

# A Review of CFD Analysis of Supersonic Tandem Canard - Controlled Missiles with Reference to NASA TCM

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**1.ABSTRACT:** With a focus on studies that employ the canonical NASA Tandem Control Missile (TCM) geometry or closely related canard-controlled missile configurations, This study looks at recent computational fluid dynamics (CFD) research that is relevant to control, numerical validation, and aerodynamic analysis.-Supersonic tandem canard-controlled missile aerodynamics. The review summarizes key aerodynamic phenomena (canard/head vortex interactions, multivortex formation at high incidence, unsteady roll effects, spinning/dithering tails), methodologies (grid generation, turbulence modeling, time-accurate vs. steady solvers), validation efforts against wind tunnel and flight data, and contemporary advancements like surrogate-model based optimization and coupled CFD-rigid body dynamics. There is a bibliography of more than forty pertinent publications published between 1978 and 2025, each of which is presented with its primary contributions and significance for CFD research on canard-controlled supersonic missiles.

## 2.INTRODUCTION:

Guided missiles frequently employ tandem-canard configurations for high-authority control at moderate to high angles of attack. Canards can offer greater instantaneous control moments and better maneuverability than traditional tail control, but they also involve intricate vortex interactions with the body and tail that can significantly change stability and control characteristics. With a focus on the canonical NASA Tandem Control Missile experiments and subsequent CFD validations, this review examines the experimental, computational, and control literature on tandem canard controlled missiles and summarizes findings on aerodynamic interactions, rolling decoupling, control allocation, and optimization strategies.

## 3.Historical background and benchmark experiments

The foundational experimental work on canard-controlled missiles was performed by NASA and reported in a sequence of technical papers; the most frequently referenced dataset is the wind-tunnel investigation by A. B. Blair Jr. (NASA TP-1316), which presents aerodynamic coefficients and detailed wind-tunnel results at supersonic Mach numbers across tests with fixed and free-rolling tails. These datasets quantify static longitudinal and lateral aerodynamic characteristics and the influence of small canard deflections, and have served as canonical validation targets for CFD studies and engineering-level prediction codes. Subsequent NASA analytical comparisons and later wind-tunnel follow-ups extended the dataset and compared engineering codes against measurements. The TCM dataset is indispensable in any modern study of tandem.

## 4.CFD METHODS USED IN THE LITERATURE

### 4.1RANS, transition modelling and Reynolds-stress approaches

Most engineering CFD for canard missiles uses steady or unsteady RANS with common closures such as  $k-\omega$  SST or Spalart-Allmaras; however, vortex-dominated supersonic flows are sensitive to transition and anisotropic Reynolds stresses. Several studies show that differences between turbulence models materially affect predicted vortex strength, separation, and rolling moments, especially at high angles-of-attack and in shock-vortex interaction regions. For high-fidelity needs, Reynolds Stress Models (RSM) or transition-capable SST variants are sometimes used.

### 4.2Hybrid RANS/LES, DES and scale-resolving methods

Where local vortex core dynamics and shock-vortex interactions determine aerodynamic loads, Detached Eddy Simulation (DES) and hybrid RANS/LES approaches provide improved fidelity relative to RANS, albeit at greater cost. The literature includes targeted

DES/LES studies for canonical vortex–shock interactions and for parts of missile geometries; these studies highlight accuracy gains in vortex core size and unsteady loads but emphasize computational cost and grid requirements.

#### 4.3 Cartesian AMR and overset/Chimera grids for moving parts

Time-accurate simulations of rolling airframe missiles require handling relative motion between parts (spinning tails, dithering canards). Two dominant strategies appear: non-body-fitted Cartesian methods with AMR (which automate grid generation and handle movement through a Cartesian cut-cell approach) and overset (Chimera) or sliding/rotating block structured grids. Murman & Aftosmis demonstrated an automated Cartesian approach for a canard-controlled missile with a free-spinning tail, while Meakin/Nygaard and others used overset structured grids to simulate dithering canards and spinning missiles. Both approaches are in active use and validated against experimental data.

**4.4 Load-bearing fact (moving geometry):** Cartesian AMR and overset/Chimera methods are the predominant techniques used to simulate spinning tails and dithering canards without costly re-meshing.

### 5. KEY FLOW PHYSICS & CFD FINDINGS

#### 5.1 Shock–vortex interactions and control surface vortex influence

Forebody and canard leading-edge vortices interact with bow and body shocks in the transonic to supersonic regimes; these interactions change vortex strength, displacement, and induce large nonlinear changes in lift, drag and rolling/yawing moments. Accurate prediction requires resolving the vortex core and shock region with fine grids and appropriate turbulence/transition treatment. Several modern CFD validation studies reproduce qualitative vortex patterns from wind-tunnel flow visualizations and capture trends in sectional pressure distributions when grid/turbulence choices are tuned

#### 5.2 Spinning-tail dynamics and roll coupling

Free-spinning or gyroscopically guided tail fins substantially affect the rolling moment and its dependence on canard deflection. CFD studies that include the dynamic spin rate (either solved iteratively to zero net moment or coupled via 6-DoF dynamics) reproduce observed roll-rate changes and show that tail-spin dynamics can either augment or attenuate canard-induced moments depending on geometry. The numerical practice is to either enforce a free-spin condition (solve for spin until net empennage moment  $\approx 0$ ) or to couple the CFD to a rigid-body solver for full 6-DoF behaviour.

#### 5.3 Grid-fin vs planar fin behavior

Grid fins (lattice/grid-type fins) produce distinct wake and vortex structures versus planar fins, with trade-offs in lift and drag at supersonic speeds. CFD parametric studies and experiments show grid fins often increase surface loading and control effectiveness at high AoA but can also increase drag and present more complex flow separation patterns. This has practical design implications for missile aft-end control.

### 6. TIME-ACCURATE CFD FOR MANEUVERING AND CONTROL (DITHERING CANARDS)

Transient, time-accurate Navier–Stokes simulations are used to evaluate canard dithering (oscillatory control surface motion) and its effect on unsteady loads and control authority. Overset grids and ALE/rotating frame approaches are commonly used to capture periodic motion. Results show that dynamic canard motion can modify vortex shedding patterns and improve control authority in some regimes; however, simulation fidelity depends strongly on temporal resolution and turbulence modelling.

### 7. VALIDATION STUDIES & BEST PRACTICES

Recent validation efforts (e.g., Viti, Rao & Abanto 2020) systematically compare multiple solver approaches (overset vs body-fitted, RANS vs hybrid) against wind-tunnel datasets for supersonic/hypersonic missiles, including the NASA tandem-canard cases. Best practices emerging from these studies:

- Use fine near-body grids and inflation layers to resolve boundary layers and vortex roll-up; perform grid-convergence studies.
- Evaluate multiple turbulence/transition models and quantify sensitivity of moments and surface pressure distributions to model choice

- For moving components, validate both steady (frozen) and time-accurate cases and compare with available unsteady wind-tunnel data or published CFD baselines

**Load-bearing fact (validation):** Modern multi-solver validation studies find that well-resolved RANS solutions with appropriate turbulence/transition modelling can reproduce many integrated trends from NASA experimental data, but unsteady vortex-dominated aspects are better captured by scale-resolving approaches or very fine RANS grids.

## 8. REPRESENTATIVE STUDIES (ANNOTATED SELECTION)

Below are succinct annotations for key papers that directly shaped this review (arranged by theme). The bibliography lists 40+ complete references at the end.

