

Article

Numerical Investigation and Hybrid Modeling of External–Internal Flow Coupling on Thrust Vector Control Performance

Yi Wang¹ , Chenyu Shi²  and Tianyi Liu^{1,*} ¹ School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China; 2332785@tongji.edu.cn² College of Automotive and Energy Engineering, Tongji University, Shanghai 200092, China; 2333060@tongji.edu.cn

* Correspondence: tianyi.liu@tongji.edu.cn

Abstract

Thrust vector control (TVC) technology significantly enhances the attitude control capability of aircraft. However, conventional multi-axis calibration is inherently cost-prohibitive and time-consuming, whereas static ground-bench calibration completely neglects the significant aerodynamic interference from external freestreams during actual flight. To resolve this operational bottleneck in engineering applications and calibration workflows, this paper proposes an agile, cost-effective hybrid modeling and process optimization methodology that seamlessly integrates low-cost ground experiments with high-fidelity numerical investigations. First, a customized one-axis force sensor test bench was developed to calibrate the baseline thrust vector performance under static ground conditions. Subsequently, computational fluid dynamics (CFD) simulations were conducted across the typical cruise speed range (30–60 m/s) of TVC aircraft to investigate the nonlinear interactions between the external freestream and the vectorized jet. The numerical results reveal that the interaction between the deflected jet exhaust and the external flow field significantly changes the flow structure and pressure distribution around the control surface. The momentum exchange, primarily governed by mass entrainment and cross-shear-layer mixing, broadens the control surface's impact scope and enhances the injection effect, resulting in nonlinear variations in the control force under different operating conditions. Considering the influence of external flow and deflected jet, a dynamic control force model was established by integrating the ground static baseline model with simulation data. The fitting results demonstrate that this control model limits match error to within 3% across both experimental and numerical datasets, effectively suppressing loop uncertainties across the entire flight envelope while maintaining a minimalist sensing architecture. From a process engineering perspective, this “Hybrid Modeling”-driven approach substitutes expensive multi-degree-of-freedom testing hardware with an integrated simulation-experimental workflow, offering a highly scalable, simplified, and analyzable process method for TVC research and application.



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1. Introduction

Thrust vector control (TVC) actively adjusts the direction of engine thrust, enabling the propulsion system to directly participate in flight attitude control while providing

thrust vectoring, thereby significantly enhancing aircraft maneuverability [1,2]. Compared with conventional aerodynamic control surfaces, TVC maintains high control effectiveness even when aerodynamic control efficiency is greatly degraded, such as at low speeds and high angles of attack. This technology is already well established in manned fighter aircraft (e.g., the F-22 and Su-35) and is increasingly regarded as a fundamental feature of high-performance aircraft [3].

Current mainstream thrust vectoring technologies include mechanical thrust vectoring (MTV) and fluidic thrust vectoring (FTV) [4]. Mechanical vector nozzles provide high-precision control but introduce structural complexity and increased weight. In contrast, FTV leverages aerodynamic effects (the Coandă effect and secondary flow injection) to enhance response speed without moving parts, albeit at the cost of some thrust loss [5–7].

With the advancement of research, thrust vectoring technology has been increasingly applied in engineering practice. The scope of application has expanded to include small unmanned aerial vehicles (UAVs) and flying-wing aircraft [8]. Zhao et al. [9] successfully achieved active fluidic control for three-axis attitude manipulation using dual synthetic jet actuators during a rudderless flying-wing aircraft flight test at a cruising speed of 70 m/s.

With the increasing application of thrust vectoring systems, the demand for accurate measurement and standardized modeling methods has intensified. Calibration and modeling of thrust vectoring systems are essential for integrating with the flight control system, directly improving thrust-vectoring control performance and flight maneuverability [10]. These methods are required to achieve high accuracy and adaptability across various operational conditions. Establishing a general modeling methodology enables the development of a comprehensive thrust vector control model, which ensures precise control and enhances the robustness of the flight control system [11].

Ground-based testing is widely used for aeroengine measurement, as it enables the acquisition of comprehensive data necessary for accurate thrust performance prediction [12,13]. The establishment of precise models based on ground test data is critical to ensuring flight safety. Thrust vector research has primarily employed multidimensional force and moment balances or advanced ground test bench systems to quantitatively assess the control characteristics of thrust vectoring nozzles and the jet control surface [14]. Typically, a six-degree-of-freedom (DoF) thrust measurement platform equipped with six DoF force sensors is adopted, allowing for the decoupling of magnitude and direction of vector control forces during ground testing [15].

Although ground-based calibration of thrust vectoring systems is indispensable, the implementation of large-scale six-degree-of-freedom ground test rigs is associated with high costs. Furthermore, conventional ground-bench testing is subject to inherent limitations, as it is typically conducted under static ambient air conditions with zero free-stream velocity. This approach does not accurately reproduce the complex aerodynamic environment encountered during actual flight, thereby restricting the fidelity of the test results.

During actual airborne flights, aircraft operate within highly dynamic, high-speed freestream environments. This introduces severe external–internal flow field interference, causing the actual thrust vector control (TVC) forces to deviate significantly in both magnitude and direction from ground static test values [16]. The control force generated by TVC is heavily coupled, depending not only on the nozzle deflection angle but also on the engine operating states and external freestream conditions. As flight speed varies, the highly nonlinear interaction between the deflected jet and the oncoming freestream leads to substantial fluctuations in the actual control moments across different operating envelopes. Traditional static modeling approaches fail to capture the complex, condition-dependent dynamics of thrust vector actuators. Consequently, directly implementing a control allocation model derived solely from ground tests into a flight control system will induce severe

model-plant mismatches, potentially triggering excessive closed-loop overshoot, control chattering, or even system instability in attitude responses [17–19].

Consequently, the study of multiphase flow and thrust-vectoring control characteristics using numerical methods has been widely adopted. Meng and Shi [20] utilized the Shear Stress Transport (SST) k - ω turbulence model within the commercial software ANSYS Fluent to numerically simulate a multi-stream supersonic nozzle, systematically elucidating the effects of multi-flow coupling on nozzle thrust performance. Afridi [21] conducted a comprehensive numerical investigation of the thrust-vectoring performance of a bypass dual-throat nozzle (BDTN) to elucidate the internal flow structures and performance metrics across varying bypass angles, nozzle convergence angles, and bypass widths. Moving beyond isolated nozzle evaluations, Zhu [22] employed numerical approaches to clarify the distinct impacts of serpentine nozzle configurations on both local flow characteristics and global aerodynamic performance of thrust vector control (TVC). Crucially, their work accounted for the non-negligible aerodynamic interference arising from the afterbody external flow and the nozzle jet. These studies have demonstrated the significant value and feasibility of numerical methods for analyzing complex multiphase flows and their thrust-vector control characteristics.

The primary challenge in applying thrust vectoring technology to aircraft is the accurate and comprehensive establishment of the control force model, which underpins the development of control laws. To simplify the calibration process and enhance the applicability of thrust vectoring control in flight control systems, previous work by the authors introduced a thrust vectoring testing method utilizing a low-cost, single-axis force transducer. This approach enables joint identification and baseline modeling of a micro-turbojet engine's thrust and vertical control force during ground testing.

Based on ground-test data, this research employs computational simulation to complement the representation of thrust-vectoring performance under realistic flight conditions. To deeply investigate control performance under flow field coupling, computer-aided process simulation and computational fluid dynamics (CFD) are important tools in modern fluid dynamics research. By constructing a full-scale three-dimensional numerical domain that includes the UAV aft-body and the TVC system, the complex flow field under flight conditions can be quantitatively reproduced. This approach effectively compensates for the ground bench's inability to simulate high-speed dynamic freestreams and supports the establishment of a control model that matches dynamic flight regimes.

In view of this, building upon our ground-based experimental work, this paper presents an air-ground integrated hybrid modeling and interference process analysis methodology for thrust vectoring. The core contributions of this paper comprise the following three aspects:

1. Adopting the baseline model established via ground one-axis force testing as the boundary control characteristic under zero-velocity conditions.
2. Employing a high-fidelity CFD simulation process to analyze the nonlinear interference mechanisms of external free-stream dynamic pressure and jet dynamic pressure on the vector control performance at typical flying-wing UAV cruise speeds ranging from 30 m/s to 60 m/s, and analyze the asymmetric flow field distribution characteristics on the windward and leeward sides.
3. Extracting a nonlinear flow field interference correction function to organically fuse the ground experimental process with the airborne simulation process, thereby constructing a flow field-corrected thrust vector model directly applicable to closed-loop flight control designs, and quantitatively validating its engineering utility in eliminating model prediction errors through comparative analysis.

2. Materials and Methods

2.1. Ground-Based Calibration Test Bench

2.1.1. Ground Test Bench

Figure 1a shows the proposed TVC system. It primarily consists of three parts: (1) a small-scale turbojet engine SW240B as the primary propulsion source; (2) a shaped nozzle conforming to the flying-wing airframe to optimize aerodynamic integration and exhaust flow guidance [23]; (3) a deflectable control surface mounted downstream of the nozzle exit enables thrust vectoring control (marked with blue in Figure 1a); and (4) a pitot tube at the nozzle outlet to measure the dynamic pressure of the jet for subsequent analysis and thrust modeling (as shown in Figure 1d).

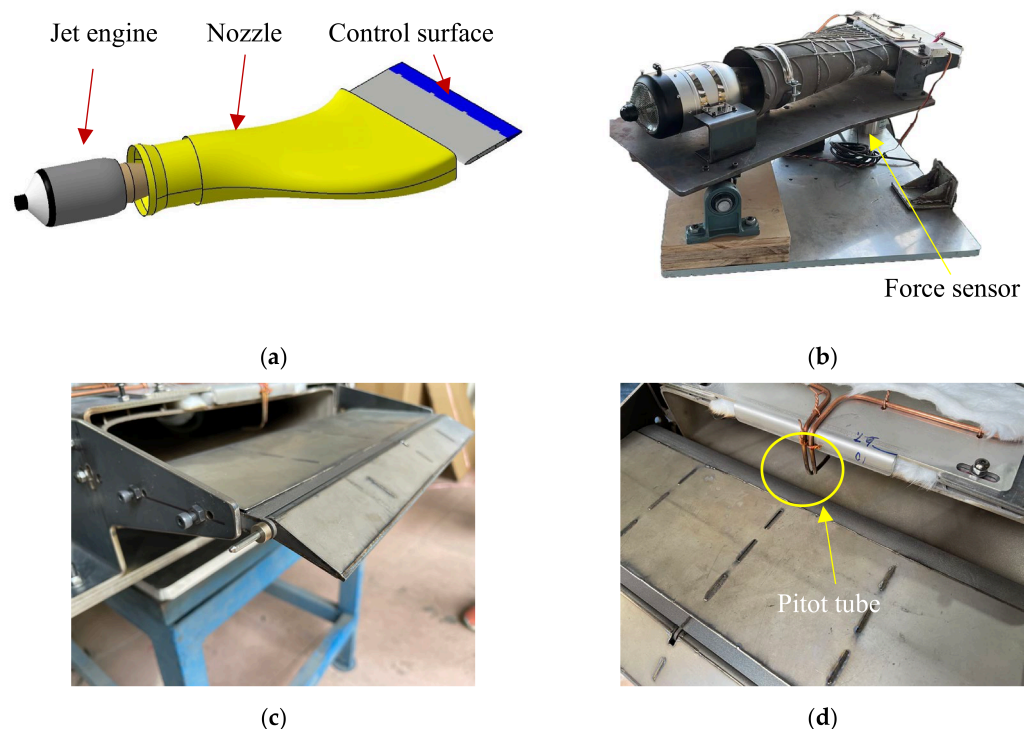


Figure 1. Thrust vector system: (a) Composition of thrust vectoring system; (b) test bench; (c) control surface; (d) jet pressure detection.

This design is intended to ensure the stability of the thrust vectoring output and enhance the efficacy of the control surfaces. Independent variation of the deflection angle for each control surface enables the generation of vector control force along the body-fixed Z-axis. Consequently, the Z-axis component of the thrust vector, denoted as F_z , is identified as the primary variable to be studied.

A single-degree-of-freedom vector thrust control system test bench was developed to establish a static reference configuration, using a low-cost uniaxial force transducer (see Figure 1b) [24]. The thrust vectoring system is mounted on the base plate with fixtures. The base plate rotates only at the hinge, while the opposite end connects to the force transducer via a rod. A coordinate system, as shown in Figure 2, illustrates the design. The rotary axis is perpendicular to the nozzle outlet and the control surface, which is parallel to the aircraft body's y -axis. The force transducer is attached to the base plate, which is secured to the steel bench with a fixture. The thrust vector force measurement system employs a ZNLBM-IIIX miniature single-axis tension-and-compression load cell constructed from high-grade stainless steel. This sensor provides a customized operational measurement range of 0–500 N and demonstrates high comprehensive precision, with a nonlinearity of $\pm 0.02\%$ of Full Scale (F.S.), a hysteresis error of $\pm 0.02\%$ F.S., and a repeatability error of $\pm 0.02\%$ F.S.

Due to its simplified single-axis structural configuration, the load cell was calibrated on-site using standard weights directly on the experimental test bench to ensure data accuracy. The calibration results demonstrated excellent linearity and zero-drift stability throughout the loading cycles, confirming that the experimental setup satisfies the stringent accuracy requirements for thrust vector control performance evaluation.

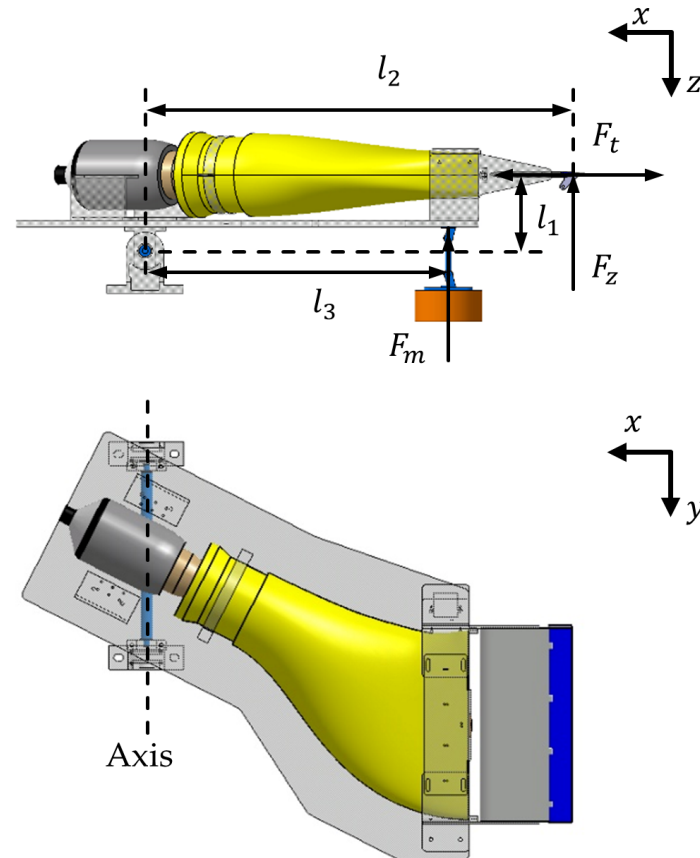


Figure 2. Geometric structure of test bench.

2.1.2. Control Force Calibration Method

As shown in Figure 2, the vector control force generated by the system can be decomposed into the horizontal plane engine thrust F_t and the Z-axis control force F_z generated by the control surface deflection. The force sensor can measure the force F_m along the Z-axis.

The following relationship can be obtained between the thrust vector and the sensor measurement value:

$$F_m = \frac{F_t l_1 - F_z l_2}{l_3}, \quad (1)$$

where l_1 is the distance from the control surface to the axis of rotation in the z direction; l_2 is the distance from the control surface to the axis of rotation in the x-direction; and l_3 is the distance from the sensor measurement point to the rotation axis in the x direction.

