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Numerical Investigation of Transient Lateral Jet Interaction in a Supersonic Interceptor Missile

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Abstract—**The main objective of this paper is to numerically investigate the effects of a divert jet on the overall aerodynamic performance of a generic interceptor missile operating at moderate angle attack. A generic missile interceptor configuration consisting of a long, slender body containing tail fins is simulated in this study. Firstly, K-ε, K-ω and S-A turbulent model are evaluated in simulating downstream vortex transmission, the results show the K-ε has good ability in capturing vortex structure, especially secondary vortex structure. Secondly, by employing K-ε turbulent model, three dimensional computations of the highly turbulent flow field produced by five pulsed, supersonic, lateral jet control thrusters interaction with the supersonic free stream and missile boundary layer of the generic interceptor missile at 10 km for the Mach number is 3.0 and 6.0 is simulated. Finally, normal force and moment as well as normal force and moment amplification factor is assessed by integrating the surface pressures and viscous shear stresses computed on the missile surfaces. These results are used to determine the Mach number influence on the interaction of transient jet and supersonic aerodynamic performed missile. The analysis predicts strong influences for the integrated normal force and moment.**

I. Introduction

THE interceptor missiles require the use of lateral control/divert jets at high speeds/altitude where conventional aerodynamic controls become ineffective. To complete its mission successfully, the interceptor missile must be highly maneuverable as it travels at supersonic or hypersonic speeds. Quick-response maneuverability, especially during the final phase of the missiles trajectory, is achieved by a rapid airframe response time to the attitude control system.

The mutual interference of the highly pressurized lateral jet with the supersonic free-stream leads to thrust and moment amplifications, mainly because the lateral jet forms high-pressure regions on the missile surface. These high-pressure regions are created by the shock structure that develops in the supersonic free-stream in front of the lateral jet. Large regions of separated flow created by the missile boundary-layer interaction with shock structure cause the high-pressure areas to increase in size. These effects amplifies the response of the divert jets. But at some missile orientations and flow conditions, the mutual interference of the jet-thruster flow field with the free-stream leads to "de-amplification". Therefore, an understanding of the controlling factors that produce thrust amplification as well as "de-amplification" is critical to developing a credible design basis for optimal missile aerodynamic performance.

The ability of lateral jet ground test is much too limited. The limitations include test duration, test section and core-flow size, and flow quality. Because of these limitations, ground test for supersonic JI flow fields can hardly simulate the required conditions as the actual flight environment has.

Fortunately, Computational Fluid Dynamic-CFD offers us the potential to predict the complex supersonic JI flow field. Through CFD solution, the size and location of the test instrumentation could be easily determined. CFD can serve as a kind of an experiment supplement database for developing improved performance prediction methodologies.

II. Validation of the Numerical Approach

A. Aerodynamic Analysis Method

For the analysis of complex JI flow field around a generic interceptor missile, the three dimensional Navier-Stokes computer code is developed for the unsteady, compressible flow. The equations are given below, the spatial flux vectors F, G, H, the viscous vectors Fv, Gv, Hv

$$\frac{\partial Q}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}+\frac{\partial H}{\partial z}=\frac{1}{\mathrm{Re}}\left(\frac{\partial F^{V}}{\partial x}+\frac{\partial G^{V}}{\partial y}+\frac{\partial H^{V}}{\partial z}\right) \quad (1)$$

FDS-Roe scheme is employed for spatial discretization and MUSCL for higher order interpolation. In order to suppress the nonphysical oscillations, Minmod limiter is used. LU-SGS scheme is also used for fully implicit time integration. K-ε, K-ω and S-A turbulence model were evaluated for vortex structure simulation, especially for present JI effects study.

B. Ogive-Cylinder Body Validation

To validate the accuracy of the developed CFD code, the test case is an ogive-cylinder body, Fig1 shows the geometry of ogive-cylinder and its corresponding grid system is shown in Fig3. The surface pressure distribution calculated by K-ε, K-ω and S-A turbulence model were compared with experimental data.

