Journal of Architectural Research and Development, 2026, Volume 10, Issue 1
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Study on Static Three-Component Aerodynamic Force Coefficients of a Streamlined Box Girder Based on CFD

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Abstract: A systematic investigation on the static three-component aerodynamic force coefficients of a streamlined box girder cross-section is conducted using the Computational Fluid Dynamics (CFD) approach. The Reynolds-Averaged Navier–Stokes (RANS) equations coupled with an appropriate turbulence model are employed to establish numerical simulation models of the bridge girder under various angles of attack. The flow field structures and aerodynamic characteristics around the main girder are simulated and analyzed in detail. By comparing the variations of lift, drag, and moment responses under different angles of attack, the characteristic curves of the three-component force coefficients are obtained. Furthermore, the locations of key flow separation points, the evolution of wake vortex structures, and their influences on aerodynamic force variations are examined to elucidate the underlying flow mechanisms governing the changes in aerodynamic coefficients. The results provide theoretical insights and technical support for wind-resistant design, aerodynamic optimization of streamlined box girders, and the selection of wind tunnel test parameters.

Keywords: Streamlined box girder; Computational fluid dynamics (CFD); Static aerodynamic force coefficients

Online publication: Jan 28, 2026

1. Introduction

In recent years, with the continuous increase in the span length of long-span bridges, bridge structures have become increasingly sensitive to wind loads, making aerodynamic characteristics a critical issue in structural design and safety assessment. Computational Fluid Dynamics (CFD) has emerged as an efficient numerical tool for predicting flow fields and aerodynamic force coefficients around bridge decks and has been widely applied in the study of bridge sectional aerodynamics.

Previous CFD studies have primarily focused on investigating the effects of different turbulence models on aerodynamic force coefficients and exploring the influence of geometric parameters on aerodynamic responses [1–5]. Zheng et al. proposed a CFD–Kriging surrogate-based shape optimization strategy to enhance the critical flutter wind speed and mitigate unfavorable aerodynamic effects, providing an effective approach for aerodynamic shape optimization [6]. Further studies analyzed the aerodynamic characteristics of twin-slot box girders under various flow conditions, demonstrating that geometric modifications can significantly alter static aerodynamic coefficient trends and flow separation behavior [7]. In addition, Li et al. conducted comparative CFD studies on the aerodynamic differences among trains, flat plates, and streamlined box girders, revealing the mechanical response characteristics of different structural forms from an aerodynamic perspective and offering valuable references for wind-induced response analysis of bridge-train systems [8].

These studies indicate that high-fidelity CFD simulations can effectively capture the sensitivity of aerodynamic force coefficients to angle of attack and geometric parameters, thereby providing a solid theoretical and numerical foundation for aerodynamic optimization of bridge structures.

In this study, a CFD-based numerical simulation method is employed to establish a comprehensive two-dimensional computational model incorporating the main girder and key ancillary components. By systematically varying the angle of attack, the drag, lift, and moment coefficients of a streamlined box girder and the corresponding flow field evolution are investigated. The objective is to provide reliable numerical evidence for wind-resistant bridge design, aerodynamic shape optimization, and the formulation of wind tunnel testing schemes.

2. Numerical model

The computational model adopts a 1:20 scaled section model, including the stiffening girder, crash barriers, and pedestrian railings, to evaluate the overall static three-component aerodynamic force coefficients. The static aerodynamic forces acting on the bridge girder section can be expressed in either the body-fixed coordinate system or the wind-axis coordinate system. The girder cross-section is shown in **Figure 1**. Mesh generation is performed using ICEM CFD, and the flow field is solved using ANSYS Fluent. The boundary conditions of the computational domain are defined as follows: a velocity inlet with a uniform incoming wind speed of 5 m/s; a pressure outlet with zero reference pressure; symmetry conditions applied to the upper and lower boundaries; and a no-slip wall condition imposed on the girder surface.

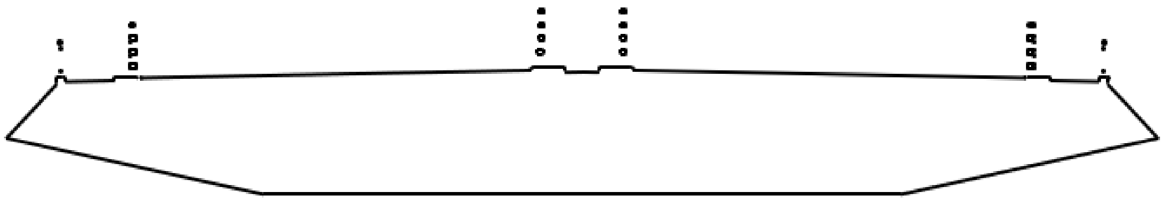

Figure 1. Schematic diagram of the main girder.

