Program Overview: Vortex Interaction Aerodynamics Relevant to Military Air Vehicle Performance

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A research program has been underway for five years to study vortex interaction aerodynamics that are relevant to military air vehicle performance. The program has been conducted under the auspices of the NATO Science and Technology Organization (STO), Applied Vehicle Technology (AVT) panel by a Task Group with the identification of AVT-316. Seven special sessions have been established to highlight accomplishments from the AVT-316 research. An overview of the AVT-316 program is presented in this paper.

Nomenclature

C_p	pressure coefficient
$C_{p,t}$	total pressure coefficient
c	wing chord
c_r	wing root chord
c_{ref}	reference chord
d	diameter
M	Mach number
mac	mean aerodynamic chord
P_t	total pressure
Re_c	Reynolds number, $U_\infty c / \nu$
U_∞	freestream reference velocity
x,y,z	body-axis Cartesian coordinates
α	angle of attack, deg.
β	angle of sideslip, deg.
Λ_{le}	leading-edge sweep angle, deg.
λ	roll angle, deg.
μ	viscosity
ν	kinematic viscosity, μ/ρ
ρ	density
σ	total angle of attack

Abbreviations:

AGARD	Advisory Group for Aerospace Research and Development
AVT	Applied Vehicle Technology
CFD	Computational Fluid Dynamics
DLR	German Aerospace Center, *Germany*
LES	Large Eddy Simulation
NATO	North Atlantic Treaty Organization
RANS	Reynolds-averaged Navier Stokes
RTO	Research and Technology Organization
STO	Science and Technology Organization
TUM	Technische Universität München, *Germany*
UCAV	Uninhabited Combat Air Vehicle
VFE-2	Vortex Flow Experiment 2

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I. Introduction

Aircraft can often develop separation-induced vortex flows at elevated load conditions. In some instances, these vortex flows have been exploited to augment high-lift performance while, in other instances, they must be tolerated as a byproduct of a configuration design and operational requirements.

For practical aircraft geometries, the vortical flows can become highly complex and involve interactions among multiple vortices, between vortices and shocks, and between vortices and vehicle components. Two examples are shown in Figure 1, and, in both examples, the vortices can be seen due to natural condensation effects. Part (a) of Figure 1 shows some of the complex vortical flow about the Eurofighter Typhoon aircraft in elevated loading due to maneuver. On the port side, a body strake vortex can be seen along with a second vortex originating from the vicinity of the wing leading edge and body juncture. On the starboard side, a succession of vortices can be seen on the wing upper surface that form at the junction of the slat with the wing. Other vortices are likely to be present that are not observed by the natural condensation (e.g., side-edge vortices from the deployed slat, tip vortices from canards). The multiple vortices are interacting among themselves as well as with the neighboring surfaces of the aircraft. Several improvements to the maneuver performance of the Eurofighter Typhoon from these vortex flows have been documented by Hitzel and Osterhuber [1].

(a) Maneuver

(b) High lift

Figure 1. Vortex interaction flows.

Part (b) of Figure 1 shows a single vortex that is formed by an engine nacelle strake that persists over the wing upper surface of a commercial transport in elevated loading for high-lift performance, i.e., takeoff and landing. For this application, the separation-induced vortex flow has been carefully designed to exploit interactions with the wing upper surface. Without the nacelle-strake vortex, the nacelle wake can result in localized wing stall at high-lift conditions typical to takeoff and landing. The nacelle strake vortex induces an attached flow over wing upper surface aft of the nacelle such that the desired high-lift performance is achieved. For this application, the interaction of the single vortex with the wing upper surface is critical to achieving the high lift necessary for takeoff and landing.

Vortex interactions can occur in many ways and can have many aircraft applications beyond these two examples just discussed. (Consider, for example, vortex generators.) A NATO research task group, AVT-316, was recently formed to select a few vortex interaction topics and assess our capabilities to understand and predict the associated vortex interaction aerodynamics. This paper provides an overview of the AVT-316 program content and serves as an introduction to 21 subsequent papers in this conference with technical details of the AVT-316 research. Background information is presented first, followed by the AVT-316 program overview.

II. Background

Three classes of vortex interactions were chosen as an organizing principle for the AVT-316 research planning. These vortex interaction classes are reviewed in this section with some basic examples on simple wing shapes. The AVT-316 research program includes more complex combinations of these basic interactions, consistent with partner and NATO interests. Since the project was performed under the auspices of the STO, a summary of the STO is also included in this section.