Due to the symmetrical structure of the thrust vectoring system with respect to the x-y plane, the magnitude of the thrust vector generated when the deflection angle δ_c of the control surface is the same when it is deflected up and down by the same angle. For a given deflection angle δ_c of the same angle, when there are corresponding F_z^+ and F_z^- for the upward deflection δ_c^+ and downward deflection δ_c^- on the control surface, that is

$$\begin{cases} F_z^+ = -F_z^- \\ F_t^+ = F_t^- \end{cases}, \quad (2)$$

Meanwhile, substitute into Equation (1):

$$\begin{cases} F_m^+ = \frac{F_t l_1 - F_z^+ l_2}{l_3} \\ F_m^- = \frac{F_t l_1 - F_z^- l_2}{l_3} \end{cases} \quad (3)$$

After calculation, the following can be obtained:

$$\begin{cases} F_z^+ = -F_z^- = -\frac{(F_m^+ - F_m^-)l_3}{2l_2} \\ F_t^+ = F_t^- = -\frac{(F_m^+ + F_m^-)l_3}{2l_1} \end{cases} \quad (4)$$

Through testing and calculation, we are able to control the force F_z and thrust under different control surface deflection angles of the thrust vector F_t .

2.2. Computational Method

2.2.1. Numerical Simulation Governing Equations and Turbulence Modeling

The fluid domain analysis is governed by the three-dimensional, steady, compressible Reynolds-Averaged Navier–Stokes (RANS) equations to solve for the conservation of fluid mass, momentum, and energy [20].

Given that the flow field involves high-speed vector jet exhaust interacting with a dynamic external free-stream, it exhibits prominent near-wall boundary layers, strong adverse pressure gradients, and far-field free shear layers. To achieve accurate numerical closure, Menter's Shear Stress Transport (SST) k - ω turbulence model is utilized. The SST k - ω model blends the robust and accurate near-wall formulation of the standard SST k - ω model with the free-stream independence of the k - ϵ model in the far-field via a specialized blending function. This formulation ensures superior accuracy in predicting boundary layer separation under severe adverse pressure gradients on the deflected control surfaces, while precisely capturing the turbulent structures and momentum exchange across the high-shear mixing layer between the jet plume and the external airflow [22,25].

2.2.2. Computational Domain and Boundary Conditions

To accurately simulate the flow field behavior without excessive computational overhead, the internal components of the micro-turbojet engine are simplified. The complex rotating turbomachinery is omitted, and only the critical interior geometry of the shaped nozzle and the external aerodynamic mold line of the flying-wing fuselage are modeled. This simplification focuses the numerical resolution on the near-field flow coupling between the fuselage boundary layer and the high-speed jet exhaust, isolating the governing physics that dictate the aerodynamic-to-thrust-vectoring normal control force F_z .

The computational domain is constructed as a large rectangular fluid enclosure surrounding the full-scale UAV model as shown in Figure 3. The total dimensions of the domain are extended to $25 L \times 10 L \times 10 L$ (where L represents the overall fuselage length). The simulation environment is calibrated by ground test conditions. Considering that the validation flight is conducted at subsonic speeds and low altitude, the standard atmospheric model is used to define the thermodynamic and transport properties of the working fluid and the ambient flow conditions. The air is assumed to be at standard atmospheric conditions, with ambient pressure and temperature set at 101,325 Pa and 273.15 K, respectively. The air density is 1.225 kg/m^3 . The specific boundary conditions are designated as follows:

Far-field Boundaries: Configured as Pressure Far-field conditions. The total pressure, static pressure, and static temperature are specified based on the targeted flight Mach number and ambient atmospheric properties.

Jet Inlet: Defined as a Velocity Inlet. The jet velocity, total pressure, and total temperature profiles are directly mapped from the ground calibration data at matching throttle points by correlating the target nozzle dynamic pressure P_{jet} .

Vector Control Surface and Fuselage Surfaces: Specified as No-slip Adiabatic Rigid Walls.

Domain Outlets: Configured as Pressure Outlet boundaries maintained at standard sea-level atmospheric static conditions.

The turbulent intensity and turbulent viscosity ratio are set to 5% and 10, respectively. No-slip adiabatic boundary conditions are applied at the wall surfaces.

The external free-stream velocity (V_∞) is parameterized across 0 m/s, 30 m/s, 40 m/s, 50 m/s, and 60 m/s to fully cover the experimental flight envelope of the physical aircraft platform. The static case ($V_\infty = 0$) serves as the anchor point for cross-validation against the ground-bench test data, while the moving cases ($V_\infty = 30\sim 60$ m/s) isolate the dynamic pressure effects of the external stream.

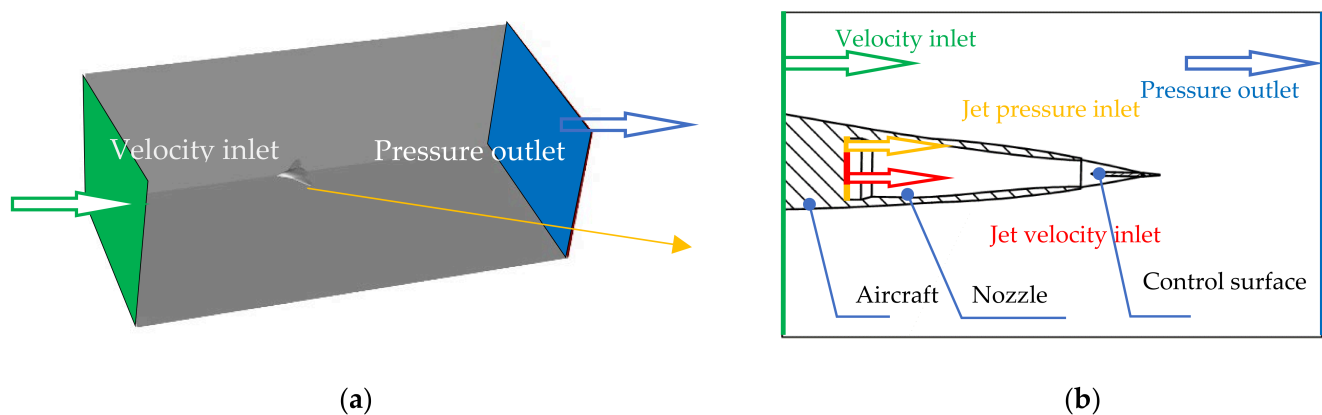


Figure 3. Simulation settings: (a) computational domain; (b) boundary setting.

2.2.3. Mesh Generation and Grid Independence Verification

A hybrid unstructured grid topology is used for fluid domain discretization. Grid refinement and local cell clustering are applied downstream of the nozzle exit along the jet trajectory to resolve localized aerodynamic interactions and precise momentum-flux characteristics around the control surface. The mesh near the nozzle and control surface is encrypted locally as shown in Figure 4, and the first-layer mesh thickness is 0.01 mm to maintain a non-dimensional wall distance of $y^+ \approx 1$. We ensured to match the turbulence model requirements and accurately resolved complex flow features.

To systematically eliminate numerical errors stemming from spatial discretization, a grid independence study is conducted [26]. Three distinct mesh densities—designated as Coarse, Medium, and Fine—are generated via global systematic refinement factors. The total grid counts are approximately 6×10^6 , 1×10^7 , and 1.8×10^7 cells, respectively.

The total control force (F_z) at the critical control surface deflection angle of $\delta_c = 45^\circ$, under full throttle conditions, was adopted as the primary evaluation parameter for grid convergence analysis. The corresponding results are summarized in Table 1. The relative error between the simulation results of medium and fine grids and the ground test results ($F_z = 75$ N) is within 1%. The GCI for the medium mesh is 4.15%, and the fine mesh is as low as 0.31%, below the 5% threshold required for asymptotic convergence. Considering both computational accuracy and efficiency, the medium mesh configuration was selected for the subsequent extensive numerical investigations.



Figure 4. Mesh generation.

Table 1. Quantitative grid independence verification results.

Mesh Level	Total Elements ($\times 10^4$)	F_z ($\delta_c = 45^\circ$) (N)	Relative Error	GCI
Coarse	600	72.9	-	-
Medium	1000	75.4	3.32%	4.15%
Fine	1800	75.2	0.27%	0.34%

3. Results and Discussion

Through ground tests and numerical investigations, this section indicates the impact of the external flow field on the performance of thrust vectoring control across various flight conditions. On this basis, a dynamic-adaptive control force model is established, driven by the external dynamic pressure (P_∞) and the jet dynamic pressure (P_{jet}). This hybrid modeling approach enables the accurate capture of dynamic variations in control force.

3.1. Ground Static Experimental Validation and Baseline Modeling

Initial ground experiments were executed on the bare micro-turbojet engine configuration (without the installation of the shaped nozzle and vector control surfaces), yielding a baseline maximum thrust of approximately 20.4 kgf (≈ 200 N). Figure 5 presents the test results. Following the full integration of the shaped nozzle and the mechanical thrust vectoring assembly, the maximum forward thrust dropped to approximately 160 N at the maximum throttle setting, indicating a system installation thrust loss of approximately 10%. Furthermore, at full throttle with the vector control surface deflected to its structural limit ($\delta = 45^\circ$), the mechanism generated a localized normal vector force of 75 N alongside an induced axial aerodynamic drag penalty of 6 N, which introduced an additional 3.75% thrust degradation relative to the undeflected thrust vector state.

The ground calibration records indicate that the baseline normal vector control force ($F_{z,g}$) maintains a highly linear correlation with both the internal nozzle dynamic pressure (P_{jet}) at the fixed surface deflection angle ($\delta = 45^\circ$). Utilizing P_{jet} as the primary scaling variable, the ground static baseline model is formulated as

$$F_{z,g} = k_1 P_{jet}, \quad (5)$$

where k_1 represents the static control force gain coefficient mapped to specific deflection angles ($\delta = 45^\circ$) determined via linear regression.

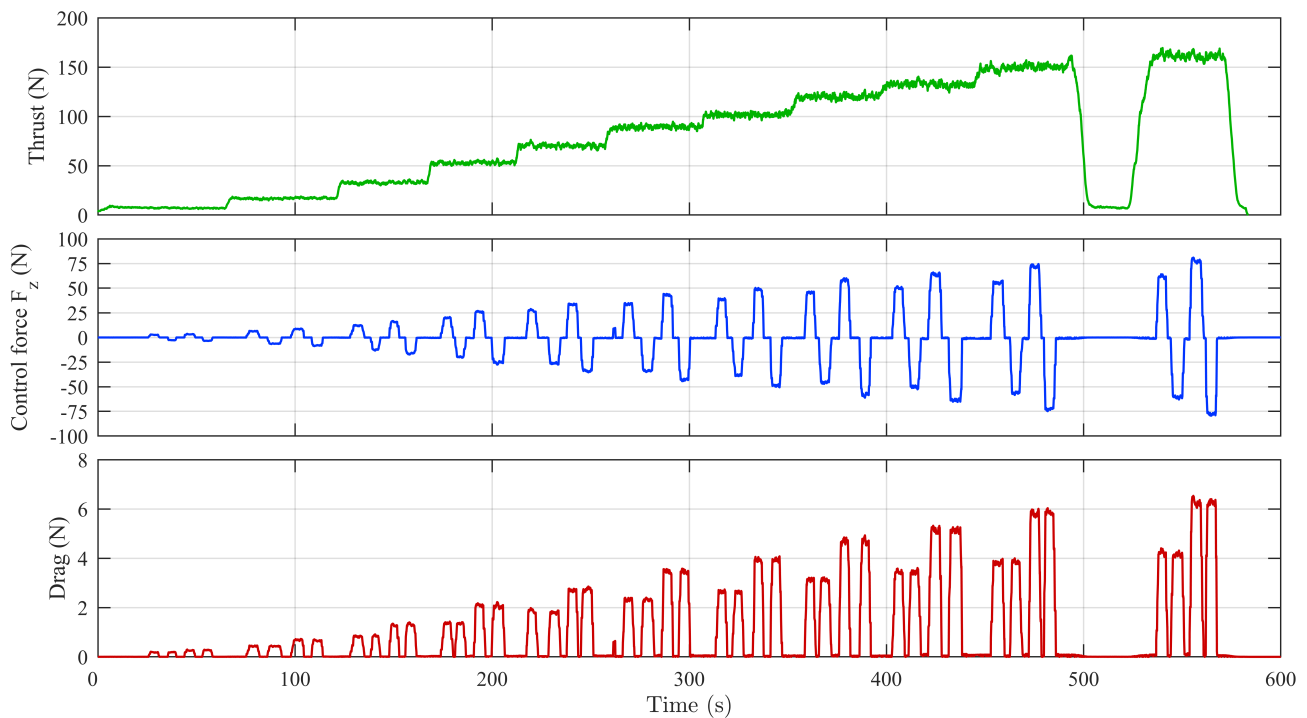


Figure 5. Results of thrust and vector control force under fixed control surface deflection angle.

The calibrated coefficient for the maximum deflection state is summarized in Table 2. Time-history tracking in Figure 6 confirms that the prediction error of this baseline model remains within 3% for all static ground testing sequences, validating its mathematical fidelity.

Table 2. Ground control force model coefficients.

Coefficient	$\delta_c = 45^\circ$
$k_1 \text{ (N} \cdot \text{Pa}^{-1})$	2.8×10^{-3}

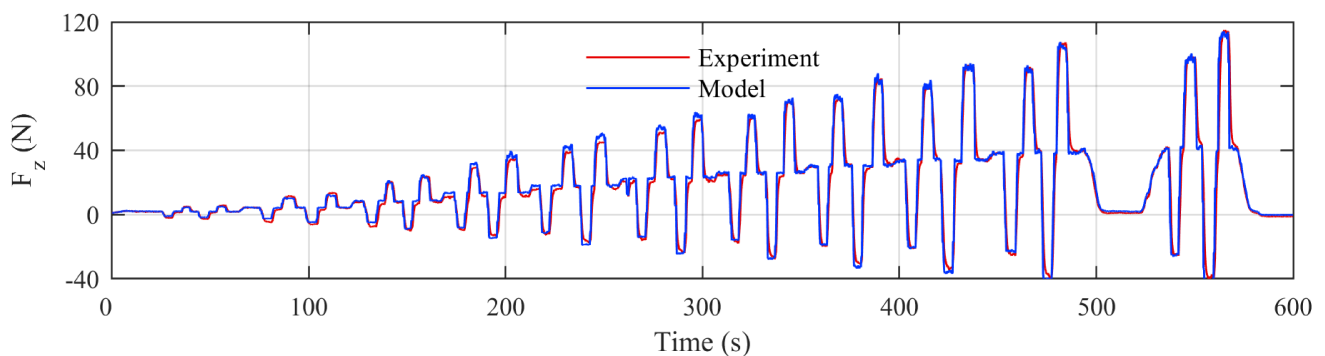


Figure 6. Comparison of control force models and experimental results.

3.2. Flow Field Coupling Mechanisms and Air–Ground Hybrid Correction Model

3.2.1. Aerodynamic Flow Field Analysis

By comparing the velocity cloud maps of four different operating conditions in Figure 7, it can be seen that there is a significant internal/external flow coupling effect between the jet and the external flow field. The core physical process can be summarized

as a nonlinear superposition of the injection effect and the virtual deflection surface, which is a deep momentum-coupling process.