The SST k–ω turbulence model based on the Reynolds-averaged framework is employed. Second-order upwind schemes are used for spatial discretization, and the time step is set to 1×10^{3} s. A hybrid mesh is adopted, with the first near-wall grid height of 1.0×10^{-5} m, 20 boundary layer grids, and a growth rate of 1.1. The total number of grid cells is approximately 420,000. **Figure 2** presents the computational domain and mesh distribution under the 0° angle of attack condition.

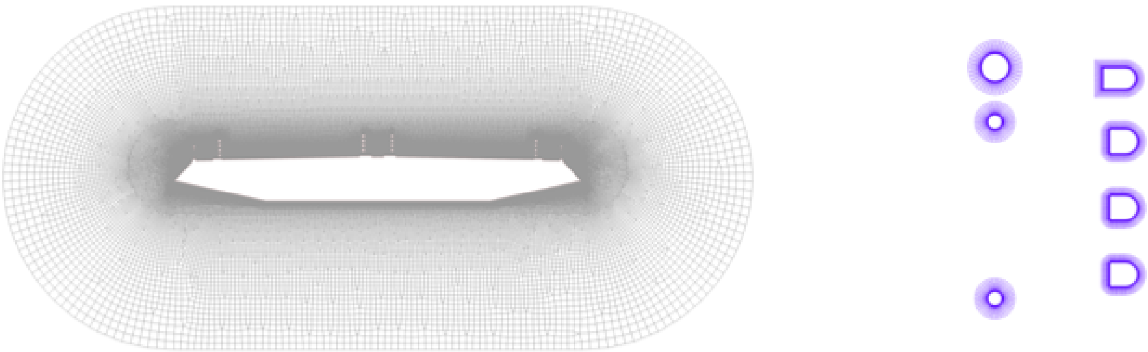

Figure 2. Overall computational domain and local mesh distribution.

3. Static three-component aerodynamic force coefficients

Figure 3 illustrates the variation of the three-component aerodynamic force coefficients in the body-fixed coordinate system as functions of the angle of attack. The results demonstrate that all aerodynamic coefficients are highly sensitive to changes in the angle of attack, reflecting the significant influence of inflow direction on flow structures and aerodynamic force distributions.

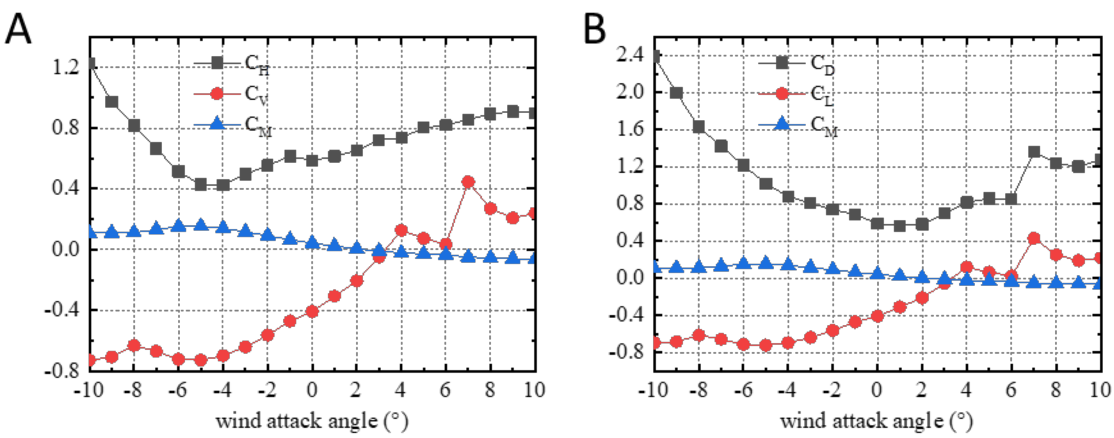

Figure 3. Static three component aerodynamic force coefficients. A. Body-fixed coordinate system. B. Wind axis coordinate system.