Flow condition:

$M_\infty = 2.5$，$\alpha = 14°$，$Re = 1.123\times10^6$

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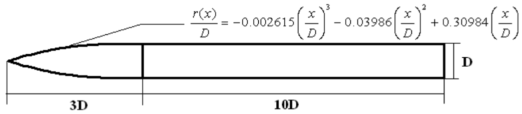


Fig.1 Geometry of ogive-cylinder body

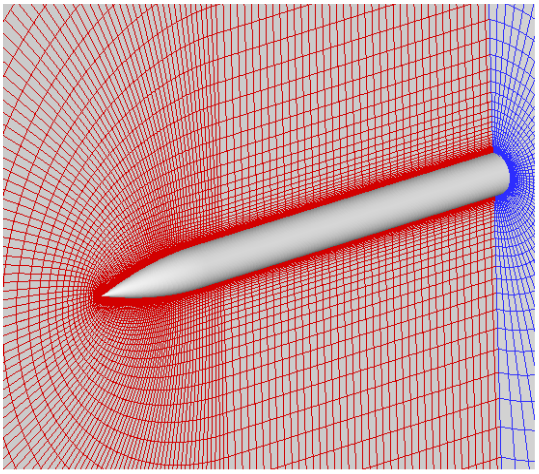


Fig.2 Ogive-cylinder body grid system

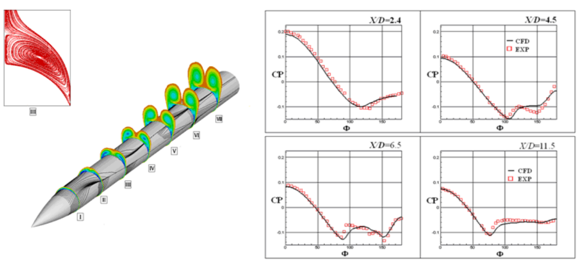


Fig.3 Results by K-□turbulent model

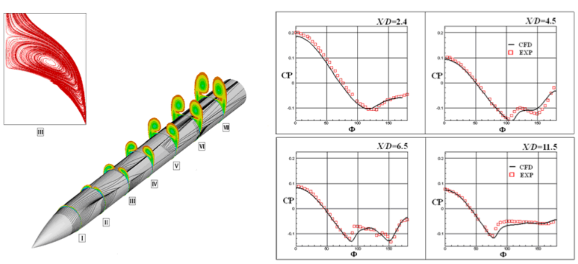


Fig.4 Results by K-□ turbulent model

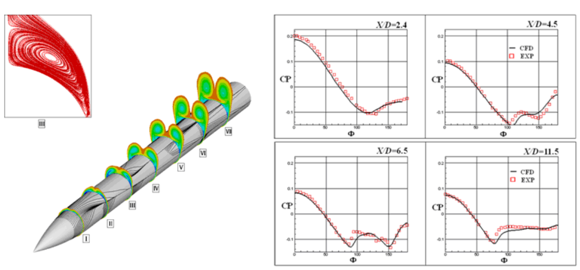
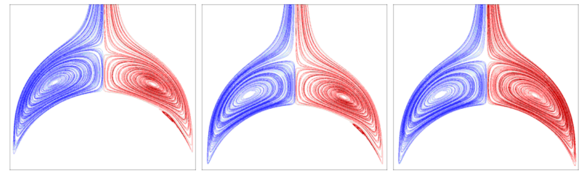


Fig.5 Results by S-A turbulent model



K-ω 与 K-ε　　　S-A 与 K-ε　　　S-A 与 K-ω

Fig.6 Comparing the ability of each turbulent model in capturing vortex structure

It can find that the CFD results are very close to the experimental results from the fig.3-5. Comparing the ability of K-□,K-□ and S-A turbulent model in capturing vortex structure, show in fig.6, we can easily get the conclusion that K-□turbulent model can get the secondary vortex structure, has a better ability in capturing vortex structure. Therefore, CFD results can be used to assess the aerodynamic influences afforded by the operation of the divert jet. We choose the K-□ turbulent model as our computing turbulent model.

III. GEOMETRY AND COMPUTATIONAL GRID

The generic interceptor missile geometry is show in fig.7, including a long, slender body, 5 pulsed divert-jet and a ×-× tail fins. Fig.8 is the computational grid structure for the missile, a half structure grid for the missile since the geometry of the missile is symmetry, including 17 blocks and approximately 962152 grid cells. An enlargement of the grid near the divert-jet location on the missile surface is show in fig.9. A very high grid density was constructed around the diverted- jet exit to obtain spatial details of the flow gradients in this complex jet interaction region.

