-off and landing as well as maneuver. The effects of these vortical flows can be further complicated by the occurrence of multiple interacting vortices from the leading edge as well as the occurrence of near-field vortex breakdown. At transonic speeds these vortices can still be present and result in complex shock-vortex interactions over the wing. All of these phenomena can be unsteady. Even for attached flows the wing boundary layers will be highly three dimensional due to the slender wing geometry.

To help advance our knowledge of these flows, Lamar[1] [2001] created and led the Cranked Arrow Wing Aerodynamics Project (CAWAP) which was focused on the development of a very unique flight data set using an F-16XL aircraft. This aircraft has a complex wing with many of the features associated with supersonic cruise aerodynamics. Initial CFD analyses by Lamar[2] [2003] showed some promising correlations with the flight-test data (especially with respect to computational restrictions of that time) while also identifying deficiencies in the predictive capability. To address this predictive inadequacy, a project was established through the Research and Technology Organization (RTO), under the auspices of NATO, to seek improved understanding and predictive capability for this particular data set. This project, dubbed CAWAPI (Cranked Arrow Wing Project, International), produced significant advances for CFD modeling of the F-16XL flows through the numerical contributions from approximately nine institutions. At the same time, two conditions proved to be unyielding to the collective effort from CAWAPI. The flow fields for these two conditions were (i) transonic low alpha aerodynamics relevant to transonic cruise and (ii) low-speed high-alpha aerodynamics relevant to takeoff and landing. Both of these conditions are critical for practical operations of the slender airframe vehicles, and particularly so for supersonic cruise vehicles from either the commercial or military sectors.

A new effort, CAWAPI-2, was then established to address these two unyielding outcomes from the CAWAPI project, and the results of this effort will be the topic of two special sessions in the AIAA 2014 Science and Technology Forum and Exposition (SciTech). The purpose for this paper is to provide an introduction and overview to the CAWAPI-2 project. First, some details of the prior CAWAP and CAWAPI will be summarized along with basic attributes of the test bed aircraft itself, the F-16XL-1. This will be followed by an overview of the CAWAPI-2 project including the focus conditions for the project, scope of participants and numerical methods, and overall solution metrics. Some comments regarding the context of this work and related multi-code multi-institution numerical campaigns will also be included.

III. Background

In this section three facets leading to the present effort will be reviewed. First, some features of the F16-XL aircraft itself will be addressed. This will include some discussion for the design philosophy that led to this aircraft as well as some aggregate vehicle characteristics. Next, the CAWAP flight-test program will be reviewed, followed by the approach and outcomes of the CAWAPI computational project.

A. F16-XL Aircraft

The F-16XL was designed jointly by General Dynamics Corporation-Fort Worth (now Lockheed Martin Aeronautics Company (LM Aero)) and NASA Langley Research Center, and built by General Dynamics. The project originated from the Supersonic Cruise and Maneuver Prototype (SCAMP) program, the purpose of which was to transition supersonic transport technology to military aircraft. NASA Langley had generated extensive data under the Supersonic Cruise Aerodynamic Research (SCAR) program, and much of these data were used in developing what became the F-16XL aircraft. The design work began around 1977, and in 1980 General Dynamics committed to a flight demonstrator program for two prototype aircraft, the F-16XL-1 (single seat) and the F-16XL-2 (dual seat). Summaries of the F-16XL aircraft development and subsequent flight test program can be found in Hillaker[3] [1983] and Talty[4] [1988], and some selected details follow.

The F-16XL was based upon the F-16, and both F-16XL aircraft were fabricated from existing F-16A aircraft. To achieve improved supersonic performance, the F-16XL incorporated a cranked-arrow wing. The fuselage was lengthened 56 inches from the full-scale development F-16A aircraft, and modified fuel and flight control systems were also included. Some overall dimensions for the F-16XL aircraft are shown in **Figure 1**.

The goals for the cranked arrow wing were to provide improved supersonic performance while maintaining low-speed handling and transonic performance comparable to contemporary F-16 aircraft. This was accomplished with a high sweep inboard panel for low drag at supersonic speeds, and a low sweep outboard panel to provide better handling and maneuverability at subsonic speeds. The wing has a leading edge sweep of 70 degrees inboard and 50 degrees outboard of the crank. This highly swept inboard panel is blended to the fuselage with an S-curve, which was designed to increase stability at high angles of attack. Based upon the reference wing planform, the wing aspect ratio is 1.75. It has an exposed taper ratio (without tip missile) of approximately 0.18. Wave drag considerations result in a thin wing with corresponding small leading-edge radii. The S-curve and the outboard 50-degree leading edges were sharp. Approximate leading-edge radii for the inboard 70-degree swept portion of the wing are shown in **Figure 2** along with approximate values from a prior slender-wing aircraft, the F-106, for reference.

Air dams are installed at the centerline of the actuator pod just inboard of the crank. The wing is equipped with inboard elevons, outboard ailerons, and outboard leading edge flaps for stability and control. The leading edge flap is additionally scheduled to deploy negatively at high speed to decamber the wing and reduce loading. The F-16XL aircraft were heavier than the baseline F-16A, although carbon-fiber composites were effective in managing the increased weight. The resultant aircraft was capable of Mach 2 flight, and despite the many changes, the F-16XL was able to maintain approximately 80% commonality with its parent F-16.

The prototype F-16XL flight test program spanned 1982 to 1985, and many of the flight test program objectives were met. Significant improvements to supersonic L/D were obtained with the F-16XL as compared to the F-16. For example, the supersonic lift-to-drag ratio was increased by about 25% compared to the F-16A baseline. The large wing volume of the cranked arrow wing increased fuel capacity, and significant increases in range were also demonstrated. At the completion of the prototype flight test program the aircraft became available for other flight test interests.

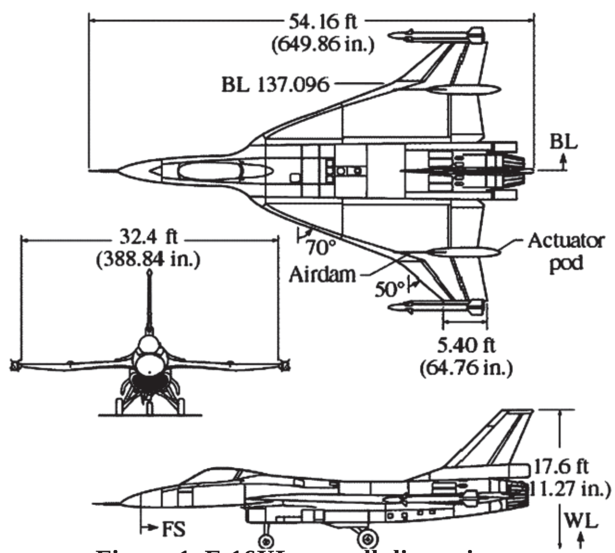


Figure 1. F-16XL overall dimensions.

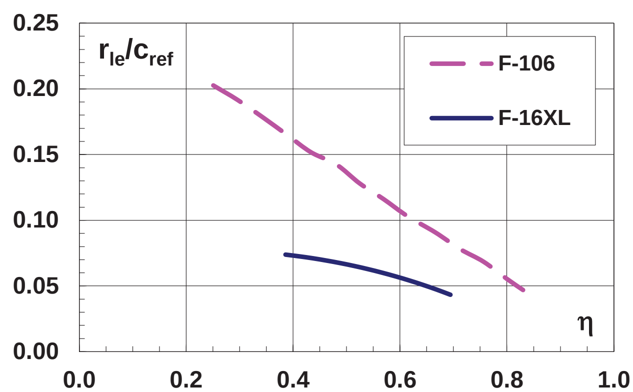


Figure 2. Spanwise leading-edge radius distribution, percent.

Figure 3. F-16XL-1 aircraft.

Flight test research was performed by NASA with both aircraft. All of the Cranked Arrow Wing Aerodynamics Project (CAWAP, CAWAPI, CAWAPI-2) results of the current paper were performed with the F-16XL-1 aircraft, and the flight test configuration of the F-16XL-1 is shown in **Figure 3**. As a byproduct of the supersonic design requirements, the combination of highly-swept leading edges with small radii can be conducive to the formation of separation-induced leading-edge vortical flows at moderate to high angles of attack, and this served as one focus of the CAWAP research to be described next. The F-16XL-2 aircraft was used for laminar flow research, and the reader is referred to Anders[5] [1999].

B. Cranked Arrow Wing Aerodynamics Program (CAWAP)

The CAWAP research was conducted during the 1990's with the F-16XL-1 aircraft and included flight conditions spanning low to high angles of attack as well as Mach numbers from subsonic to supersonic speeds. Ninety-nine flight conditions were reported by Lamar[1] [2001]. Flight data were obtained over a broad range of conditions shown in **Table 1**, with about 2/3 of the data corresponding to1-g level flight conditions. This work was originally aligned with the NASA High-Speed Research program (HSR) since the F-16XL wing is broadly similar to high-speed civil transport wing concepts.

Table 1. CAWAP nominal flight condition ranges.

Parameter	Minimum	Maximum
h	5,000 feet	44,500 feet
M	0.24	1.30
$\mathbf{R_{cref}}$	27.4 x 10^6	123.5 x 10^6
α	2.3^o	20^o
β	0^o	+/- 5^o

The flight data measurements began in 1994 and were focused on the wing upper surface flow properties. Instrumentation was distributed on both wings, and included pressure-based, video-based, and hot-film based measurements. Static surface pressure measurements were obtained with a combination of flush-mounted pressure taps and pressure belts on the right (starboard) wing semispan. The static taps were used near the leading edge where the wing boundary layers were anticipated to be too thin for proper use of the pressure belts. Data were obtained at a total of 326 stations with 280 stations on the upper surface and 46 on the lower surface. Boundary layer velocity profiles were obtained with surface-mounted rakes at four stations on the left (port) wing semispan. The rakes were sized to obtain approximately 16 measurements in the boundary layer. Sizing and orientation of the rakes were based upon pre-test CFD predictions. Skin friction measurements were performed at sixteen locations on the left wing semispan. The measurements were obtained with Preston tubes modified to provide integral static and total pressure measurements. These Preston tubes were also oriented to align with local flow directions predicted from CFD.

Wing upper surface flow visualization was performed primarily on the left wing semispan with three measurement techniques, surface-mounted tufts, oil flows, and liquid crystals. The visualization was recorded with

Figure 4. CAWAP flight instrumentation, F-16XL-1 aircraft.

six external cameras added to the aircraft and occasionally a seventh camera to help document flight conditions from the cockpit heads-up display (HUD). Upper-surface wing targets were also included to help register the optical data from the various cameras. Finally, hot-film sensors were mounted on the left wing semispan near the leading edge. Twelve measurements stations were active, and the gages were used to assess the boundary layer state (laminar/turbulent). Such a broad range of measurements is unusual for a flight-test program. A photograph of the F-16XL-1 research aircraft is shown in **Figure 4** that illustrates some of the in-flight surface instrumentation used for flow visualization on the wing upper surface.

Initial data analysis and CFD assessments were presented in 2001 by Lamar[2] [2003] at a NATO Research and Technology Organization (RTO) symposium on Vortex Flow and High Angle of Attack for Military Vehicles. The range of conditions analyzed by Lamar is shown in **Table 2** along with the quantities compared between flight experiment and CFD predictions in that report. Lamar's computations were performed with the blocked/structured code CFL3D as developed by Thomas[6] [1989] and the aircraft was modeled as a semispan with 30 blocks and approximately 1.37 million cells. All the target conditions were at high (full-scale) Reynolds numbers, and wall functions were used to represent the inner regions of the turbulent boundary layers. At the time of this work the discretization was considered to be a minimal number of cells to capture key flow physics while staying within available numerical resources for the body of anticipated runs.

Table 2. CAWAP flight conditions, nominal values.

FC	M	R_{cref}	α, deg.	Comparison
01	0.52	77.7×10^6	5.5	C_p
07	0.30	44.4×10^6	11.9	b.l. , $C_{f,cfd}$
19	0.36	46.8×10^6	11.9	$C_{f,exp}$
46	0.53	44.9×10^6	10.4	C_p , Oil flow
70	0.97	88.8×10^6	4.4	C_p

These CFD predictions showed promising correlation with overall flow features. An example from Lamar[2] [2003] is shown in **Figure 5** where computational oil flow traces (yellow) are overlaid with the experimental wing-tuft flow visualization. By inference from this comparison, some major vortical structures appear to be in about the same locations. Global C_p contours also looked promising, further implying that the vortical strengths may be roughly similar between the numerical and experimental results. However, quantitative comparisons for boundary layers and skin friction were less than desirable. In addition, the quantitative pressure coefficient comparisons from Lamar[1] [2001] were mixed; some good correlations were achieved, while many other correlations were less accurate than would be desired. Only five conditions were available for this analysis, and in some cases the correlation quality varied spatially over the wing at fixed conditions.