The drag coefficient exhibits a pronounced decreasing trend as the angle of attack increases from −10° to approximately −3°, reaching a minimum at a small negative angle of attack. This behavior indicates improved flow attachment along the girder surface and reduced wake size within this range, resulting in lower overall drag. As the angle of attack further increases, the effective windward projected area enlarges, accompanied by the development of local flow separation and recirculation zones, leading to a gradual increase in the drag coefficient, which remains relatively high at larger positive angles of attack. The lift coefficient shows an overall monotonically increasing trend with increasing angle of attack. It is negative in the negative angle range, gradually approaches zero, and becomes positive at positive angles of attack. This variation is closely associated with the redistribution of pressure on the upper and lower surfaces of the girder, indicating that changes in inflow direction significantly modify pressure gradients and dominant vortex structures. A local peak in the lift coefficient appears around angles of attack of 6–8°, which may be attributed to the intensification of separated vortex structures and changes in vortex shedding patterns. The moment coefficient maintains a relatively small magnitude across the entire range of angles of attack but exhibits a clear variation trend. At negative angles of attack, the moment coefficient is positive and decreases gradually with increasing angle, changing sign near zero angle of attack, indicating a reversal of the aerodynamic moment direction about the reference point. At positive angles of attack, the moment coefficient remains slightly negative, suggesting a certain degree of aerodynamic stability under these conditions. Overall, the numerical results reasonably capture the aerodynamic force variations of the streamlined box girder under different angles of attack, showing good consistency and continuity in the trends of the aerodynamic coefficients.

4. Flow field characteristics

Figure 5 presents the streamline distributions around the girder under different angles of attack. The results reveal that variations in the angle of attack significantly affect flow separation locations, wake morphology, and vortex structure evolution.

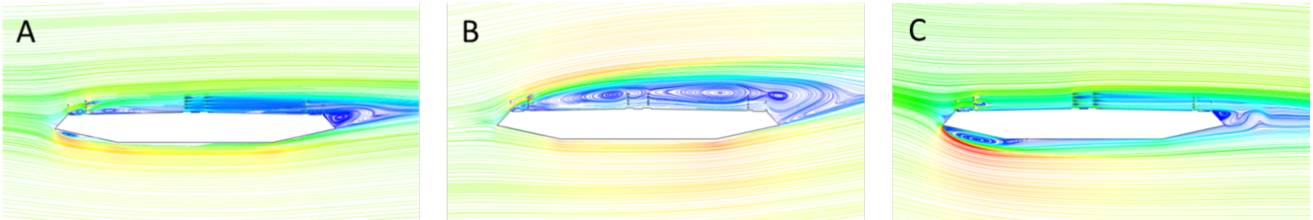

Figure 4. Surface streamline patterns of the main girder. A. 0° angle of attack. B. + 5° angle of attack. C. −5° angle of attack.

At 0° angle of attack, the incoming flow develops nearly along the girder axis, with relatively smooth streamline distributions on the windward side. The flow experiences slight acceleration near the leading edge and maintains good attachment along both the upper and lower surfaces. Although flow separation and recirculation occur in the wake region, the recirculation zone remains limited in size, and the wake is relatively narrow and symmetric, indicating a stable flow pattern with small aerodynamic force fluctuations.

When the angle of attack increases to + 5°, the flow field undergoes notable changes. The streamlines on the upper surface bend more sharply, and after local acceleration, flow separation occurs rapidly, forming a large recirculation zone and closed vortex structures above the girder. The separated vortices extend downstream and intensify in the wake region, significantly widening the wake. Meanwhile, the flow on the lower surface becomes more densely packed and remains more attached, resulting in pronounced asymmetry in surface flow characteristics and pressure distributions.

At −5° angle of attack, the flow separation behavior exhibits an opposite trend compared to the positive angle condition. The lower surface becomes the primary separation region, with noticeable flow deflection near the leading edge and the formation of a local recirculation zone. Although the size of the separated region is smaller than that observed at + 5°, it still significantly influences the wake structure. The upper surface flow remains largely attached, and the wake vortices develop predominantly along the lower surface, leading to an asymmetric wake displacement. A comparative analysis across different angles of attack indicates that variations in angle of attack substantially alter surface flow separation locations and wake vortex configurations, thereby changing the magnitude and direction of the aerodynamic forces acting on the girder.

5. Conclusion

Based on CFD numerical simulations, a systematic investigation is conducted on the static three-component aerodynamic force coefficients and corresponding flow mechanisms of a streamlined box girder under various angles of attack. The numerical results demonstrate that the static aerodynamic force coefficients are highly sensitive to changes in the angle of attack, with drag, lift, and moment coefficients exhibiting clear and continuous variation trends.

Changes in the angle of attack significantly affect flow separation locations on the girder surface and wake structure morphology, leading to modifications in pressure distributions and aerodynamic force responses. Analysis of streamline patterns and vortex structure evolution shows that the variations in aerodynamic force coefficients with angle of attack can be consistently and reasonably explained by the corresponding changes in flow field structures, indicating strong agreement between aerodynamic response characteristics and underlying flow mechanisms.

Disclosure statement

The authors declare no conflict of interest.

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