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Numerical study on lateral jet interaction in supersonic crossflows

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ABSTRACT

This paper presents numerical analyses of lateral jets in supersonic cross flows on a flat plate and on a generic missile. The freestream Mach number is 4 for the flat plate and 3 for the missile, and the jets are sonic for both cases. The numerical results are validated with wind tunnel data such as Schlieren images and surface pressure distributions. The flow structure due to the jet interaction with the supersonic free-stream is examined in terms of the vortex structure. A 3-dimensional compressible RANS solver is used for the study. To describe the effects of high temperature, a thermally perfect gas is assumed. When high temperature is applied, the shock structure changes, which affects the separation region and recirculation zone. Next, the effects of turbulence models on the jet interaction flow are investigated. The Spalart–Allmaras, Menter's shear-stress transport k–ω, Huang and Coakley's k–ε, and Coakley's q–ω models are used to analyze the flows. The differences in pressure distribution among the turbulence models are larger in the case of the flat plate than the missile. In addition, several numerical flux functions are compared to investigate their effects on the jet interaction: the Roe scheme with Sanders's H-correction, RoeM scheme, and the HLLE scheme. Although the HLLE scheme shows a little difference at the indent of the barrel shock, the three numerical flux schemes give similar C_P distributions on the wall.

1. Introduction

A Divert and attitude control system (DACS) uses the thrust of lateral jets for missile control. As shown in Fig. 1, a DACS can generate a normal force or a moment depending on the position of the jet relative to the center of gravity (C.G.). A lateral jet near the C.G. can induce sideslip of the missile, while a rear lateral jet can change its attitude and angle of attack [1]. The system is especially useful when the dynamic pressure is too low to generate a sufficient aerodynamic control force with fins, such as at high altitude or low speed [2].

However, a lateral jet has complicated interactions with the supersonic free-stream. Fig. 2 presents a schematic of the jet interaction flow [3]. Since the lateral jet is generally in an under-expanded condition, the jet gas expands rapidly so that the flow accelerates to supersonic speed to cause a barrel shock and a Mach disk to form. The barrel shock acts as a blunt obstacle against the supersonic free-stream. As a result, a bow shock forms in front of the barrel shock. The bow shock interacts with the boundary layer on the missile surface and causes the flow to separate. The separated flow interacts with the free-stream and causes a horse-shoe vortex to form in front of the separation region. Similarly, several vortex pairs form behind the barrel shock. The bottom vortex pair induces a recirculation zone on the surface. This complex flow causes a pressure rise in front of the jet and a pressure drop in the rear. As a result, the jet interaction flow induces a nose down moment.

Spaid and Zukoski [4] conducted an experimental study on the jet interaction with various flow conditions and investigated the major parameters of the jet interaction flow field. Aso et al. [5] also experimentally investigated the effect of the jet pressure ratio and the width of the jet on the jet interaction. They studied the effect of the incoming boundary layer on the jet interaction with the supersonic inflow. Won et al. [6] carried out a numerical study based on these experiments [4,5] and conducted a grid refinement test with varying cell numbers and y^+.

Wallis [7] conducted a jet interaction test on a flat plate using a supersonic wind tunnel, and used Schlieren images to observe the shock structure as well as pressure-sensitive paint to obtain a surface pressure map. Viti et al. [8] performed a CFD analysis of Wallis's wind tunnel test and captured the detailed physical phenomena of the jet interaction. Stahl et al. [9] conducted an experiment on the jet interaction using cold lateral air jets as well as hot gas jet for a generic missile model. Gnemmi et al. [10,11] performed a numerical analysis of the experiment by Stahl et al. [9] and investigated the details of the vortex structure. They also attempted to numerically analyze the hot gas jet interaction of two missile models with various CFD solvers. However, they used the

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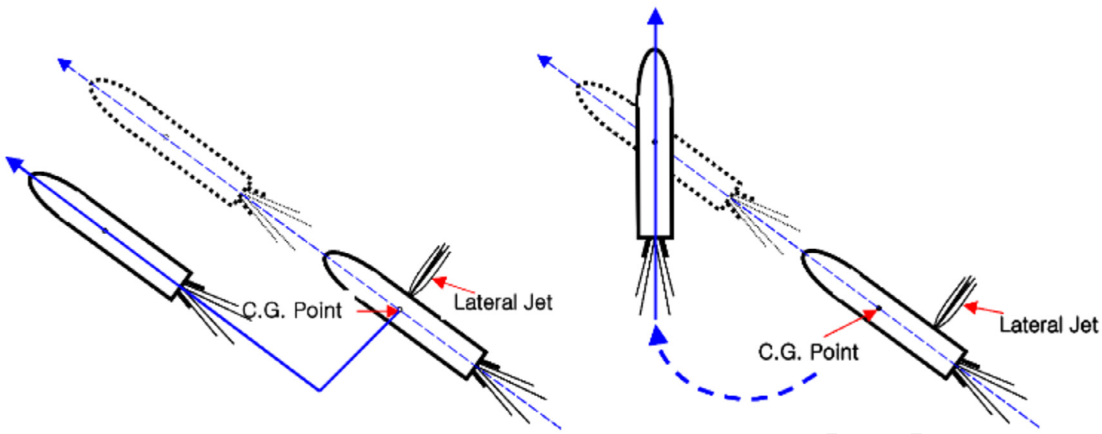

Fig. 1. Concept of missile control using lateral jet [1].