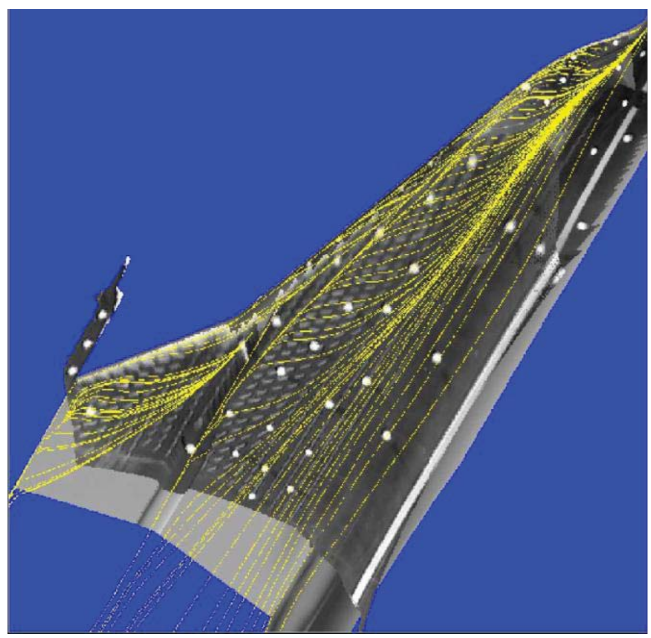


Figure 5. Flow pattern comparison. FC-46, $M_\infty = 0.53$, $R_{cref} = 46.9\times10^6$, $\alpha = 10.4^o$. From Lamar[2] [2003].

Lamar demonstrated that some of the overall features of the complex flow about the F-16XL-1 aircraft were being captured by his simulations; at the same time the simulations were not accurate enough (some cases were not very good) and the sources for these predictive deficiencies were unclear. More importantly, the a priori distinction for which aerodynamics would be well predicted and which would not was also unclear.

These computations had been a significant undertaking and demonstrated some very significant findings, and yet there were results from only one code, with one particular numerical modeling approach. Improvements to the CFD predictive capability were sought, and this resulted in an international collaborative effort coordinated through the Research and Technology Organization. The RTO facilitates scientific and technical collaborative activities that are of mutual interest among member nations of the North Atlantic Treaty Organization (NATO). This subsequent activity will be discussed next.

C. Cranked Arrow Wing Aerodynamics Program, International (CAWAPI)

The subsequent activity, Cranked Arrow Wing Aerodynamics Project, International (CAWAPI), was accomplished through RTO Task Group AVT-113 entitled "Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft". This brought many CFD practitioners from within the NATO community to focus on this challenge. The project roughly spanned 2004 to 2008 and built upon Lamar's findings from 2001.

The flight conditions for this work are shown in **Table 3** and **Figure 6**. The four mandatory conditions came directly from the Lamar RTO report[2] [2003]. Three optional conditions were added to address low-speed high angle of attack performance and sideslip effects. From Figure 6 it can be observed that the CAWAPI conditions encompassed (i) a single low-speed high-alpha condition, (ii) a family of moderate-speed moderate-alpha conditions, and (iii) a single high-speed (transonic) low-alpha condition.

The scope of CFD contributions to this project was greatly expanded from Lamar's original work and is summarized in **Table 4**. Ten codes from nine institutions were used. Most of the codes were RANS with a few DES/DDES contributions. A rather full suite of turbulence models were included, and many unstructured formulations had matured sufficiently to now contribute to the CAWAPI work. Almost all the computations were steady with non-adapted grids. Compared to Lamar's original work, grid sizes were increased by roughly an order of magnitude for the CAWAPI computations.

Table 3. CAWAPI flight conditions, nominal values.

FC	M	R_{cref}	α, deg.	β, deg.
Mandatory Conditions				
07	0.30	44.4 x 10^6	11.9	-0.1
19	0.36	46.8 x 10^6	11.9	0.6
46	0.53	44.9 x 10^6	10.4	0.7
70	0.97	88.8 x 10^6	4.4	0.3
Optional Conditions				
25	0.24	32.2 x 10^6	19.8	0.7
50	0.43	39.4 x 10^6	13. 6	5.3
51	0.44	39.0 x 10^6	12. 9	-4.6

A number of topics were addressed with the CAWAPI work. Among these were (i) F-16XL-1 geometry modeling, (ii) grid tessellation/density effects, (iii) numerical formulation/modeling effects, (iv) turbulence modeling effects, and (v) effects/issues with the flight data. The scope of these issues and assessments requires a teamed approach in order to build the necessary analyses among multiple CFD practitioners, multiple numerical methods and models, and so forth. This RTO Task Group represented one particular teamed approach, and a number of others are in practice (e.g., the Drag Prediction Workshop activities). Additional comments on this aspect of our current computational aerodynamics research will be provided later in the paper.

After approximately six years considerable progress was demonstrated. Two special sessions at the 2007 45th AIAA Aerospace Sciences meeting highlighted these individual contributions and a summary reporting of the results can be found among the contributions from Obara[7] [2009], Boelens[8,9] [2009], Görtz [10] [2009], Fritz[11] [2009], and Rizzi[12] [2009] to a special edition of the AIAA Journal of Aircraft. A few examples follow, and additional details may be found in the full RTO report[13] [2009] for the AVT-113 research.