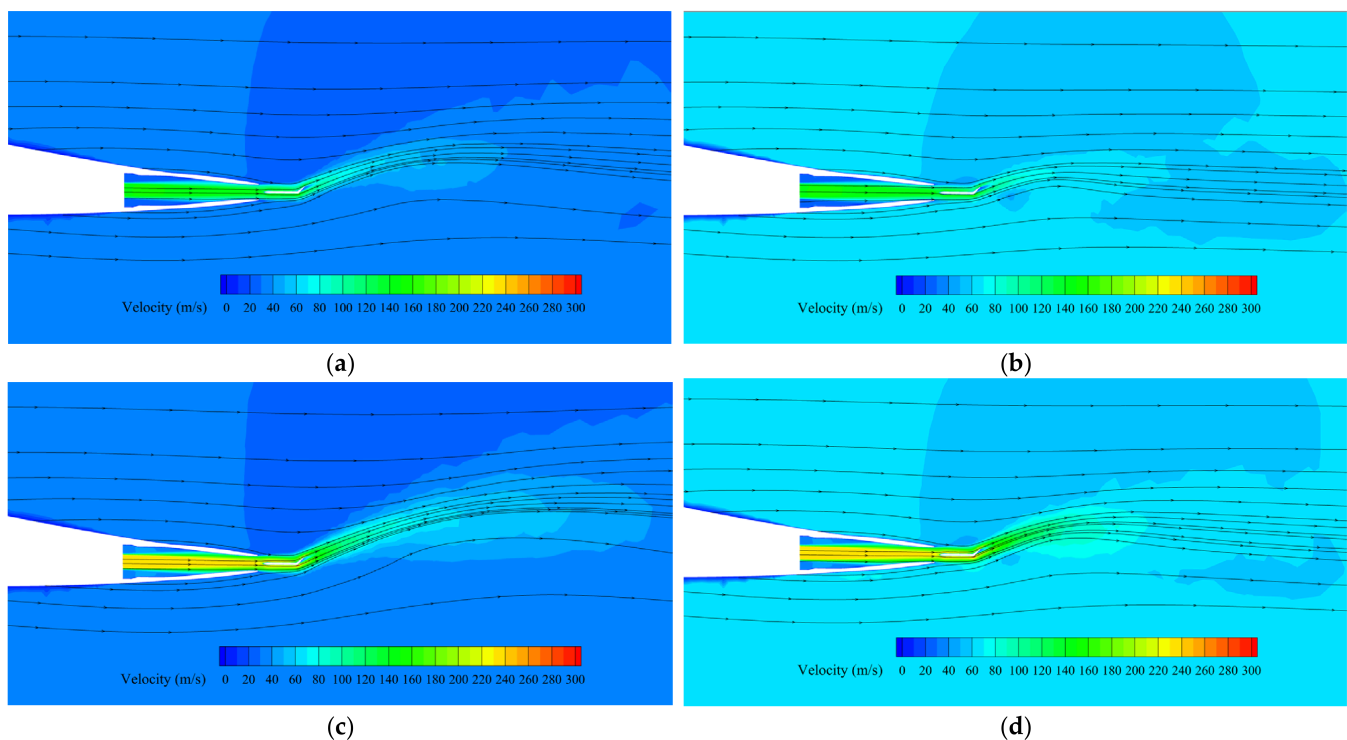


Figure 7. Velocity contours and pathline distributions of airflow coupling under different setting conditions: (a) Case 1 ($P_{jet} = 10,642.59$ Pa, $V_{\infty} = 30$ m/s); (b) Case 2 ($P_{jet} = 10,202.66$ Pa, $V_{\infty} = 60$ m/s); (c) Case 3 ($P_{jet} = 26,949.87$ Pa, $V_{\infty} = 30$ m/s); (d) Case 4 ($P_{jet} = 25,856.85$ Pa, $V_{\infty} = 60$ m/s).

Comparing Figure 7a,b, it can be observed that, at the same jet intensity, an increase in the external flow velocity enhances the absolute momentum transfer from the injection effect. Although high-speed inflow will exert a certain compression effect on the jet, within the parameter range described in this study, the increase in external velocity is accompanied by the participation of multiple gas flow rates in momentum exchange, thereby enhancing the effectiveness of the control force. This trend can also be observed in Figure 7c,d.

Comparing Figure 7a,c, it can be seen that as the jet intensity P_{jet} increases, the deflected jet's influence range increases significantly, and the effective thickness of the virtual control surface increases. This also causes more interaction between external currents, compared to the lack of free flow on the ground, which deflects external currents and amplifies the effect of the control force.

Figure 8 shows the pressure distribution on the control surface for the four cases. This pressure distribution induced by jet flow is equivalent in effect to adding a larger solid control surface, exerting influence on the external flow and thereby achieving higher vector gain than ground static thrust testing.

Two cross-sections are set on the jet control surface, namely the jet core region a-a and the non-core region b-b. Figure 9 shows the pressure distribution of the same jet intensity at different speeds on the jet core cross-section. It can be seen that the pressure distribution structure is almost the same at different speeds. In the core area of the jet, the control force mainly comes from high-intensity deflected jets.

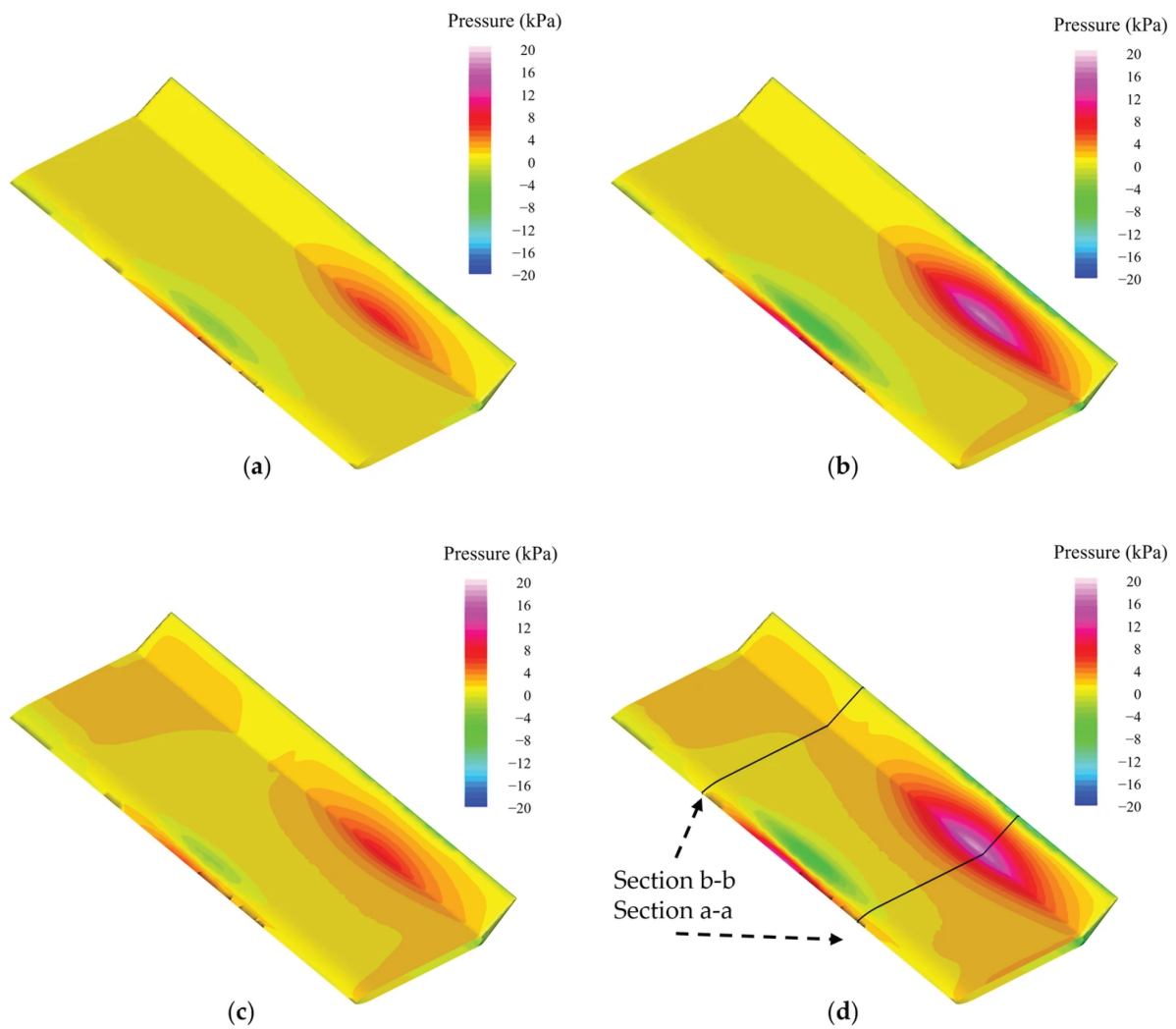


Figure 8. Pressure distribution under different setting conditions: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

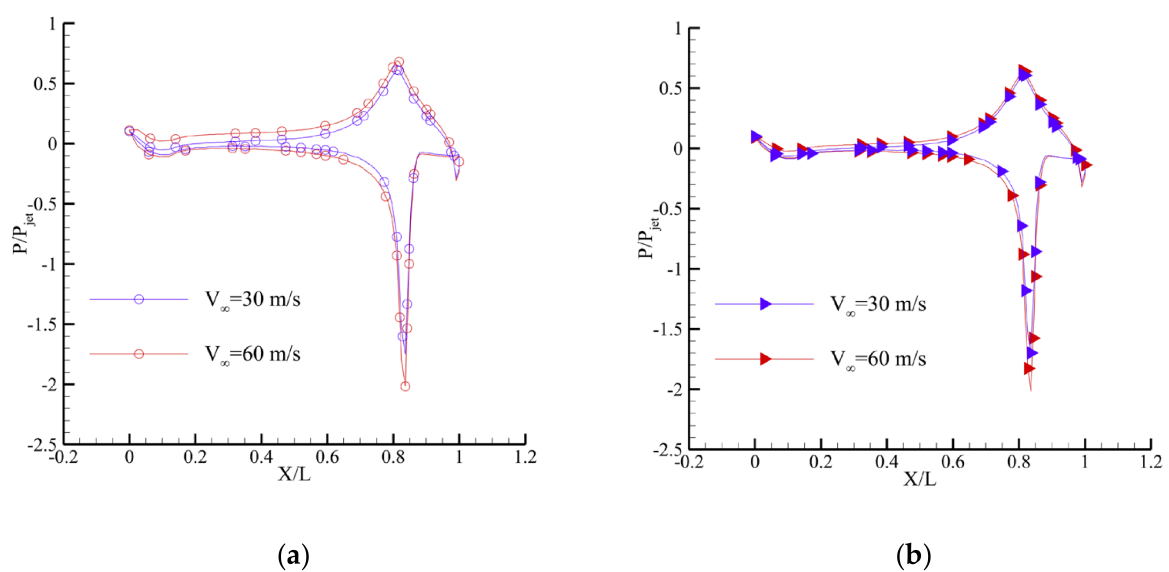


Figure 9. Pressure distributions (P/P_{jet}) on section a-a: (a) comparison between Case 1 and Case 3; (b) comparison between Case 2 and Case 4.

Jet Core Region (Section a-a): Figure 9 depicts the surface pressure distribution along the jet core cross-section (a-a) under identical jet intensities across various freestream velocities. It is observed that the pressure distribution profiles virtually overlap, indicating that within the jet core region, the control authority is absolutely dominated by the high-energy deflected jet, rendering it highly immune to external freestream interference due to strong jet momentum rigidity.

Non-Core Region (Section b-b): In contrast, the non-core region (b-b) illustrated in Figure 10 exhibits pronounced velocity-dependent discrepancies in pressure peaks.

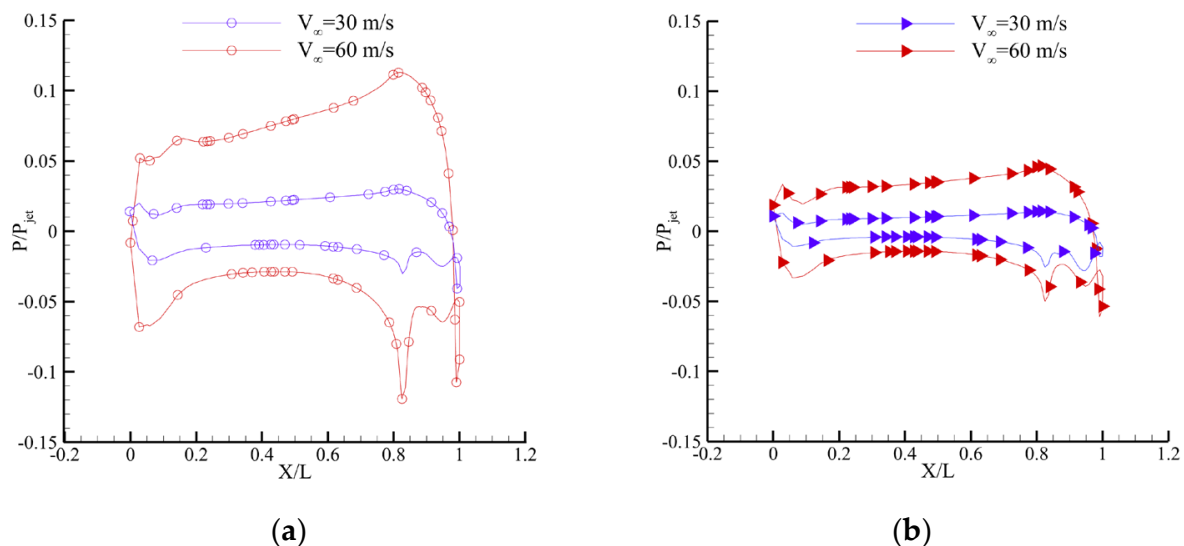


Figure 10. Pressure distributions (P/P_{jet}) on section b-b: (a) comparison between Case 1 and Case 3; (b) comparison between Case 2 and Case 4.

Figure 10a compares pressure distribution, characterized by the ratio of surface static pressure to jet dynamic pressure (P/P_{jet}), under similar jet intensities.

At $X/L = 0.8$, the maximum P/P_{jet} values for Case 1 and Case 2 are 0.03 and 0.11, respectively, representing a 3.65-fold. In Figure 10b, due to the distinct coupling states of the external flow field, the discrepancy between the two cases settles at 2.3-fold.

These quantitative empirical results demonstrate that the aerodynamic–propulsion interaction is strongly coupled. This validates that the internal and external flow fields interact via highly nonlinear coupling rather than simple linear superposition.

Under low jet intensity conditions, the relative contribution of the fluidic virtual aerodynamic control surface, formed by entrainment and momentum exchange, increases within the total control authority. At higher jet intensities, although the enhanced entrainment effect increases spatial momentum exchange, the direct momentum vector of the primary jet remains the main source of the normal control force.

This microscopic mechanism is supported by the macroscopic performance curves in Figure 11, which show that the coupling of different jet intensities and external dynamic pressures results in distinct flow topologies and surface pressure distributions.

An integral approach, derived from the control-volume momentum theorem, was employed to investigate the momentum-conversion mechanism driven by jet deflection and the control surface. A computational control volume measuring $2\text{ m} \times 1\text{ m} \times 2\text{ m}$ was defined around the control surface (Figure 12). Under all evaluated conditions, the integrated net increments of the Z-axis momentum flux (ΔM_z) demonstrate excellent agreement in both trend and magnitude with the directly extracted single-sided aerodynamic forces (as shown in Figure 13 and Table 3), thereby validating the fidelity of the numerical method for momentum-transfer predictions. Notably, the Z-axis momentum flux variation of the

entire domain aligns well with the control force, with the downstream surface variation dominating the total balance. This confirms that the momentum flux modifications are inherently governed by the deflected jet and the perturbed external airflow.

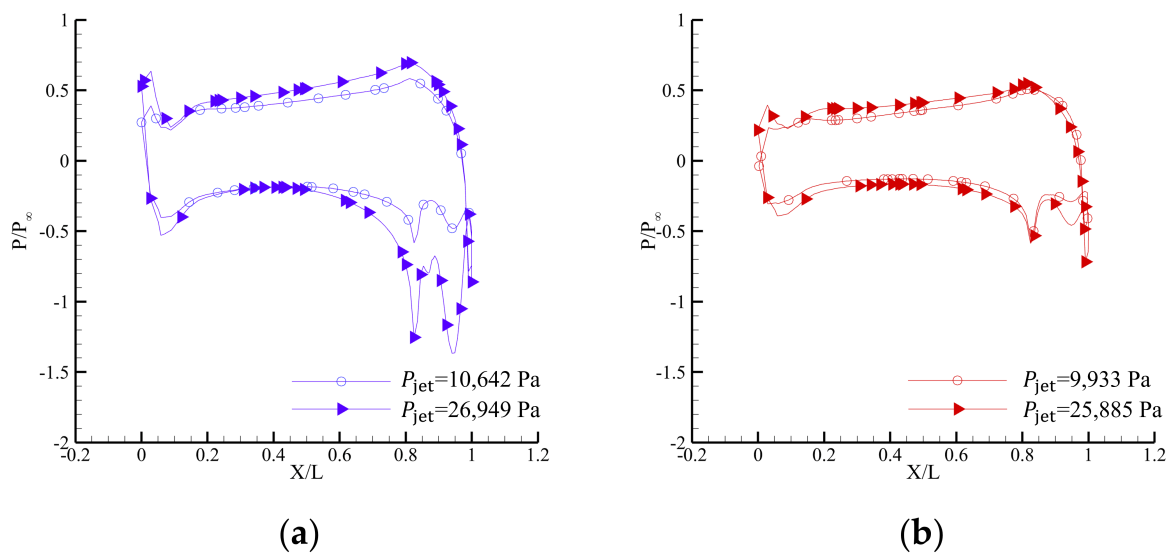


Figure 11. Pressure distributions (P/P_∞) on section b-b: (a) comparison between Case 1 and Case 2; (b) comparison between Case 3 and Case 4.

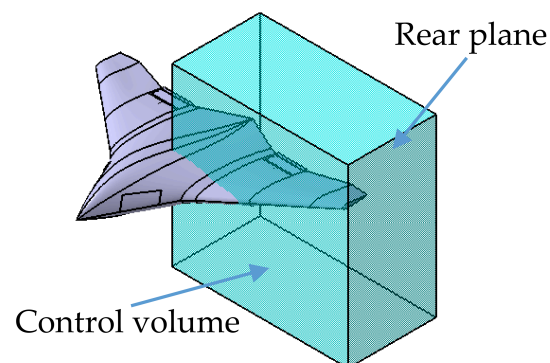


Figure 12. Momentum flux calculation domain.

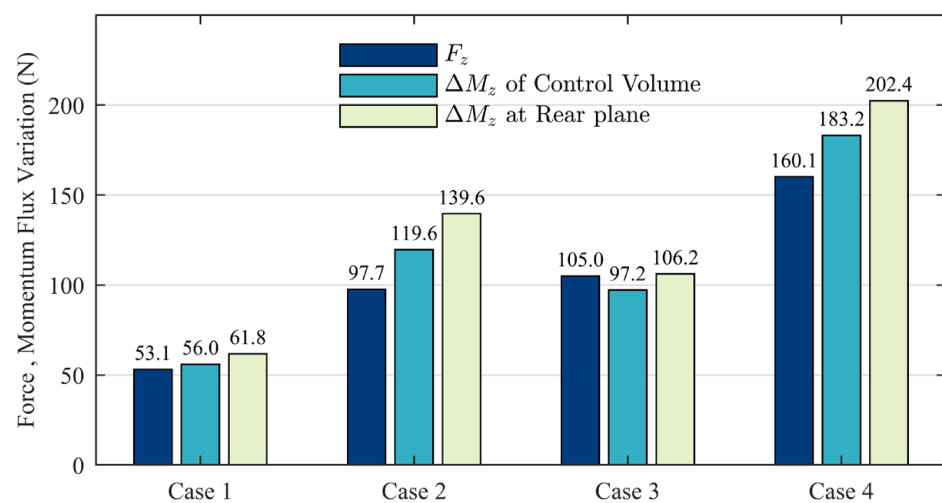


Figure 13. Compare the control force F_z and momentum flux ΔM_z changes of several operating conditions.

Table 3. Control forces F_z and momentum flux variations ΔM_z with different conditions.

Case	P_{jet} (Pa)	V_∞ (m/s)	F_z (N)	ΔM_z of Control Volume (N)	ΔM_z at Rear Plane (N)
1	10,642.59	30	53.1	56.0	61.8
2	10,202.66	60	97.7	119.6	139.6
3	26,949.87	30	105.0	97.2	106.2
4	25,856.85	60	160.1	183.2	202.4

A deviation is observed between the increment of momentum flux within the control volume and the actual force exerted on the control surface. This discrepancy is mainly caused by the additional variation in momentum flux resulting from the interaction between the external freestream and the fuselage surface as the flow passes through the defined control volume. Furthermore, a certain degree of momentum exchange persists on the aircraft surface within the control domain. However, this physical deviation does not affect the validity of employing momentum flux variations to assess the performance of thrust vector control modifications.

These simulation visualizations of the flow field and pressure distribution indicate that the jet intensity after deflection by the mechanical control surface is much higher than that of the external free stream, and a shear layer with a velocity gradient forms at the interface between the two. Under the influence of fluid viscosity and turbulent mixing, high-speed jets gradually suck up and redirect the external airflow originally parallel to the flight direction through momentum transport, gradually aligning its flow direction with the deflected jet.

This flow field intermixing process significantly enhances the coupling between the jet and the outflow and macroscopically increases the fluid mass flow rate involved in deflection control. At the same time, when the high-speed jet flows through the deflected mechanical control surface, the deflected jet constructs a “virtual control surface” that breaks through the physical geometric boundary in space. The fluid barrier formed by the high-speed jet after leaving the control surface extends the control force range to the far field of the trailing edge.

This strongly coupled, nonlinear aerodynamic interference poses significant challenges for aircraft attitude control. When synthesizing thrust-vectoring flight control laws, conventional constant-gain allocation methods can induce severe loop uncertainties. Consequently, this environment-adaptive dynamic control force model must be explicitly integrated into the Control Allocation framework as a primary scheduling parameter to guarantee high-fidelity tracking and closed-loop stability across the entire operational flight envelope.

3.2.2. Performance of Control Force Under the Influence of External Flow Field

From the analysis in the previous section, it can be seen that the external flow field and the strength of the deflected jet will, to some extent, affect and alter the thrust vector control capability. In actual flight attitude control, the lack of accurate thrust-vector control models significantly affects the accuracy and robustness of flight control laws.

In this section, a dynamic vector control model considering the external flow field intensity and jet intensity will be established. To facilitate integration with subsequent control force modeling, the external flow field strength is consistently represented by the flow pressure P_∞ . In experimental measurements, the jet dynamic pressure P_{jet} is measured using a pitot tube at a monitoring point near the nozzle outlet. In CFD simulations, dynamic pressure values are directly extracted from designated collection points in the jet’s core

region, corresponding to the positions used in ground tests. The external flow pressure P_∞ is calculated according to classical fluid mechanics equations.

$$P_\infty = \frac{1}{2} \rho V_\infty^2, \quad (6)$$

where the ρ is the air density, and the V_∞ is the setting external free stream velocity.

To quantitatively describe this enhancement mechanism, this data analysis introduces the injection gain coefficient η , defined as the ratio of the control force in the presence of outflow to the predicted value of the static ground model:

$$\eta = \frac{F_{z,\infty}(P_\infty > 0)}{F_{z,g}(P_\infty = 0)}, \quad (7)$$

From the simulation results in Table 4, it can be seen that, under the same P_{jet} , with P_∞ increases to 551.25 Pa ($V_\infty = 30$ m/s), 980 Pa ($V_\infty = 40$ m/s), 1531.25 Pa ($V_\infty = 50$ m/s) and 2205 Pa ($V_\infty = 60$ m/s), F_z continues to rise. The gain coefficient can more than double.

Table 4. Simulation results of control force under different operating conditions.

Notes	V_∞ (m/s)	P_{jet} (Pa)	F_z (N)	η
Without external	0	10,838.28	30.0	1
		16,652.36	46.0	1
		21,561.97	59.7	1
		27,076.77	75.4	1
Without jet	30		13.7	
Case 1		10,642.59	53.1	1.77
		16,470.43	71.7	1.56
		21,411.94	87.8	1.47
Case 3		26,949.87	105.0	1.39
Without jet	40		24.5	
		10,387.46	66.5	2.22
		16,102.72	87.4	1.9
		21,060.37	103	1.73
		26,609.76	121.3	1.61
Without jet	50		38.6	
		10,268.22	80.4	2.69
		15,969.52	102.6	2.23
		20,863.85	119.7	2.01
		26,194.41	139.9	1.86
Without jet	60		56.3	
Case 2		10,202.66	97.7	3.26
		15,916.96	119.2	2.59
		20,183.43	139.7	2.34
Case 4		25,856.85	160.1	2.12

Taking the maximum jet intensity as an example, when $\delta_c = 45^\circ$, the value of F_z increases from 75.4 N at $P_\infty = 0$ to 160.1 N at $P_\infty = 2205$ Pa, corresponding to $\eta = 2.12$.

The gain is more significant under low jet conditions: at the minimum jet dynamic pressure of $P_\infty = 10,202.66$ Pa, η further increases to 3.26 ($\delta_c = 45^\circ$), indicating that external inflow can increase the effective control force to more than three times the static value. This phenomenon indicates that the actual effectiveness of thrust vectoring systems may be severely underestimated by traditional static models during low-thrust cruising or high-altitude rarefied atmospheric flight.