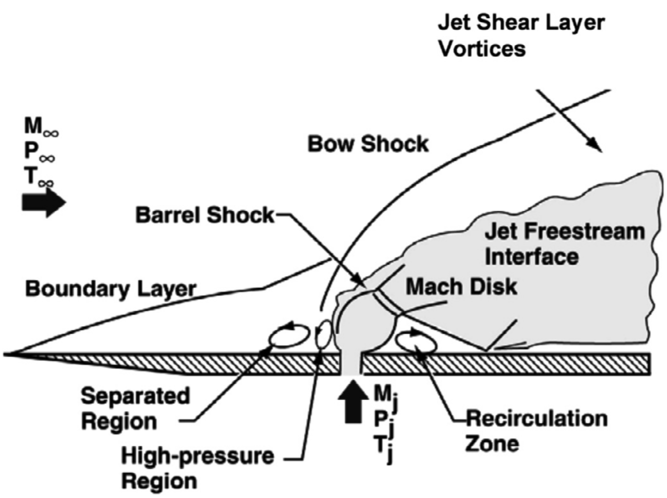

Fig. 2. Flow structure of jet interaction [3].

equation of state for calorically perfect gas. Kang et al. [12] conducted numerical and experimental analysis of the jet interaction of a supersonic missile to obtain an aerodynamic database.

Since flow separations occur near the jet exit, it is important to select an appropriate turbulence model. Kwak et al. [13] presented the effect of turbulence models on the separation flow using a wing-body configuration. They investigated the performance of turbulence models by comparing the separation flow and the wall C_P distributions. Christie [14] and DeSpirito [15] compared the effects of turbulence models on the jet interaction flow. Christie [14] compared the numerical results of a flat plate and a missile with four turbulence models. DeSpirito [15] compared the jet interactions of cold air, hot air and hot gas jet cases using nine turbulence models derived from the standard one and two-equation turbulence models. He also used the calorically perfect gas assumption in his computations.

A previous numerical study investigated the jet interactions of a generic missile in several jet conditions and compared the effects of flux functions [16]. We showed that just increasing the jet temperature would not yield accurate results for the hot gas case and suggested that more physics should be included in the numerical simulations. Both Gnemmi [11] and DeSpirito [15] described the hot gas jet as a multi-species gas mixture. However, they assumed that the gas was calorically perfect gas. Since the specific heat is no longer a constant value at high temperature, it may be necessary to assume that the gas is thermally perfect.

Roe's approximate Riemann solver [17] was presented with the calorically perfect gas assumption. Grossman and Walters [18] and Vinokur [19] suggested modifications to the Roe scheme for general equations of state. Grossman and Walters' modification [18] was based on an approximation of the specific heat ratio in a Jacobian matrix. In contrast, Vinokur [19] derived an exact definition of the Roe-average state. Several approximations were used to avoid indeterminate results in an equilibrium state.

It is widely known that upwind schemes suffer numerical instabilities near strong normal shocks such as Mach disks. The shock instabilities arise due to a lack of numerical dissipation near strong normal shocks when the shocks and grid lines are aligned. Sanders [20] introduced multi-dimensional dissipation to the Roe scheme through entropy correction. Kim et al. [21] performed a linear perturbation analysis on an unstable shock problem and introduced numerical damping to the Roe scheme through Mach number-based functions, which led to a shock-stable Roe scheme. The HLLE (Harten, Lax, van Leer and Einfeldt) solver [22,23] is an approximate solution to the Riemann problem, which is only based on the integral form of the conservation laws and the largest and smallest signal velocities at the interface.

In this study, we numerically analyze the jet interaction flows of the flat plate and the generic missile model. A 3-dimensional Reynolds Averaged Navier–Stokes (RANS) solver known as MSAPv [16,24] is used for the CFD simulation. The λ_2-method [25] is employed to identify vortices and investigate the vortex structure that arises from the jet interaction. Streamlines around the vortex cores are visualized to enhance the understanding of the vortical flows. Next, the shock structures with and without the high temperature effect are compared. The effects of the turbulence models on the jet interaction are also examined. The turbulence models used in this paper are Spalart–Allmaras (S–A) [26], Menter's k–ω SST [27], Huang and Coakley's k–ε [28], and Coakley's q–ω models [29]. Lastly, we compare the effects of inviscid flux schemes on the jet interaction flow. The jet interaction flow induces complex shock structures. Research on the effects of numerical flux schemes on the jet interaction is rare.

2. Numerical schemes

2.1. Governing equations

MSAPv [16,24] uses the 3-D RANS equations as governing equations to simulate the jet interactions. The governing equations are discretized with a finite volume method (FVM) in a structured grid system. The governing equations are: