Control of Plume Interference Using a Porous Extension

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다공확장벽을 이용한 플룸간섭의 제어

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ABSTRACT

The physics of the plume-induced shock and separation particularly at a high plume to exit pressure ratio and supersonic speeds up to Mach 3.0 with and without a passive control method, porous extension, were studied using computational techniques. Mass-averaged Navier-Stokes equations with the RNG k-ε turbulence model were solved using a fully implicit finite volume scheme and a 4-stage Runge-Kutta method. The control methodology for plume-afterbody interactions is to use a perforated wall attached at either the nozzle exit or the edge of the missile base. The Effect of porous wall length on plume interference is also investigated. The computational results show the main effect of the porous extension on plume-afterbody interactions is to restrain the plume from strongly underexpanding during a change in flight conditions. With control, a change in porous extension length has no significant effect on plume interference.

1. Introduction

Supersonic speeds are the rule for most modern missiles, which require a very high thrust level within a limited cross sectional area. The aerodynamic designs in recent years, therefore, have focussed on understanding several problems associated with the plume expansion at high speeds and altitudes. These configurations generally have a highly underexpanded jet plume[1,2] downstream of the exhaust nozzle exit, leading to considerable interactions between the exhaust plume and freestream near the tail of missile bodies. The boundary layer separation[3,4] and pitching and yawing moments that result from the interactions can have significant effects on missile stability and control[5,6].

A detailed understanding of plume interference phenomena for an arbitrary missile configuration is indispensable to missile design. However, due to excessive assumptions to solve complex viscous-inviscid interactions and simple pressure measurements provided through most theoretical and experimental studies to date, the current knowledge base built in this research area is not adequate to provide an overall insight into the physics involved. CFD (Computational Fluid Dynamics) analyses, therefore, offer a way forward for the development of such a design. Very recently, some computational work[7,8] has been made mainly on base flow problems but, to the

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authors knowledge, no CFD study has been conducted for the control of plume interference phenomena.

In this research, a CFD investigation was conducted for missile models with a simple afterbody and with a porous extension to simulate highly underexpanded exhaust plumes at supersonic speeds. A fully implicit finite volume scheme was applied to mass-averaged Navier-Stokes equations with a two-equation turbulence model, RNG k-ε. The present numerical study may develop a basic understanding into the influence of the porous extension on the plume-induced shockwave and separation, leading to the effective and efficient control of flight bodies.

2. Numerical Simulations

Fig. 1 shows the schematic diagrams of missile models tested in this CFD analysis. The present computational model can be basically represented as an ogive forebody and straight afterbody without tail fins, identified as Model Simple. The 13-calibre missile body for the code validation had a 4-calibre tangent ogive nose and a cylindrical afterbody diameter of 63.5 mm. A convergent-divergent nozzle, having a design Mach number of 2.7, an exit diameter of D_e = 50.9 mm and a divergence angle of 20, was used to acquire supersonic plumes downstream of the nozzle exit. For porous extension models, Model PD and PDE with a porous wall length l_p and porosity of 0.5, a perforated wall is attached to the afterbody edge and nozzle exit respectively. The afterbody models given here were tested in order to evaluate the effectiveness of the control of the flow features which may adversely affect overall missile performance.

Axisymmetric compressible Navier-Skokes computations were conducted via a commercial CFD code, Fluent 5, which has the ability to predict the flow fields involving strong shock interactions with shear layers and boundary layers so that is expected to provide high quality simulations for the flow fields around missile bodies with highly underexpanded plume. The main parameter to characterize plume-freestream interactions was the freestream Mach number M_∞ up to 3.0 at a plume pressure ratio p_c/p_a of 170.9, which represents a highly underexpanded plume for the present missile models. Freestream pressure and temperature were assumed to be constant with values of 1 atm and 288.15 K respectively.

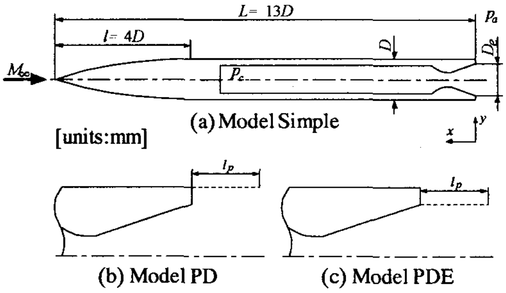

Fig. 1 Testing model configurations

Basically, solutions were considered converged when the residuals for all equations drop by three orders of magnitude, typically 10^{-4} with the mass imbalance check for flow inlet and outlet boundaries.

3. Results and Discussion

At M_∞ = 2.0 and p_c/p_a = 170.9, Fig. 2 presents computed Schlieren images to describe the detailed flowfields in the control range for Model Simple and porous extension models. On the afterbody of Model Simple, a clear λ -shaped reflection of the shock system is generated by separation and reattachment of the boundary layer approaching the plume expansion. As a porous extension is attached to the nozzle exit (Model PDE), the shock moves to the tailing edge with a considerably reduced angle of plume expansion, flattening the curvature of the compression corner. On the other hand, as the device is attached to the afterbody edge (Model PD), no distinct downstream shock movement is observed though plume dimensions are smaller than those of Model Simple. It can be observed that Model PD produces intense flows emitted from the perforated wall, making the back flow in the separation region very strong and thus resulting in poor control performance.