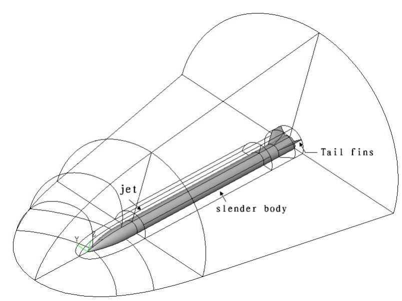


Fig.7 Computation geometry and surface definition

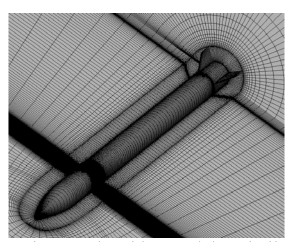


Fig.8 Body grid around the missile

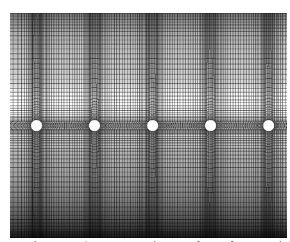


Fig.9 Close-up view of surface grid around jet exit

IV. Results and Discussion

The numerical simulation of transient lateral-jet interaction with supersonic freestream is operated with the thrust of the divert-jet alter with time, show as fig.10. The thrust is 0N at time=0s, and quickly increase to -558.84N (the minus means the direction of the thrust is downward) at 0.00000204s, after a short-time slowly rising it sharply increase again from -594.83N at time=0.00317s. The time between 0s and 0.01482s is the divert-jet shut-up time, and the thrust reach a maximal value of -3127.07N. And then the divert-jet runs into a range of shut-down time from 0.01482s. The thrust diminish as the time increase, and return to 0N again at 0.03s while the lateral jet shut-off completely. The numerical computation operated to 35s in order to get a steady force and moment.

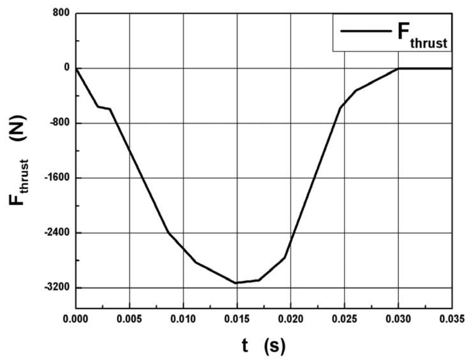


Fig.10 The thrust of divert-jet alter with time

The normal force and moment (related to the center of mass) versus time by integrating the surface pressure of interceptor missile at moment time for altitude condition 10km, Mach number corresponding to 3.0 and 6.0 at angle of attack 20 degree is shown in fig.11. It indicates many similar in Fig.11 (a), (b), (c), (d), (e) and (f) for they all get from a same jet condition. They all have a similar form as the thrust of jet vary with time, all have a mild bounce at the most beginning microsecond, and then sharply decrease or increase, and reach a extremum at approximate 0.01482s, and they all return to the most origin value at last. However, there are much detail difference and have a much difference in magnitude by comparing the value at Mach number 3.0 and 6.0. The origin normal force is approximate 167500N for Mach number 6.0, which is about 2.5 times bigger than 48500N for 3.0 Mach number. The force for both two condition will then decrease a same magnitude force approximate 16400N to obtain a minimal value about 32100N for mach number 3.0 and 151100N for 6.0 at 0.0149s, and after some milliseconds then all increasing to the most first value which is the divert-jet shut-down times. The normal force for the Mach number 3.0 is return to the beginning value at 0.034s which is 0.0015s later for the Mach number 6.0. The times which is longer then 0.03s we will named it as postponing time.

The variation of moment versus time for Mach number 3.0 and 6.0 is shown in Fig.11 (b) and (e). Here, we notice the moment of interceptor missile is decreasing from nearly 1000N.m for Mach number 3.0 and -12500N.m for 6.0 at 0s until obtained a minimal value of -20933N.m for Mach number 3.0 and -33064N.m for 6.0. Beyond which there is a tardive and then a quickly increase in moment.

We now turn our attention to the normal force and moment amplification factor presented in fig.11(c) and (f) for Mach number 3.0 and 6.0 respectively. The normal force amplification factor K_F is defined with F_{JI} and F_J as (2).

$$K_F = (F_J + F_{JI})/F_J \tag{2}$$

Where, F_J is the jet thrust and F_{JI} is the jet interaction force which is defined as (3)

$$F_{JI} = F_{Jet-on} - F_{Jet-off} \tag{3}$$

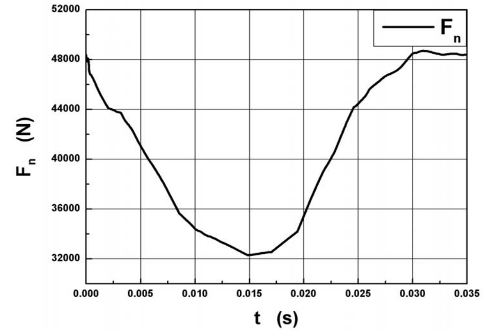
Similarly, the amplification factor can be defined a same form as the normal force amplification factor, presented as (4).

$$K_M = (M_{JI} + M_J)/M_J \tag{4}$$

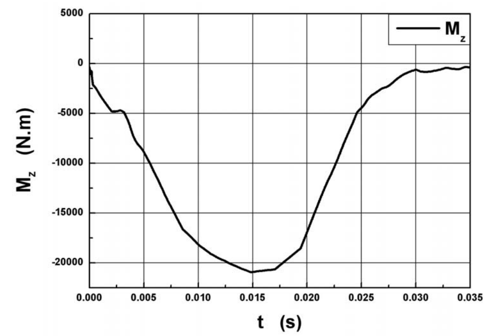
Where, M_J is the moment caused by jet thrust and M_{JI} is the jet interaction moment.