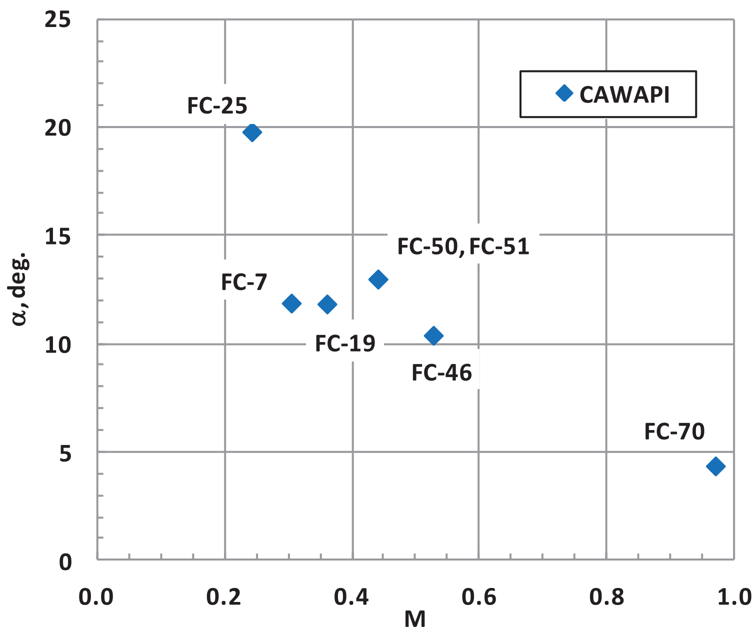
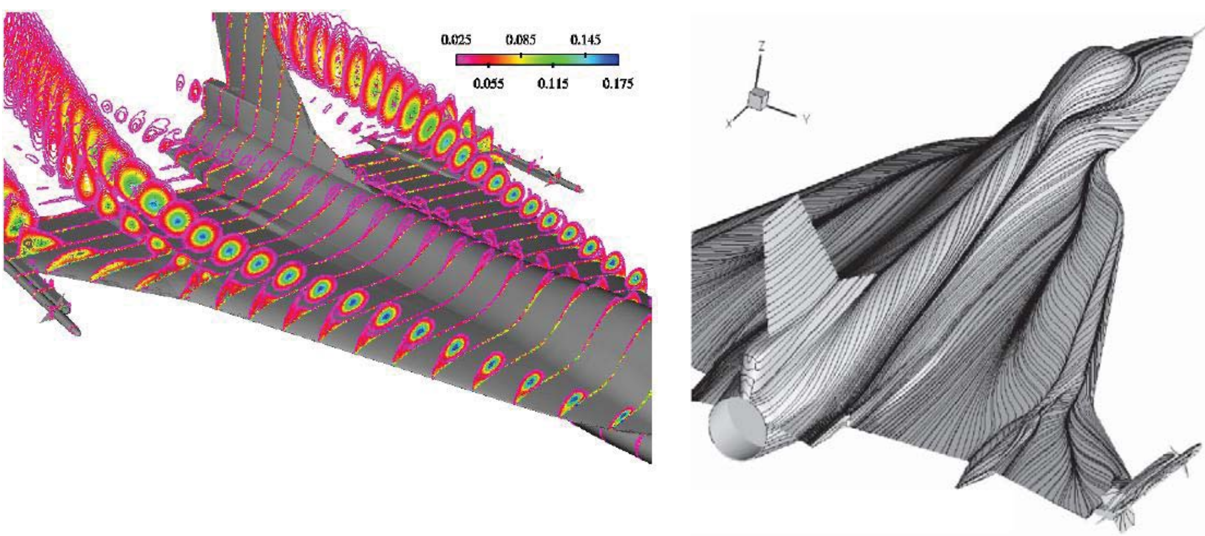


Figure 6. CAWAPI parameter space.

Improved fidelity of F-16XL-1 surface modeling as well as the increased field resolution from the higher grid densities contributed to better resolved flows about the aircraft. An example from Rizzi[14] [2007] and Boelens[15] [2007] is reproduced in **Figure 7** for flight condition 7. A very good resolution of this vortical flow was achieved, including multiple wing vortices, and is a representative subsonic solution for this condition. Most of the computed results were in fairly good agreement among themselves except in the region of the peak suction from the leading-edge vortex. An example is shown in **Figure 8** from Rizzi[14] [2007]. Here the solutions are presented only as a collective without distinguishing the details among the individual simulations. For this comparison flight-test data were included from nearby conditions at slightly higher angles of attack (13.5°, 13°) and also at higher subsonic Mach numbers (0.37, 0.40). Flight Condition 7 was a benchmark case for the original CAWAP research, but unfortunately the flight pressure data at this condition were not recoverable. There was a consensus decision among the CAWAPI participants that data from the near-by conditions shown in Figure 8 could be useful for comparisons against CFD computations of FC-7.

Table 4. CAWAPI partners, topics, and computational methods.

#	Partner	Topics	Code	Flow Modeling	Temporal Modeling	Structured/ Unstructured	Grid Size (Semispan)	Grid Adaptation
1	Boeing	Subonic, Transonic	BCFD	RANS; SA, SST RANS-SST/LESb	Steady, Unsteady	UnStr	23.3 M cells	Manual
2	EADS	Subonic, Transonic	DLR-TAU	RANS; SA, k-ω	Steady	UnStr	~ 21 M points	Manual, Solution Based
3	KTH/FOI	Subonic, Transonic	EDGE	RANS; SA, EARSM k-ω DES RANS-LES	Steady, Unsteady	UnStr	11.9 M cells	None
4	Lockheed Martin	Subonic, Transonic	Falcon	RANS; k-kl	Steady	UnStr	13.9 M points	None
5	NASA LaRC	Subonic, Transonic	PAB3D	RANS; k-ω, EARSM	Steady	Str	14.8 M cells	None
6	NASA LaRC	Subonic, Transonic	USM3D	RANS; SA, k-ε	Steady	UnStr	16.2 M cells	None
7	NLR	Subonic, Transonic	ENFLOW	RANS; TNT k-ω	Steady	Str	14.8 M cells	None
8	UL	Subonic, Transonic	PMB	RANS; k-ω	Steady	Str	14.8 M cells	None
9	US Air Force Academy	Subonic, Transonic	Cobalt	DES; SARC DDES; SARC	Unsteady	UnStr	11.9 M cells	None
10	UTSIM	Subonic, Transonic	TEN ASI	RANS; k-ω/k-ε hybrid	Steady	UnStr	13.9 M points	Manual



a) Total pressure contours **b) Surface streamlines**

Figure 7. F-16XL-1 computational results. FC-7, M = 0.304, R_{cref} = 44 x 10^6, α = 11.9°. From Rizzi[14] [2007], Boelens[15] [2007].

From the overall CAWAPI effort a number of the moderate-alpha, moderate-Mach conditions appeared to be much better understood with some of these warranting further refinements. However, despite the collective CAWAPI accomplishments two of the flight conditions were not well predicted by the team. These conditions were (i) FC-25, the subsonic high-alpha case and (ii) FC-70, the transonic low-alpha case.

For the subsonic high-alpha case the greatest discrepancies among CFD results as well as with experiment occurred on the outboard 50-degree swept wing panel. Here the outboard separation had become very complicated with multiple vortical flows interacting. For the transonic, low-alpha case the CAWAPI CFD results collectively missed the experimental measurements. An example is shown in **Figure 9** from Rizzi[14] [2007] where the longitudinal location of the wing shock is significantly different between CFD and flight test measurements. Some correlations at other stations were better, others were worse. Flow details of each of these cases will be discussed in the next section.

Both of these cases were singular in terms of the CAWAPI suite of conditions, that is, there were no other neighboring conditions from the CAWAP data set that had been chosen for the CAWAPI investigations. At the completion of the CAWAPI research, there did not appear to be a quick resolution of these unsatisfactory predictions and the team collectively thought they would warrant a new effort to leverage the lessons learned from CAWAPI toward understanding why these particular correlations with experiment had been unsatisfactory and hopefully arrive at improved predictive capability. This became the focus for the CAWAPI-2 effort which is described in the next session.