A. Vortex Interactions

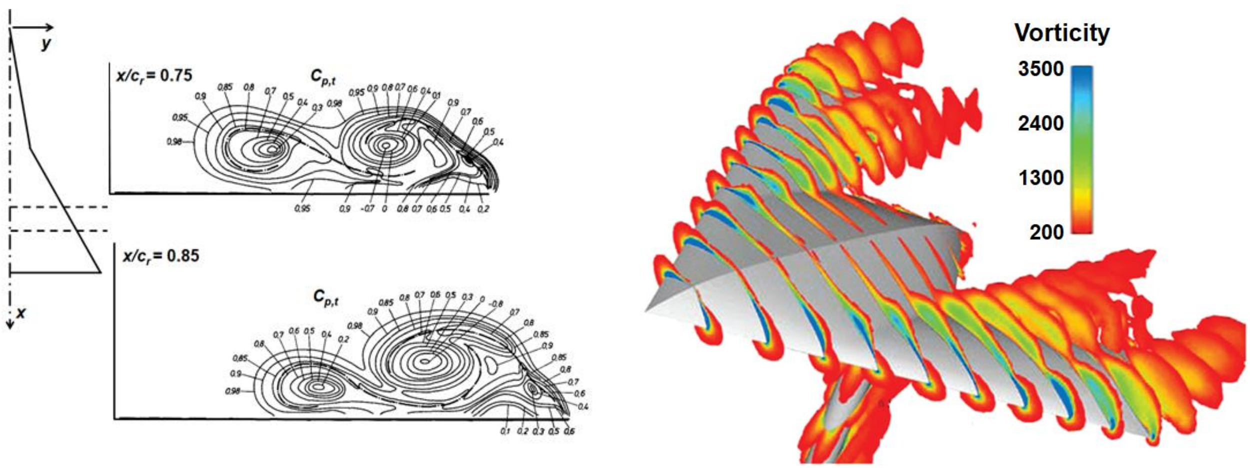
Vortex interactions can occur in several ways, and the different vortex interactions will stress different physics of the vortical flows. The vortex interactions that arise on complex aircraft geometries have been decomposed into classes based upon the underlying physics of the vortex interaction. There can certainly be more than one way to organize and/or decompose vortex interactions, and the approach used in the initial planning of the AVT-316 research was to identify three classes of vortex interactions:

- Vortex-vortex interactions
- Vortex-shock interactions
- Vortex-surface interactions

Different fluid entities (e.g., shear layers, shocks, boundary layers) will be stressed differently among these three classes of vortex interactions. Each of these interaction classes will have different consequences as regards numerical modeling effects and physical measurement interests. Each of these interaction classes will be described in the subsections that follow using flowfields from simple geometries.

1. Vortex-Vortex Interactions

Multiple vortices often form on a configuration from separate vehicle components or from geometric changes of a single component. An example of vortex-vortex interactions from a single component is shown in part (a) of Figure 2 for a double delta wing tested by Brennenstuhl and Hummel [2]. This example is for Wing VI from their studies with Λ_{le} = 80°/60° for the inboard/outboard wing portions, respectively. The abrupt change in leading-edge sweep results in both an inner and an outer vortex forming over the wing. The figure shows spanwise contours of the total pressure coefficient at two longitudinal stations and illustrate the inner and outer vortices. For this vortex-vortex interaction, the vortex shear layers have begun to merge and the two stations shown evidence a convective merging process. At a lower angle of attack, the vortices can be unmerged, and at higher angles of attack, or greater distances downstream, they can provide evidence of viscous merging. For the case shown, the vortices are coupled and the coupling is manifested through a vortex shear layer interaction.



(a) Sweep effect.
M ~ 0.1, Re_c = 1.3 × 10^6, α = 12°

(b) Leading-edge radius and thickness effects.
M = 0.144, Re_{cref} = 1.6 × 10^6, α = 16.83°