From a fluid dynamics perspective, the influence of the external flow field on the thrust vectoring control authority is a highly nonlinear fluid–structure coupling mechanism rather than a simple linear superposition of separate forces. Figure 14 also illustrates that the coupling between internal and external flow fields is highly nonlinear. The straightforward superposition of isolated jet deflection and external aerodynamic forces when predicting thrust vector changes is incorrect. When contrasting the control forces generated independently by the jet (F_z Pure Jet) and the freestream (F_z Pure External Flow) against the fully coupled condition (F_z Hybrid), the numerical results reveal a pronounced enhancement rather than a linear combination. Driven by the strong fluidic entrainment and aerodynamic induction at the nozzle–afterbody interface, the actual control force consistently exceeds the linear sum of its isolated counterparts across all tested cases. This coupled force increment (Δ) scales up significantly with the intensification of flow energy, reaching a maximum enhancement of 28.4 N in Case 4. In conjunction with the flow topologies discussed in Section 3.2.1, these quantitative findings rigorously validate the microscopic physical mechanisms governing variations in thrust vectoring under freestream interference. From a control engineering perspective, this explicitly demonstrates that the actual control authority under flight conditions cannot be reliably predicted via linear formulations of internal and external dynamic pressures. Consequently, incorporating these coupled nonlinear flow effects is a strict prerequisite for constructing high-fidelity control allocation models and eliminating closed-loop instability.

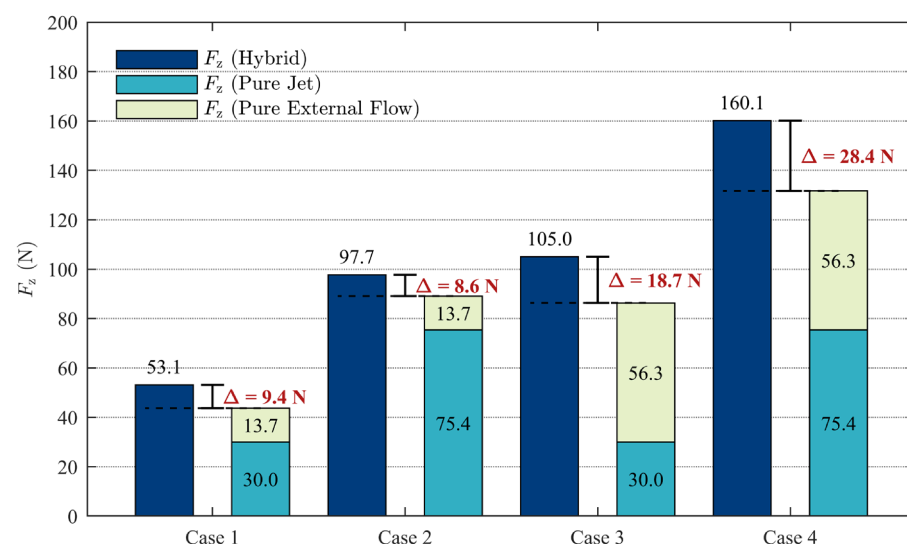


Figure 14. Gap between the actual hybrid control force and the isolated control force.

3.2.3. Dynamic Control Force Model

This fluid–structure interaction produces a significant velocity-dependent enhancement of the actual vector control force (F_z), demonstrating a strong speed-gain characteristic. To capture these multi-physics interaction effects within an explicit formulation suitable for real-time flight control allocation, a dynamic hybrid model is derived by compiling the parametric CFD datasets. The total normal control force (F_z) under forward flight conditions is formulated as a composite function superimposing the ground static baseline model and an airborne aerodynamic interference correction term:

$$F_z = \underbrace{k_1 P_{jet}}_{\textcircled{1} F_{z,g}} + \underbrace{\left(k_2 \sqrt{\frac{P_{jet}}{P_\infty}} + k_3 \right) P_\infty}_{\textcircled{2} F_{z,extra}} \quad (8)$$

where k_2 and k_3 are the identified aero-interference coupling coefficients, and their values are listed in Table 5.

Table 5. Coefficient of dynamic control force model.

Coefficient	$\delta_c = 45^\circ$
k_1 (N·Pa ⁻¹)	2.8×10^{-3}
k_2 (N·Pa ⁻¹)	5.3×10^{-3}
k_3 (N·Pa ⁻¹)	2.1×10^{-2}

The model structure demonstrates the actual physical meaning. When $P_\infty = 0$ (ground test condition), the gain term naturally disappears, and the model degenerates into a traditional ground calibration model; as P_∞ increases, the control force F_z also exhibits nonlinear growth, demonstrating the influence of flight speed on thrust vector control force.

This hybrid model possesses a clear physical foundation: the coupled square-root term ($k_2\sqrt{P_{jet}\cdot P_\infty}$) characterizes the nonlinear momentum mixing driven by the injection effect of internal and external flow fields, while the linear term (k_3P_∞) represents the independent aerodynamic contribution of the virtual surface acting under external dynamic pressure. Quantitative regression shows that the proposed control force model closely matches the testing and simulation data, achieving an R^2 of 0.998 and a mean absolute percentage error (MAPE) of only 1.32% (comparison in Figure 15). This provides a high-fidelity model representation for the adaptive control laws detailed in further research.

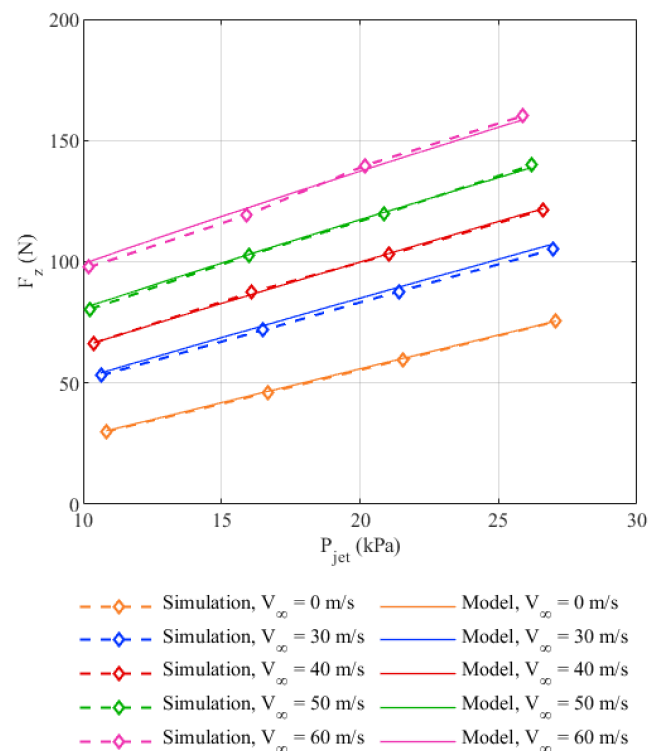


Figure 15. Comparison of dynamic control force model and CFD simulation data.

4. Conclusions

In this study, a hybrid modeling method integrating ground experiments and numerical simulations is proposed. The mechanism by which the external flow field influences thrust vector control performance is investigated, and a nonlinear dynamic control force model is established. The main conclusions are as follows:

1. The proposed hybrid modeling framework addresses the mechanical complexity and high costs associated with conventional six-axis test benches, thereby simplifying the calibration process. Furthermore, it enables evaluation of the interaction mechanisms between the external flow field and the thrust-vectoring jet through numerical simulations, which allows for accurate characterization of nonlinear variations in control authority under dynamic flight conditions.
2. The control force characteristics of TVC aircraft within the cruising speed range of 30 to 60 m/s were quantitatively analyzed using numerical simulation. The results indicate that the interaction between the deflected jet exhaust and the external flow field leads to significant modifications in the flow structure and pressure distribution around the control surface. The momentum exchange, primarily governed by mass entrainment and cross-shear-layer mixing, broadens the control surface's impact scope and enhances the injection effect, resulting in nonlinear variations in the control force under different operating conditions.
3. A dynamic control force model was established by integrating the ground static baseline model with simulation data. The match error between the fitted control force model and the results from ground tests and simulations is within 3%. The model utilizes a simplified sensing scheme that requires only two measurable parameters: nozzle outlet dynamic pressure (P_{jet}) and external freestream dynamic pressure (P_{∞}). This configuration ensures reliable real-time computation by the onboard flight control computer under various flight conditions.
4. A standardized and cost-effective simulation–experimental workflow is established, providing a scalable and analyzable design process and research method for advanced thrust vector control (TVC) aircraft. This workflow supports systematic investigation and application in TVC aircraft development.

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Abbreviations

The following abbreviations are used in this manuscript:

TVC	Thrust vector control
MTV	Mechanical thrust vectoring
FTV	Fluidic thrust vectoring
CFD	Computational Fluid Dynamics
RANS	Reynolds-Averaged Navier–Stokes
SST	Shear Stress Transport
DoF	Degrees of Freedom
JI	Jet-Interaction

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