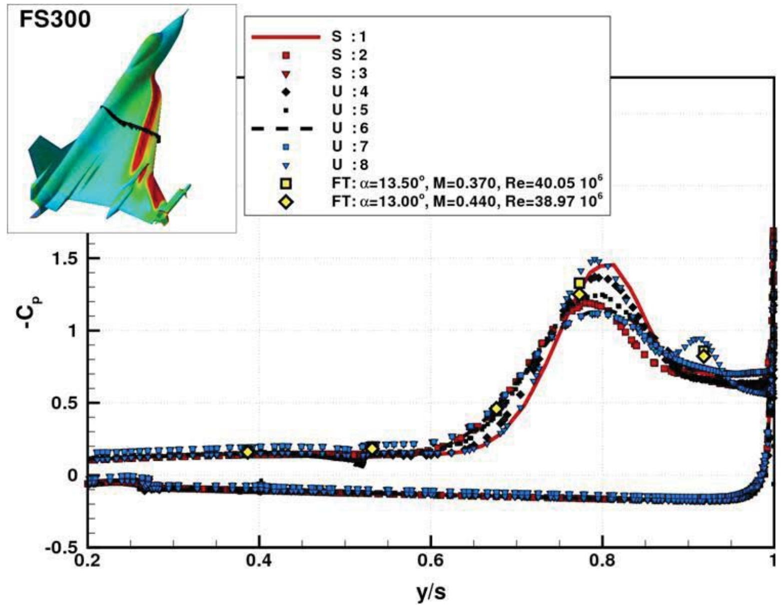


Figure 8. Spanwise pressure distributions, Fuselage Station 300. CFD for FC-7, M = 0.304, R_{cref} = 44 x 10^6, α = 11.9°. Experiment for nearby flight conditions. From Rizzi[14] [2007].

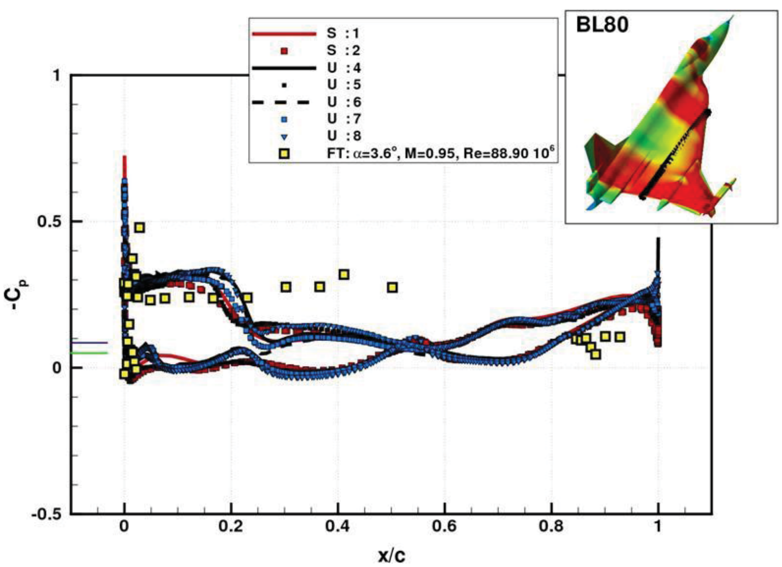


Figure 9. Chordwise pressure distributions, Butt Line 80. FC-70, M = 0.97, R_{cref} = 89 x 10^6, α = 4°. From Rizzi[14] [2007].

IV. Current Program, CAWAPI-2

After some planning and business preparation the CAWAPI-2 effort was initiated in 2010. Original plans were for a three year activity, and the work now is scheduled to complete in 2015. The focus conditions for this project along with the overall approach are reviewed next.

A. Focus Conditions and Partners

The two conditions with poor correlation from CAWAPI were reviewed and sustained as the focus conditions for CAWAPI-2. Advances in computational technology appeared promising for further investigation to these flows, and there was sustained interest among the participating researchers as well as their sponsors. Some details of these conditions are reviewed next.

1. Subsonic, High Angle of Attack

A representative solution for the subsonic high angle-of-attack case is shown in **Figure 10** from the new work of the National Aerospace Laboratory, NLR. Compared to the moderate angle of attack work from CAWAPI (see, for example, Figure 7), the wing vortices are in much closer proximity over the outboard panel. From the image one can see the primary leading-edge vortex from the inboard 70^o swept leading edge, a second primary vortex from the outboard 50^o swept leading edge, and a third counter rotating primary vortex between these two leading-edge vortices that forms from the exposed edge of the wing air dam. Secondary vortices will most likely be present for each of these three primary vortices. Vortex interactions could be very important to the outer panel flow field, and at this angle of attack vortex breakdown is likely to occur over the wing among some of these primary vortices. Thus, flow unsteadiness could also be important to the outer panel aerodynamics from either the vortex interaction or the vortex breakdown flow physics perspective. FC-25 was the only high-angle-of-attack flight condition included in the CAWAPI work.

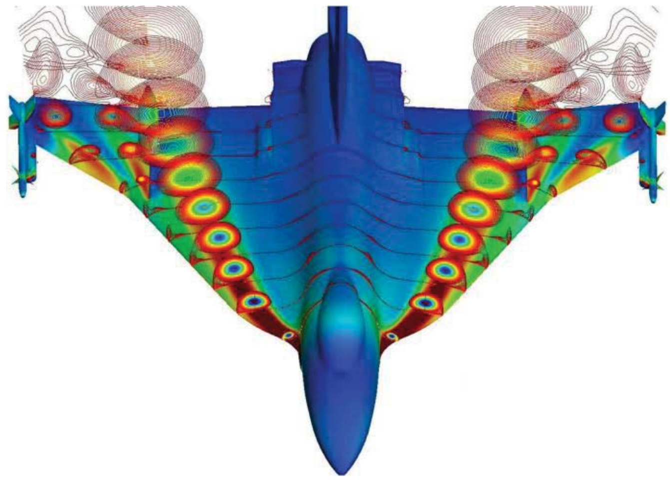


Figure 10. Subsonic high angle-of-attack case. FC-25, M = 0.24, R_{cref} = 32 x 10^6, α = 20^o.

2. Transonic, Low Angle of Attack

A representative solution for the transonic low angle-of-attack case is shown in **Figure 11** from Davis[16] [2007]. This image shows Mach 1 iso-surfaces colored by total pressure. A succession of three shock structures is evidenced about the aircraft; smaller but similar structures are present on the tip missiles as well. These shocks are certainly dominant flow structures, but it can be anticipated that any vortical flows will result in complex shock-vortex interactions on the wing upper surface. Flow unsteadiness could again be important to this condition due to shock induced separation. FC-70 condition was the only transonic flight condition included in the CAWAPI work.

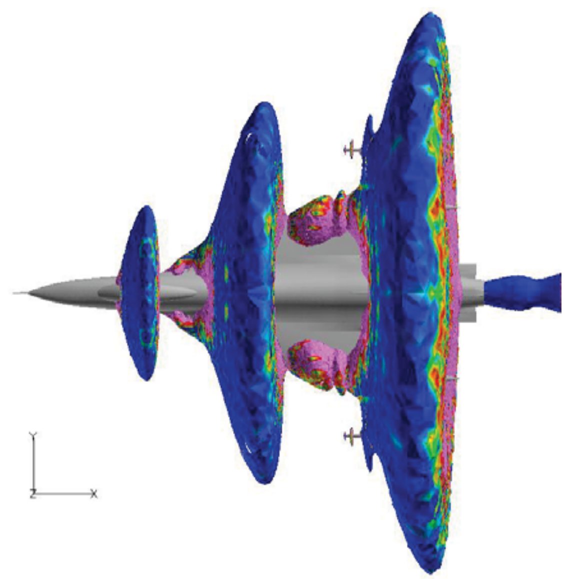


Figure 11. Transonic low angle-of-attack case. FC-70, M = 0.97, R_{cref} = 89 x 10^6, α = 4^o. From Davis[16] [2007].

3. Partners

Participation in the CAWAPI-2 effort was smaller than that of CAWAPI in part due to budget restrictions as well as competing priorities and schedules. None the less, a team with diverse skills was established to conduct the current investigations. Five institutions with four computational methods were able to commit to the present effort. Partners contributing computational results were (i) Airbus D&S: Airbus Defense and Space Company (Military Aircraft), Germany, (ii) KTH: Royal Institute of Technology, Sweden, (iii) LaRC: NASA Langley Research Center, America, and (iv) NLR: National Aerospace Laboratory, the Netherlands. A fifth partner, Lockheed-Martin, was able to provide expert consulting for the F-16XL-1 aircraft. All partners were also participants from the predecessor CAWAPI effort. Details of the individual numerical approaches will be discussed in the next section.

B. Approach

Analysis for the focus cases spanned a variety of topics including (i) additional flight data and aircraft operation considerations (e.g., flap settings, aeroelastics), and (ii) improved numerics (e.g., flow modeling, grid effects). Conditions and methods were selected to help isolate and understand some of the underlying flow physics that were anticipated to be affecting the flows at the focus conditions.

1. *Flight Data Parameter Space and Aircraft Operations Considerations*

Early in the CAWAPI-2 project the overall flight test matrix was reexamined to seek additional flights that could add information to the two focus cases described above. Twelve more flight conditions were found and the resulting CAWAPI-2 matrix of initial and expanded flight conditions is summarized in **Table 5** and **Figure 12.** (In Figure 12 the CAWAPI-specific FC labels are omitted for clarity).

Table 5. CAWAPI-2 flight conditions, nominal values

FC	M	R_{cref}	α, deg.	β, deg.
Initial Conditions				
25	0.24	32.2×10^6	19.8	0
70	0.97	88.8×10^6	4.4	0
Expanded Conditions				
26	0.24	32.2×10^6	19.8	5
27	0.24	32.2×10^6	19.8	-5
40	0.28	29.6×10^6	20	0
41	0.28	29.6×10^6	20	5
55	0.32	27.4×10^6	20	0
56	0.32	27.4×10^6	20	5
43	0.81	69.6×10^6	5	0
68	0.90	88.8×10^6	3.7	0
79	0.90	88.8×10^6	9.3	0
69	0.94	88.8×10^6	3.6	0
80	0.95	88.8×10^6	8.8	0
81	0.98	88.8×10^6	8.1	0

For the subsonic high-alpha case six additional cases were found. All of these were at or very near to 20^o angle of attack. The first two expanded flight conditions in Table 4, FC 26 and FC 27, were sideslip companions to the focus condition FC 25. By simple sweep reasoning, each of these cases would modulate the leading-edge vortex strengths and outer-panel vortical interactions. There was also a sense that some very approximate flight-test measurement uncertainty information might be gleaned from these two flights. The remaining four subsonic expanded conditions provided additional data at slightly increased Mach numbers (M = 0.28, 0.32) for zero and five degrees sideslip. Subsonic compressibility effects would be small over this range of free-stream Mach numbers, so these data were anticipated to also help address measurement and flight-operations uncertainty as much as or perhaps more than addressing aerodynamic effects.

Six additional flights were also found for the transonic low-alpha case. The transonic focus condition was at a very high transonic Mach number, M = 0.97, so cases were selected to provide a succession of transonic Mach numbers (M = 0.81, 0.90, 0.94, 0.95, 0.98) building up to and slightly exceeding the FC-70 condition to better understand the transonic compressibility effects. These conditions were also selected to include low (α = 3.6^o, 3.7 ^{o}, 5^o) and moderate (α = 8.1^o, 8.8^o, 9.3^o) angles of attack. In this manner shock-vortex effects would be modulated between the low and moderate alpha cases and provide additional information for CFD code assessments. Some uncertainty in the control surface settings for the FC-70 flight condition was discovered, and the expanded transonic flight conditions were also selected to help

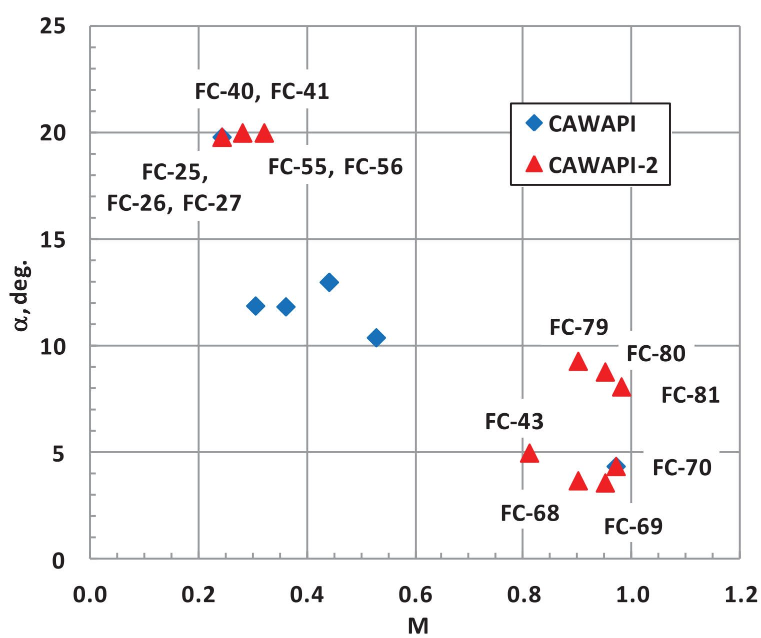


Figure 12. CAWAPI and CAWAPI-2 parameter spaces.

address this concern. Additional considerations for engine setting effects and aeroelastic effects were included in both the transonic and low-speed focus conditions.