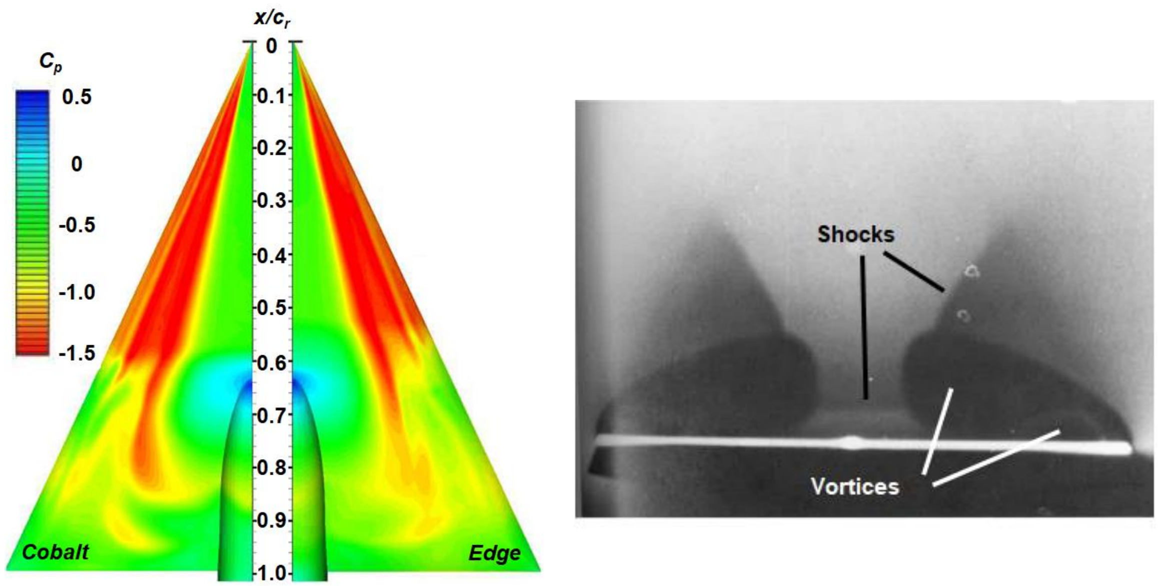
Figure 2. Vortex-vortex interactions.

A second example is shown in part (b) of Figure 2 with a CFD simulation due to Frink et al. [3] about a UCAV configuration known as SACCON [4]. SACCON has a straight leading edge, Λ_{le} = 53°, but the leading-edge radius varied spanwise. This variation in leading-edge radius is a primary source for the multiple leading-edge vortices observed in Frink's solution. Additional vortices are present due to a spanwise thickness variation effect identified by Schütte et al. [5] and a blunt leading-edge vortex separation effect discussed by Frink et al. [3] and summarized by Luckring [6]. The spanwise variations in leading-edge radius and thickness are smooth, and a host of vortex-vortex interactions are still present on SACCON despite its seemingly simple geometry. The simulation provides evidence of shear layer interactions as well as of some possible viscous merging. Interactions among these vortices were shown to be a source of nonlinear and adverse pitching moment trends for SACCON (see Schütte et al. [5]).

Shear layer interactions and the subsequent viscous merging of vortices could be important for vortex-vortex interactions.

2. Vortex-Shock Interactions

The vortex-vortex interactions were shown for low subsonic speeds. At higher speeds, both vortices and shocks can form in proximity to one another and this leads to vortex-shock interactions. A first example of vortex-shock interactions is shown in part (a) of Figure 3 for a delta wing developed by Luckring [7] that formed the basis for Vortex Flow Experiment 2 [8]. The VFE-2 wing had a leading-edge sweep of Λ_{le} = 65° and the case shown in Figure 3 is for a sharp leading edge. Results are shown from Schiavetta et al. [9] for hybrid RANS/LES simulations from the Cobalt and Edge flow solvers at M = 0.85. For this example, the leading-edge vortex and a wing shock are formed independently. The leading-edge vortices are formed from the sharp leading edge and the shock is formed from the nose of the sting. As such, the leading-edge vortex encounters the shock which, in this case, induces vortex breakdown. For this interaction, much of the shear layer flow will pass through the shock whereas the flow moving axially down the vortex will experience most of the shock effect. Coupling between the vortex and shock flows will occur through the wing circulation. Shiavetta observed that the simulations were unsteady.



(a) Vortex encounters shock. **M = 0.85, Re_{mac} = 6 × 10^6, α = 23°**

(b) Vortex induces shocks. **M = 2.8, Re_{mac} = 2.5 × 10^6, α = 20°**

Figure 3. Vortex-shock interactions.