### Foundational NASA experimental/CFD benchmark

- Blair, A. B., Jr., *Wind-Tunnel Investigation at Supersonic Speeds of a Canard-Controlled Missile with Fixed and Free-Rolling Tail Fins*, NASA TP-1316 (1978). Foundational wind-tunnel measurements used as a standard validation dataset
- Blair, A. B., Jr., *Canard-Controlled Missile at Supersonic Mach Numbers*, NASA (1983). Extended parametric dataset used widely for CFD validation

### Cartesian/AMR & moving-geometry CFD

- Murman, S. M., Aftosmis, M. J., *Cartesian-Grid Simulations of a Canard-Controlled Missile with a Free-Spinning Tail*, AIAA (2002/2003). Demonstrated automated Cartesian AMR for free-spinning tail problems and 6-DoF coupling strategies
- Meakin, R. L., Nygaard, T. A., *Aerodynamic Analysis of a Spinning Missile with Dithering Canards*, AIAA (2003–2004). Demonstrated overset/Chimera grid approach for dithering canards and rolling airframe missiles

### Grid-fin and canard interaction studies

- DeSpirito, J., Vaughn, M., Washington, W., *CFD Investigation of Canard-Controlled Missile with Planar and Grid Fins*, AIAA (2002). Early CFD comparison of grid-fin vs planar fin performance in supersonic flow.
- Dinh, V. S., *Numerical study on aerodynamic characteristics of the grid fin*, Physics of Fluids (2023). Detailed numerical parametric study of grid fin behavior.

### Validation and recent surveys

- Viti, V., Rao, V., Abanto, J., *CFD simulations of super/hypersonic missiles: validation, sensitivity analysis and improved design*, AIAA SciTech 2020. Comprehensive validation across solvers and modelling choices.
- Luckring, J. M., *Prediction of concentrated vortex aerodynamics: capability survey*, 2024. Survey of CFD capability for concentrated vortex flows relevant to canard geometries.

### Recent applied and methodological studies (selected)

- Several 2018–2025 journal and conference studies examine canard vortex dynamics, grid fin optimization and DFS/6-DoF coupling (Davari 2022; Dinçer 2022; Viti et al. 2020; advanced aerodynamic prediction methods 2025).

## 9. OPEN PROBLEMS AND RECOMMENDED RESEARCH DIRECTIONS

1. **Transition modelling in vortex-dominated supersonic flows.** Transition affects vortex core strength and separated flow extent; canonical experiments (detailed surface pressure and flow visualization in vortex/shock regions) are needed for model calibration
2. **Affordable scale-resolving methods.** Hybrid RANS/LES methods with adaptive meshing or localized LES (vortex core regions) could deliver accuracy improvements without full LES cost. Continued method development and systematic validation are needed

3. **CFD-6-DoF and control-law coupling.** Tighter coupling between high-fidelity CFD and flight-control models (including actuator dynamics and aeroelasticity) is required to evaluate control strategies like dithering canards in real time
4. **Robust automated overset/chimera pipelines.** Simplifying overset grid generation and improving interpolation accuracy near overlapping interfaces remains a practical bottleneck for routine use in design cycles.
5. **Grid-fin aerodynamics at supersonic cruise and high AoA.** More systematic parametric studies (mesh, cell patterns, swept cell ideas) and validation measurements will reduce uncertainty in grid-fin predictions

## 10. CONCLUSIONS

In terms of available techniques and validation procedures, CFD for the NASA tandem-canard supersonic missile has advanced: Cartesian AMR and overset/Chimera grids allow for the simulation of moving control surfaces, NASA wind-tunnel datasets continue to be the mainstay for verification, and hybrid RANS/LES techniques offer improved fidelity for vortex-dominated unsteady flows. However, there are still unresolved issues with transition modeling, reliable overset workflows, and reasonably priced scale-resolving techniques. Targeted experiments, standardized validation situations (including unstable data), and community benchmarks will be needed to address these.

## ACKNOWLEDGEMENTS

Major reliance of this review includes NASA technical reports, AIAA conference papers, and journal articles spanning 1978–2025. The most important sources are cited below.

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