2. Flow Models

The CAWAPI-2 computational methods are summarized in **Table 6**. Most calculations were still RANS-based with some limited DES simulations included. Because all practitioners and methods were experienced from the prior

Table 6. CAWAPI-2 partners, topics, and computational methods.

#	Partner	Topics	Code	Flow Modeling	Temporal Modeling	Structured / Unstructured	Grid Size (Semispan)	Grid Adaptation
1	A-D&S, Mil. Aircraft	Subsonic, Transonic	DLR-TAU	RANS; SAE, k-ω U-RANS; SAS	Steady, Unsteady	UnStr	45.0 M points	Manual
2	KTH	Subsonic	EDGE	RANS; SA, EARSM URANS; EARSM	Steady, Unsteady	UnStr	30.3, 44.1 M points	None
3	KTH	Transonic	EDGE	RANS; SA, EARSM, DRSM Hybrid RANS-LES	Steady, Unsteady	UnStr	30.3, 37.6, 44.1 M points	Solution Based
4	KTH	Transonic Aeroelastic	EDGE	Euler RANS; SA	Steady	UnStr	3.8 M points, Euler 44.1 M points, RANS	Aeroelastic
5	NASA LaRC	Subonic	USM3D	RANS; SA, k-ε, SST	Steady	UnStr	19.4, 62.5, 143.0 M cells	Error Quantification
6	NLR	Transonic	ENSOLV	RANS; TNT k-ω	Steady	Str	14.8 M cells	None

CAWAPI work, these computations were initiated from a well-informed perspective. One could consider the particular approaches used in the present effort (such as turbulence models) as a down-select from the predecessor CAWAPI efforts. For CAWAPI-2, and perhaps consistent with the times, most methods were unstructured. Average semispan grid resolution more than doubled compared to the prior CAWAPI effort with one grid being an order of magnitude larger. In addition, three of the six studies included some form of grid adaptation to further provide improved resolution of key flow features. As such, an assessment among these adaption technologies became another facet of CAWAPI-2.

3. Improved Understanding

What was learned in CAWAPI basically is that we do understand, and can reasonably compute, the flow physics involved in the flight conditions FC-7, FC-19, FC-46, FC-50 and FC-51, those in the mid-section of Figure 10, but the understanding for the two outlying conditions: FC-25 at almost twice the angle of attack, and FC-70 at double the Mach number was less complete and requires further study. In order to advance the knowledge of what is happening in these two extreme cases, we need to look more closely at answers to:

(i) Flight data – are there issues with in-flight measurements, especially surface pressures?
(ii) Aircraft conditions – are these known precisely enough so we are actually computing the correct condition?
(iii) Flow physics – is our understanding correct for the physics in the aircraft conditions?
(iv) Airframe/physics interactions - how are the flow physics and the aircraft operations/geometry related?
(v) Flow modeling – are we correctly modeling the flows?

For all these questions, and for the flow modeling in particular, we would seek to distinguish what is important, what is not, and do so with some sense of confidence. As was the case for CAWAPI, our primary yardstick to measure progress in answering questions like the above is how well our computed pressure distributions compare with measured flight pressure distributions.

Let us summarize the understanding of the two extreme cases, FC-25 and FC-70, from the conclusion of CAWAPI:

FC-25 – Increasing α → Unsteady Low-Speed Flow at High Angle of Attack. The only unsteady modelling approach taken was that by the USAFA with a DES turbulence model in time-accurate mode to capture large-scale unsteadiness (Morton[17] [2007]), and their results demonstrated that the effect of increasing alpha from that in FC-7 to that in FC-25 is the onset of substantial unsteadiness over the outboard wing panel, with associated strong interactions between the three vortices shed respectively from the (i) inner wing, (ii) actuator pod,/air dam, and (iii) crank, possibly including breakdown of the inner vortex. One of Morton's unsteady SARC/DES results from Ref. 15 for FC-25 is reproduced in **Figure 13**. Note that the flow in the vicinity of the wing tip is made even more complex because of the vortex wake off of the missile fins, especially at this angle of attack. The USAFA unsteady modelling produced the best comparisons with measured surface pressure.

<u>*FC-70 - Increasing Mach → Strong Shock-Vortex Interaction - Steady Low α Transonic Flow.*</u> For this condition there are fewer vortices, essentially just the inner vortex and it is weak, barely just rising out of the boundary layer. However, strong shocks appear that interact forcibly with the inner vortex. All of the results computed in CAWAPI-1 results agree with each other, but not with measured pressure. Possible explanations for this discrepancy have been suggested, e.g. some or all of the control surfaces were deployed during the flight testing (these were not modeled in the computations), and possible aeroelastic deflections of the airframe (outer wing panel) due to the high dynamic pressure.

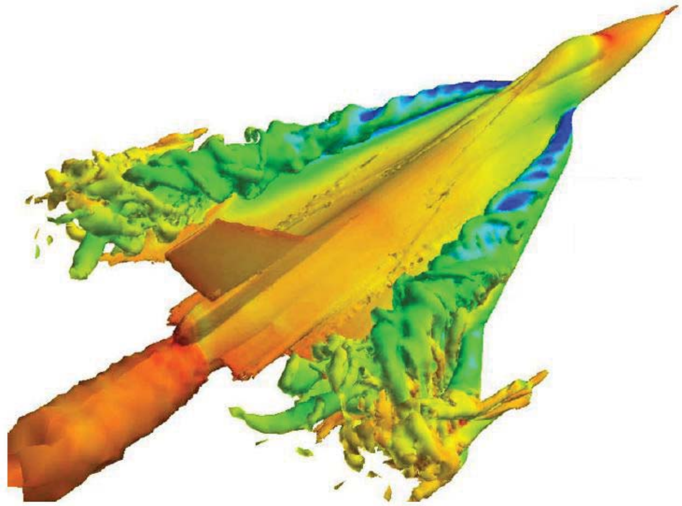


Figure 13. Vorticity magnitude iso-surfaces colored by pressure. FC-25, M = 0.24, R_{cref} = 32 x 10^6, α = 20°. From Morton[17] [2007].

Strategies need to be devised to put in place approaches to improve the simulation of these two extreme conditions that take into account the considerations (i) - (v) at the beginning of this Improved Understanding section. For both conditions clearly denser more highly resolved grids are called for, including adaptation to features like vortices and shocks. For condition FC-25, accurate unsteady modeling appropriate to the flow physics expected must be employed, e.g. hybrid RANS-LES physical models.