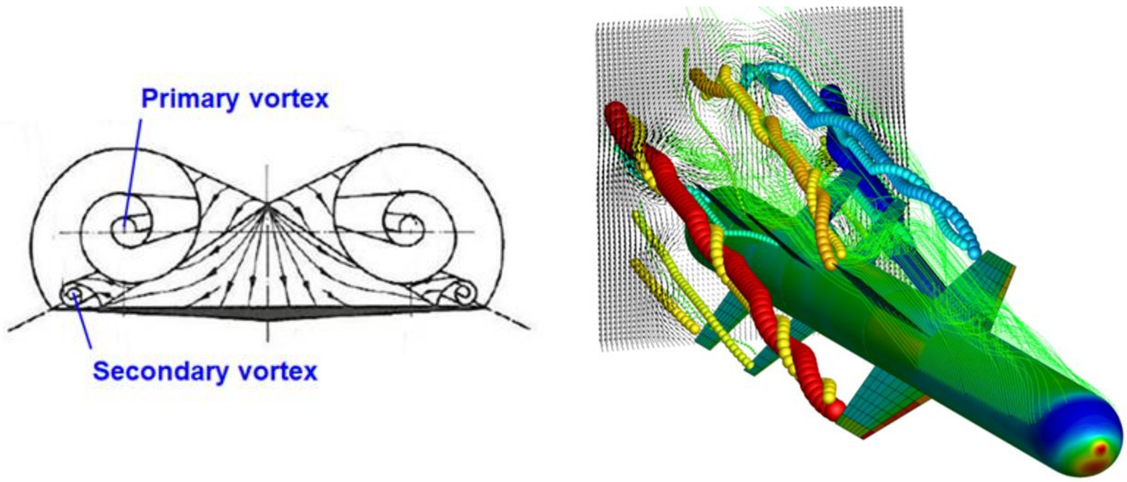
A second example of vortex shock interactions is shown in part (b) of Figure 3 from an experiment by Miller and Wood [10]. The figure shows a crossflow-plane vapor-screen image for supersonic flow about a delta wing with a sharp leading edge and a leading-edge sweep of Λ_{le} = 75°. The observer is looking upstream and the vapor screen shows both shocks and vortices. For this case, the shocks are induced by the leading-edge vortex flow. For this interaction, the vortex shear layer will experience most of the shock effect whereas the axial flow down the vortex will not be affected as much.

Vortex-shock interactions can take on several forms depending on the relative orientations of the shock and the vortex.

3. Vortex-Surface Interactions

Vortices generally form in proximity to lifting surfaces and the third example of vortex interactions is for vortex-surface interactions. An example is shown in part (a) of Figure 4 from Hummel's analysis of low-speed delta wing flows [11]. Hummel's sketch comes from his experimental work with an AR = 1 delta wing, and a primary and a secondary vortex are labeled. Primary separation occurs at the sharp leading edge and the subsequent vortex-surface interaction between the primary leading-edge vortex and the wing upper surface results in an induced boundary layer flow in the spanwise direction toward the leading edge. The accelerated spanwise flow is responsible for much of the well-known vortex lift. The vortex-induced boundary layer flow itself separates, and this secondary separation results in the formation of the secondary vortex.

In this example, the vortex-surface interaction also results in a vortex-vortex interaction between the primary and secondary vortices. Although the secondary vortex is small, the two vortex flows are strongly coupled. Hummel demonstrated experimentally that the difference between laminar and turbulent secondary separation not only altered secondary vortex separation but also significantly altered the primary vortex strength and location.



(a) Delta wing, *AR* = 1. **(b) Generic missile. *M* = 0.6, σ = 24º, λ = 0º**

Figure 4. Vortex-surface interactions.

A second example of vortex-surface interactions is shown in part (b) of Figure 4 from an analysis of a generic missile configuration with a slender-body method developed by the Nielsen Engineering and Research (NEAR) company [12]. In this example, wing-tip wake vortices from the upstream fins are concentrated and interact with the downstream fins. Proximity of the upstream vortex with the downstream fins has a significant effect on the maneuver properties of the missile and especially configuration rolling moment or localized properties such as fin buffet.

Vortex-surface interactions can introduce new scale resolution interests, such as for a secondary vortex, and can also stress vortex propagation needs such as for vortex-fin interactions.

4. Aircraft manifestations, vortex interaction aerodynamics

Practical aircraft geometries can result in numerous vortices at maneuvering conditions, and these flowfields can have many instances of the vortex interactions just discussed. An example is shown in Figure 5 for the low-speed flow about the X-31 at wind tunnel test conditions and a maneuver angle of attack of approximately 20°. The results are from a turbulent Reynolds-averaged Navier Stokes (RANS) simulation by Boelens [13] using the blocked structured-grid solver ENSOLV [14]. The computations used a relatively modest grid for an aircraft configuration of approximately 25 million cells. The solution shows numerous vortices associated with the canard, fuselage, inlet, and wing, and many vortex interactions can be observed in Boelens' solution. For example, a vortex-vortex interaction is seen between the strake vortex and the wing leading-edge vortex as they merge along the wing-body juncture. Other interactions, such as vortex-surface interactions to produce

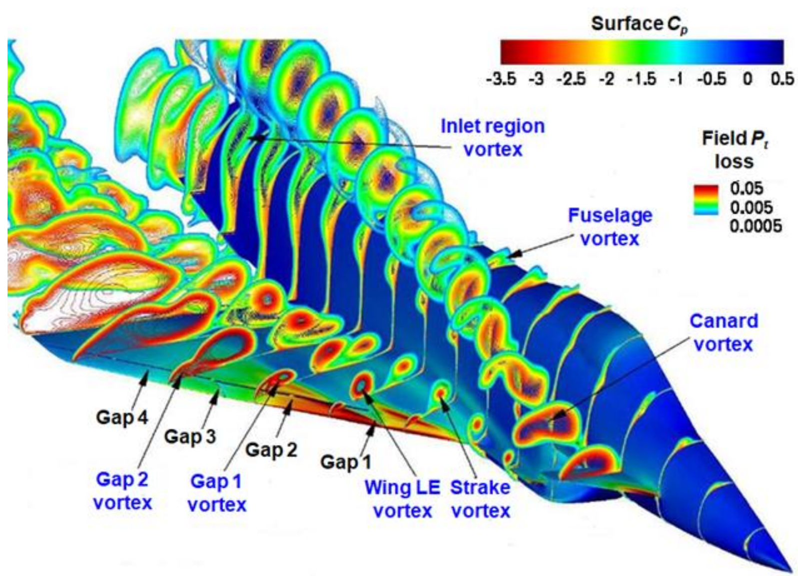


Figure 5. Complex vortex interactions, X-31.
M = 0.18, Re_{mac} = 2.07 × 10^6, α = 20.06º

secondary vortices, would logically be present but cannot be observed in this image.

Boelens also modeled the flow through the gaps between the leading-edge flap segments, and the gap flow produced another succession of leading-edge vortices. Flap gaps are a practical attribute of aircraft geometries but are rarely modeled in CFD simulations. The succession of gap vortices presents another instance of vortex-vortex interactions, and these interacting leading-edge vortices fundamentally altered the wing outboard flow as compared to Boelens' simulations without the flap gaps. In this later case, the simulations had a single leading-edge vortex. Improved pitching moment correlations with experiment were also achieved with the solutions that included the flap gap effects. Boelens' work was performed at wind tunnel test conditions, and it seems likely that this gap effect could become more pronounced at the high Reynolds numbers associated with full-scale aircraft.

Boelens' simulation is a useful reminder of the vortical complexities that can occur at maneuver conditions for practical aircraft geometries. AVT-316 explored selected complex interactions while working within the STO, and a brief summary of the STO follows.

B. Science and Technology Organization (STO)

The Scientific and Technology Organization's charter is to address the collective science and technology needs of NATO. It is a subsidiary body of NATO that was established in 2012 from the Research and Technology Organization (RTO) which, in turn, was created in 1996 by a restructuring of the Advisory Group for Aerospace Research and Development (AGARD). AGARD was founded in 1952 by Theodore von Kármán to promote and conduct cooperative scientific research as well as the exchange of technical information of mutual benefit amongst NATO member nations and organizations, a vision that originated with his father, Maurice. A photograph of Theodore von Kármán is shown in Figure 6.

Figure 6. Theodore von Kármán.

Many of the same AGARD objectives have been sustained through the RTO and the STO, although both the RTO and STO have a more vehicle-centric slant than did AGARD. With each reorganization the organization grew, and the STO is now the largest such body in the world. It currently embraces 30 NATO nations, approximately 40 NATO partner nations, and over 3500 scientists and engineers. The STO supports a suite of scientific activities that include symposia, specialist meetings, lecture series, and research task groups and working groups. Like AGARD, the STO is organized into Panels that span a contemporary scope of science and technology interests such as Sensors and Electronics Technology, NATO Modeling and Simulation, Systems Concepts and Integration, Applied Vehicle Technology, and several more.

In 2017, the Applied Vehicle Technology Panel sponsored an Exploratory Team, ET-175, to assess the interest and needs to study vortex interaction effects that were relevant to NATO air and sea vehicles. The outcome from this Exploratory Team was the creation of Research Task Group AVT-316, and the research program of that task group is summarized in the following section of this report.

III. AVT-316 Research Program

The AVT-316 Research Task Group was established to study vortex interaction aerodynamics that are relevant to military air vehicles. A four-year research program was initiated in 2018 and extended by one year to compensate for research delays related to the Covid-19 pandemic. Completion is now planned for the end of 2022.