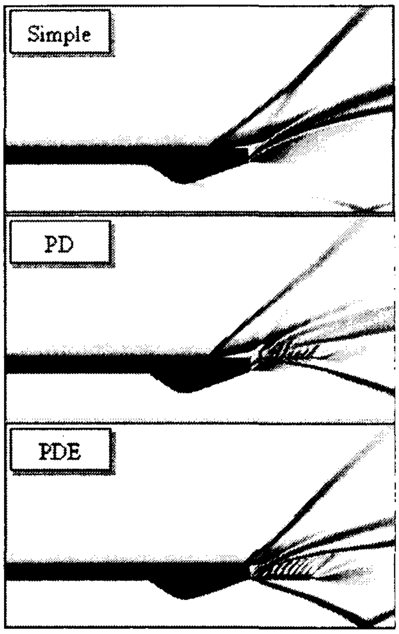

Fig. 2 Computed Schlieren images for Model Simple, PD and PDE (M_∞ = 2.0 and p_c/p_a = 170.9)

At M_∞ = 2.5 and p_c/p_a = 170.9, Fig. 3 shows the surface pressure distributions from the trailing edge towards upstream. For Model PD, when compared with Model Simple, there is no significant enhancement in shock movement and the pressure rise behind the shock is increased, while Model PDE gives a downstream location of the shock with considerably reduced strength. The location of the porous extension, therefore, must be chosen carefully and the nozzle exit would be a good recommendation.

Pressure distributions in Fig. 4 explain the effects of the freestream Mach number on shock interactions in the cases a porous wall is attached at the missile base. The plume-induced shock largely moves downstream as the missile accelerates from Mach 1.5 to 2.0, but it is nearly fixed with a further increased Mach number. The porous wall restrains the initial expansion of the plume near the nozzle exit and makes shock movements less severe so that may help the effective control of missiles.

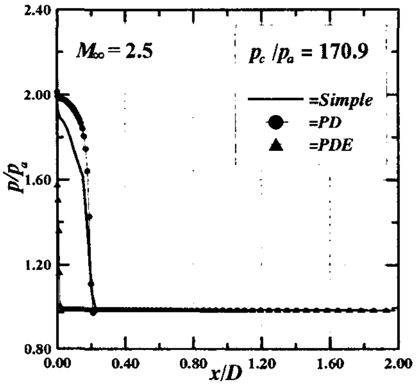

Fig. 3 Static pressure distributions along the afterbodies of Model Simple and porous extension models

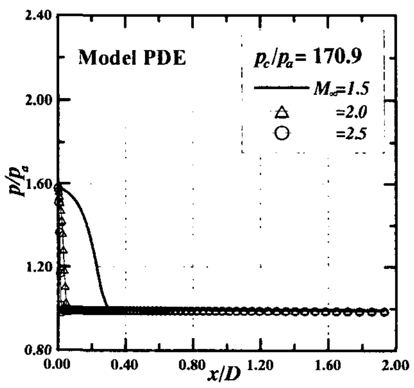

Fig. 4 Static pressure distributions along the afterbody of Model PDE with various freestream Mach numbers

At M_∞ = 2.0 and p_c/p_a = 170.9, Fig. 5 shows the surface pressure distributions for several porous wall length l_p in the range of $D/4$ ~ D. Compared with Model Simple, a change in porous wall length has no significant effect on shock strength. In Fig. 6, it can be also observed that there is actually no variation in the shock location for difference porous wall length except one case with $l_p=D/4$ and a low Mach number of 1.2, which shows a slight upstream location from other cases. Therefore, it is understood that the control of plume interference with a porous extension should be performed in consideration of the position of the device rather than its length.

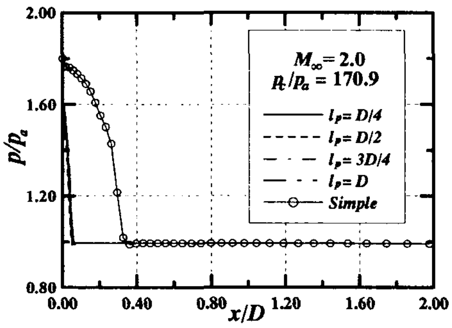

Fig. 5 Surface pressure distributions for Model PDE with various porous wall length

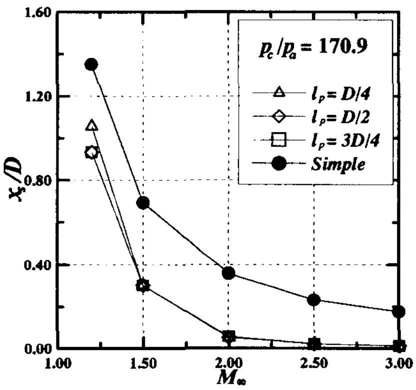

Fig. 6 Shock locations for several porous wall length

4. Conclusions

In the present work, missile models with a simple and two rounded afterbodies were simulated using axisymmetric Navier-Stokes computations. The compressible flow field around the missile models at transonic/supersonic speeds was investigated at plume pressure ratio of 50 ~ 350 with an ogive forebody and a supersonic nozzle. The convergent-divergent nozzle with a design Mach number of 2.7 was selected to give moderately and highly underexpanded jets downstream the nozzle. The effect of a porous wall attached at the missile base on shock interactions was mainly to restrain the plume from strongly underexpanding as the change in the flight condition. Control performance was strongly dependent on the device location but a change in porous extension length had no significant effect on the control. Therefore, this control method should be employed in consideration of the device location rather than the device length.

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