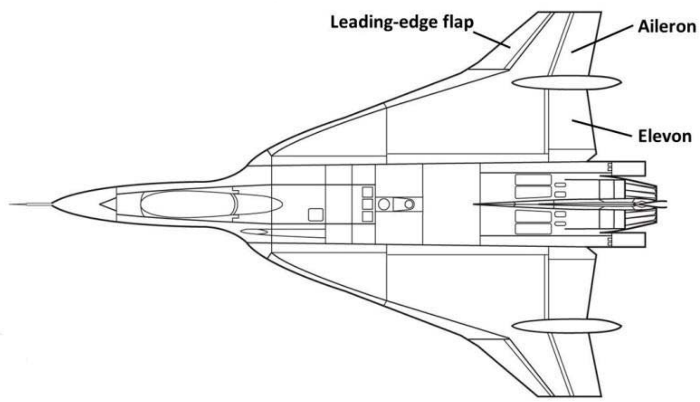


Figure 14. F-16XL control surfaces.

Several approaches are specific to the transonic low-alpha condition (FC-70). The CAWAPI CFD was all performed with no control surface deflections. This assumption was based in part on the fact that the F-16XL was basically a neutrally stable aircraft, thus requiring only small deflections for trim. However, the control surfaces are not small, especially as regards the outer wing panel, **Figure 14**. Even small deflections of these surfaces could be important, and some flight data imply control surface deflection effects. It could be instructive to account for or better assess the effects of possible control surface deflections during flight, either by modelling the surfaces in the simulation, or by examining neighbouring flight conditions where the deflections are known with more certainty. Some of this analysis has been carried out by Boelens[18] [2014].

Second, the dynamic pressures associated with transonic flight conditions could warrant rough first-order estimates of the aeroelastic effects. Only limited knowledge about the structural model of the aircraft could be available, but a sense of whether elastic effects move the rigid CFD in the direction of the flight measurements would still be useful.

C. Collaborative CFD Assessment Campaigns

The F-16XL-1 computational work has benefited significantly by establishing a collective for the numerical investigations. While single-code/single-investigator CFD assessments will continue to advance our craft, there are problems that virtually require (or at a minimum significantly benefit from) this teamed and sustained approach to the numerical investigation. The diversity of opinion and numerical formulation along with the opportunity to assess numerical uncertainty can provide a rich environment for understanding complex aerodynamic phenomena. Of course, dispersion of the work across the necessary computers doesn't hurt either.

The F-16XL-1 work is by no means alone or unique in this collective approach to computational aerodynamics. This approach goes back at least to the inception of the Drag Prediction Workshops, and by now a number of these campaigns have been initiated to address various challenging problems closely connected to aircraft performance. A summary for some of the more aerodynamic/aircraft-performance centric activities is shown in **Table 7** to illustrate part of the scope that this class of work has taken on. In the interest of brevity, Table 7 only includes the year for a first workshop or workshop-like event, the number of workshop/reporting cycles, the number of institutions that have contributed results, and the number of codes that have been used. The scope of participation is noteworthy, and the depth of investigation is richer than this simple table can indicate (e.g., some activities, such as BANC, are sponsoring multiple focus studies). At this time all of these campaigns are active in one form or another. Each of these campaigns has a unique aerodynamic focus which, in turn, stresses different underlying flow physics.

Table 7. Some Collaborative CFD Assessment Campaigns.

Name	Initiated	Cycles	Institutions	Codes
Aeroelastic Prediction Workshop (AEPW)	2012	1	18	19
Benchmark Problems for Airframe Noise Computations (BANC)	2009	2	29	23
Cranked Arrow Wing Aerodynamics Projects (CAWAP, et al.)	2003	2	10	10
Drag Prediction Workshop (DPW)	2001	5	54	46
High-Lift Prediction Workshop (HLPW)	2010	2	32	25
Low-Boom Prediction Workshop (LBPW)	2014	1	~ 13	~ 17
Shock Boundary-Layer Interaction Workshop (SBLI)	2010	1	8	10

For CFD to provide predictive capability requires simulation of such relevant underlying flow physics with sufficient fidelity. However, a priori knowledge of just what the relevant physics are, and just what sufficient fidelity really constitutes can be elusive. One common outcome from these efforts is the identification of new experiments that are required to help elucidate critical physics relevant to meaningful CFD predictive capability. As a case in point, virtually all of the activities listed in Table 7 are spawning new wind-tunnel tests to better understand the particular focus topics and to possibly provide validation-class data for code assessment and improvement. The notable exception is the CAWAP activities which have been tied to flight-test data. This class of collaborative CFD assessment with focused validation-like experimentation that is directed toward the particular program objectives for enhanced CFD predictive capability appears to be a very fruitful approach for future advancements to computational aerodynamics.

D. Context Comment

While the F-16XL provides a significant opportunity for CFD assessments and improved understanding of slender-wing aerodynamics, it must be pointed out that the detailed geometry of this aircraft is governed by International Traffic in Arms Regulations (ITAR). As such, special provisions apply for access and use of the geometry. All information in this report is unclassified and unrestricted.

V. Summary

A review has been presented for an effort directed at predicting the slender-wing aerodynamics of an F-16XL aircraft with state-of-the-art computational fluid dynamics. The overall work has spanned nearly 20 years and included international collaboration.

The flight data set was created by NASA and is very unique. In addition to static surface pressures, the in-flight measurements include boundary-layer profiles, surface skin friction measurements and several types of surface flow visualization. Targeted transition detection measurements were also performed. Data were obtained at flight conditions spanning low to high angles of attack and subsonic to supersonic Mach numbers. About 2/3 of the data set were obtained in level 1-g flight.

After some preliminary CFD efforts at NASA, an international campaign was initiated through the Research and Technology Organization (RTO) to seek improved understanding and predictive capability from a wide variety of CFD methods. This approximately six-year effort produced considerable advancement and also identified two unyielding cases for further investigation. A second collaborative CFD effort was initiated and the scope of this new effort has been reviewed. The results of this new campaign will be reported in subsequent papers.

The F-16XL affords a very unique data set for CFD assessments, and the documented collective results of the various efforts also help provide understanding to the flow fields and aerodynamics of this class of slender-wing vehicle. Many other conditions are available within the flight data for future analysis.

VI. Acknowledgments

The initial approach to the expanded transonic analysis was developed by Willy Fritz of EADS/Cassidian, and the authors gratefully acknowledge this contribution along with other insightful discussions. This work was supported in part by the Fundamental Aeronautics Program, High-Speed Project.

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