Three primary objectives were established for the AVT-316 task group:

- To evaluate the capability of current CFD to predict vortex-interaction effects for select air configurations;
- To extend the understanding of vortex-interactions through numerical and physical experimentation;
- To enhance the predictive capability for vortex interaction effects and provide recommendations for future research.

In addition, the following three topics were established for inclusion in the program:

- Vortex interactions that occur between vortices, between vortices and shocks, and/or between vortices and vehicle components;
- Vortex interactions that are relevant to maneuver performance of military air vehicles;
- Numerical and experimental investigations.

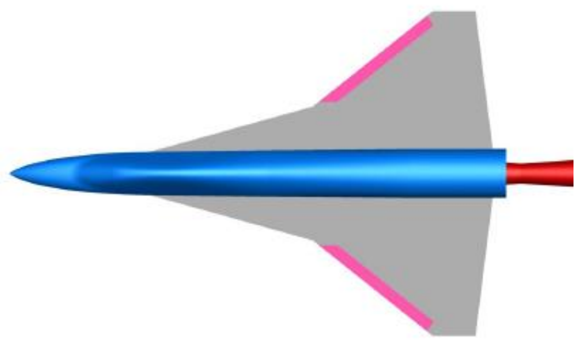
Substantial interest was established early in the research planning phase of the program that came from two sectors of the aircraft community, maneuvering aircraft and missiles. Overall, the task group has had sustained participation from approximately 47 research engineers and scientists representing 22 institutions and 9 countries. This participation also provided access to both supercomputing and wind tunnel facilities. The task group was organized into two research teams referred to as the Aircraft Facet and the Missile Facet. As mentioned earlier, the STO has an emphasis on vehicle-centric research that is relevant to NATO, and leadership for each facet came from private industry to help assure alignment of the AVT-316 research with industry and STO interests. Leadership of the Aircraft Facet was provided by Dr. Stephan Hitzel (Philotech, formerly of Airbus Defense and Space) and leadership of the Missile Facet was provided by Dr. Nigel Taylor (MBDA UK Ltd.). Some general features of each facet research program are presented in the next two sections.

A. Aircraft Facet

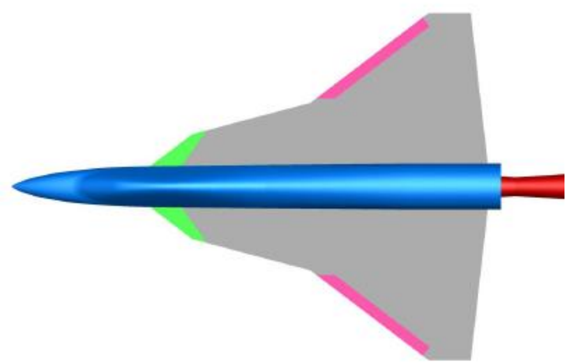
The Aircraft Facet leveraged a research program that had already been initiated by Airbus Defense and Space in Germany to study vortex flows that were relevant to future interests in maneuvering aircraft. Several configurations had been designed to exhibit vortical flows of interest to Airbus D&S at subsonic and transonic speeds, wind tunnel models had been fabricated, and testing was underway. The configurations were designed for focused research purposes and could be shared for the purposes of mutual collaborative interests.

Two of the configurations established a focus for the Aircraft Facet research program and are shown in Figure 7. These double- and triple-delta wing configurations correspond to the low-speed wind tunnel model geometries. High-speed geometries differed slightly due to model load and facility considerations.

Data were used to help identify analysis conditions for the facet. Focus conditions were chosen at M = 0.15 to correspond with low-speed testing underway at the Technische Universität München (TUM) in Munich and at M = 0.85 to correspond with high-speed testing underway at the DLR in Göttingen. Initial anchor points for CFD comparisons were established at α = 8º, 16º, and 24º for the subsonic condition. At subsonic speeds, these angles of attack roughly corresponded to weak vortex-vortex interactions, strong vortex-vortex interactions, and strong vortex-vortex interactions with vortex breakdown. The anchor points were replicated for the transonic focus condition. Additional angles of attack up to α = 32° and a sideslip condition for β = 5° were also included. Some additional Mach numbers were also included in the Aircraft Facet assessments. Data comparisons included static forces and moments, surface pressure coefficients, and, at low speeds, off-body flowfield properties.



(a) Double-delta wing



(b) Triple-delta wing

Figure 7. Aircraft Facet configurations.

Numerical sensitivity assessments were also included in the Aircraft Facet studies. These included iterative and grid convergence as well as effects due to turbulence models, effects due to different flow solvers (same equation set) and due to equation sets (i.e., RANS vs. hybrid RANS/LES). Static and adaptive mesh results were also included.

The Aircraft Facet had sustained participation from approximately 21 research engineers and scientists representing 9 institutions and 6 countries. Computations were provided from 6 CFD codes that included RANS and hybrid RANS/LES formulations. As indicated above, wind tunnel test campaigns were performed in 2 facilities at subsonic and transonic speeds. An image of an Aircraft Facet flowfield is shown in Figure 8. This corresponds to a transonic condition, M = 0.85, Re_{cref} = 12.53 x 10^6, α = 20º. The simulation shows a vortex-vortex interaction between the wing inboard and outboard leading-edge vortices and indicates a shock at the aft portion of the configuration. Details of the Aircraft Facet research program can be found in the paper by Hitzel [15] followed by the facet technical findings [16-24]. Several papers also address design interests for this class of flow.

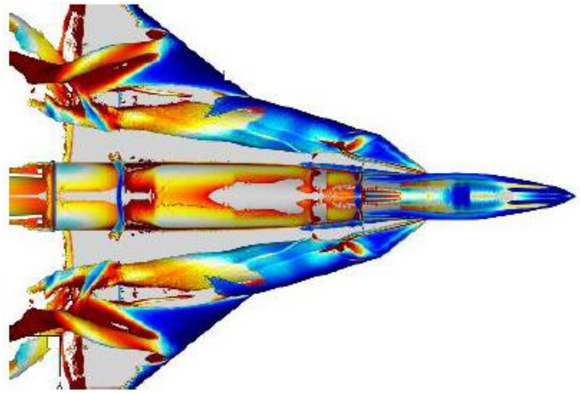


Figure 8. An Aircraft Facet flowfield.
M = 0.85, Re_{cref} = 12.53 x 10^6, α = 20º.

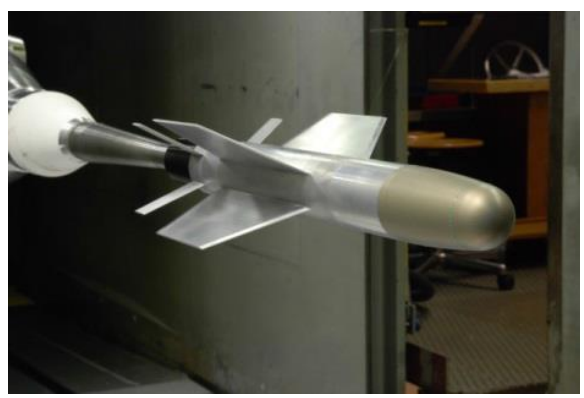
B. Missile Facet

The Missile Facet leveraged corporate interests at MBDA for missile concepts that incorporate very low-aspect-ratio plates along the fuselage. At maneuver conditions, these missiles develop complex and interacting vortical structures that can interact with downstream fins on the missile and effect maneuver performance. A configuration was designed that exhibited the flow features of interest to MBDA but that could be shared for the purposes of mutual collaborative interests.

This configuration became known as Open Test Case 1 (OTC-1) and is shown in part (a) of Figure 9. MBDA was interested in increasing the reliability of CFD to predict the subject flow fields of interest, and the OTC-1 configuration served as the focus for detailed numerical assessments at a stipulated full-scale-flight supersonic flow condition (M = 1.4, Re_d = 4.89 x 10^6, σ = 15º, λ = 2.5º). For this study, the assessments were performed in the absence of experimental data, i.e., they were blind CFD assessments. Computations at this condition were mandatory for members of the Missile Facet.

The numerical assessments included a suite of the usual topics such as iterative and grid convergence, effects due to turbulence models, effects due to different flow solvers (same equation set) and due to different equation sets (i.e., RANS vs. hybrid RANS/LES), and effects due to adaptive meshes. Several less common numerical modeling effects, such as due to limiters, were also included.

(a) OTC-1



(b) LK6E2

Figure 9. Missile Facet configurations.

A second configuration, the LK6E2, was also included in the Missile Facet studies. The LK6E2 is shown in part (b) of Figure 9 mounted in the DLR high-speed wind tunnel TWG located in Göttingen, Germany. Data were available for the LK6E2 from a previous test and a new test was also performed. Interest in this configuration was for transonic maneuver flows, nominally at M = 0.85. Different vortex interaction flowfields were to be expected, not only due to the transonic condition, but also due to the possible differences in vortex interaction flow physics in association with the different geometry of the LK6E2. Initial simulations for the LK6E2 were based upon the lessons learned from the OTC-1 portion of the Missile Facet program, and further studies were performed based upon numerical and experimental assessments with these initial simulations.

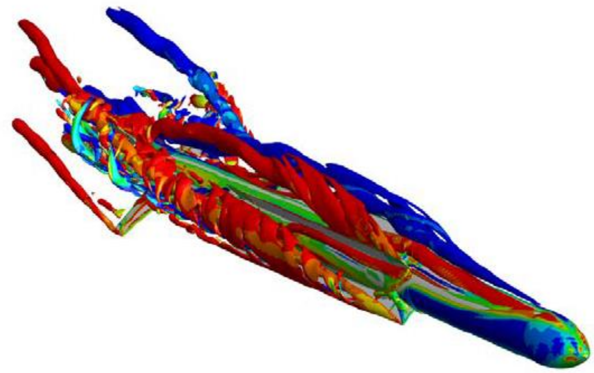


Figure 10. A Missile Facet flowfield.
$M = 1.4$, $Re_d = 4.89 \times 10^6$, $\sigma = 15^o$, $\lambda = 2.5^o$.

The Missile Facet had sustained participation from approximately 16 research engineers and scientists representing 8 institutions and 6 countries. Computations were provided from 7 CFD codes that included RANS and hybrid RANS/LES formulations. As indicated above, a wind tunnel test campaign was performed in one facility at transonic speeds. An image of a Missile Facet flowfield is shown in Figure 10. This flowfield corresponds to the supersonic blind test case condition. The simulation shows a complex vortex-vortex interaction between the missile forebody vortex and the low-aspect-ratio plate side-edge vortices in proximity of the missile fins. Vortex-fin interactions can have large effects on maneuver performance, in some instances changing the sign of the rolling moment coefficient. Details of the Missile Facet research program can be found in the paper by Taylor et al. [25] followed by the facet technical findings [26-35].

C. SciTech 2022 Special Sessions

AVT-316 is entering its final year of research, and seven special sessions have been established to highlight the AVT-316 research findings to date. See Table 1. This paper provides an overview of the AVT-316 program content.

The first four sessions include this overview and address Aircraft Facet findings with 10 papers [15-24]. An opening paper summarizes the facet research program details and a closing paper summarizes the facet research findings. In addition, an open-forum discussion is planned for the concluding Aircraft Facet session, APA-23.

The remaining three sessions address Missile Facet findings and include 11 papers [25-35]. An opening paper summarizes the facet research program details and a closing paper summarizes the facet research findings. In addition, an open-forum discussion is planned for the concluding Missile Facet session, APA-82.

Table 1. AVT-316 special sessions, SciTech 2022.

Session	Topic	Day	Papers
APA-07	Aircraft Aerodynamics I	Mon	3
APA-98$	Aircraft Aerodynamics II	Mon	3
APA-08	Aircraft Aerodynamics III	Mon	3
APA-23*	Aircraft Aerodynamics IV	Tue	2
APA-39	Missile Aerodynamics I	Wed	4
APA-59	Missile Aerodynamics II	Wed	4
APA-82*	Missile Aerodynamics III	Thu	3

**Includes open forum* *$Virtual Session*

IV. Concluding Remarks

The STO Task Group AVT-316 has examined the capability of current CFD methods to predict complex vortex-interaction effects on select configurations that are of interest to private industry. The work has included both numerical studies as well as new experimental investigations. The research was organized to focus on vortex interaction effects for two vehicle classes, missiles and maneuvering aircraft. The missile focus was coordinated with interests from MBDA, United Kingdom, and the maneuvering aircraft interests were coordinated with Airbus Defense and Space, Germany. Both the missile and aircraft studies were focused on conditions with complex vortex interaction involving multiple vortices, shocks, and vehicle components.

Although the AVT-316 program has one year left for completion, several findings are in hand. For the missile studies, the scatter among CFD predictions for a benchmark supersonic maneuver condition has been significantly reduced through detailed numerical assessments. For the aircraft studies, predictions of vortex interaction aerodynamics for double- and triple-delta wings has significantly improved as compared with new experimental findings. Final accomplishments are anticipated for a NATO technical report to be produced at the end of 2022.

V. Acknowledgments

Dr. Luckring appreciates the opportunity to participate in this research project while working in the Configuration Aerodynamics Branch at the NASA Langley Research Center.

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