Investigating the fig.11(c) and (f), the force amplification factor and moment amplification factor all begin from 0 and finally return to 0, which attained a maximal value of nearly 1 at about 0.0149s. It means there is a most strong interaction for the normal force and moment at 0.0149s and the divert-jet can reach a most efforts at that moment.

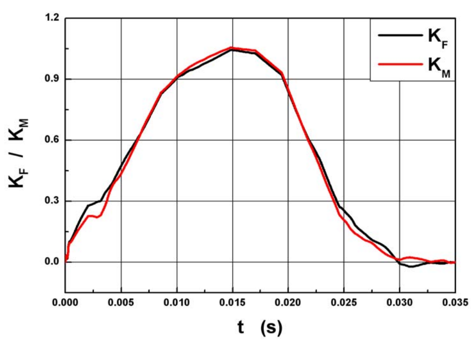
Fig.12 is the stream lines over the surface of the missile at 9 different moments for the condition of Mach number 3.0 at 10 kilometers altitude, 20 degree the angle of attack. Fig.13 is the stream lines at 9 different moments for the condition of Mach number 6.0 at a same altitude and same the angle of attack. We can see five circle similar fluid regions, produced by the fluid well out from the divert-jet, clearly at the center of the pictures. It indicates a strong interaction between the lateral-jet and free stream. The interaction is strengthened as the jet thrust increase. There is a large flow separation region upstream of the jet and low pressure area at the downstream, which all supply amplification of the normal force and moment and make the control of the missile more complex. The flow separation is more serious when the thrust of the jet increased, and the flow around missile positions at the lateral-jet is more serious. Many vortexes around the jet exit are formed by the jet flow blocking off the free stream and this make a more complex flow field.



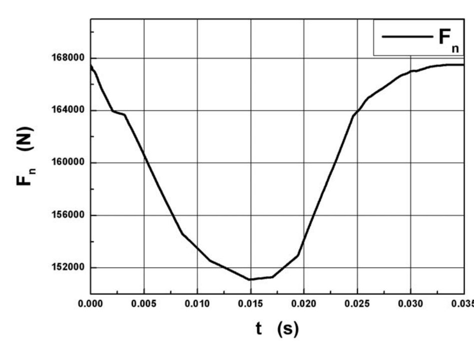
(a) Normal force for Mach number 3.0



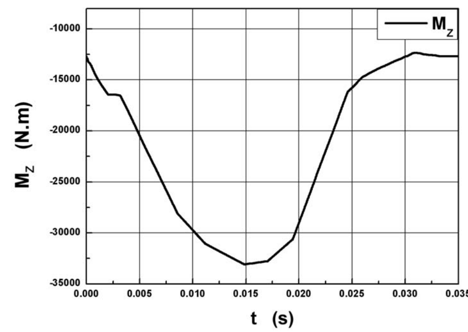
(b) Moment for Mach number 3.0



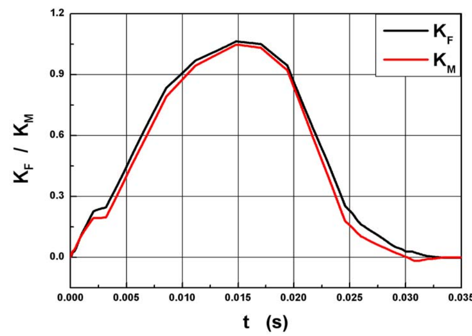
(c) Normal force and moment amplification factor for Mach number 3.0



(d) Normal force for Mach number 6.0



(e) Moment for Mach number 6.0



(f) Normal force and moment amplification factor for Mach number 6.0

Fig.11 Normal force and moment, normal force and moment amplification factor for Mach number 3.0 and 6.0

V. SUMMARY

Numerical investigation using CFD technical is used to analyze the transient effects of a divert jet on the overall aerodynamic performance of a generic interceptor missile operating at moderate angle attack. The analysis of the turbulent model indicates the CFD can be used to assess the force and moment on the interceptor missile and k-□turbulent model has a better ability in capturing the vortex. The Mach number has a strong effect to the normal force and moment. And we can get the conclusion that there is a stronger interaction at low Mach number than high Mach number by investigating the normal force amplification factor and moment amplification factor. The strong transient lateral jet interaction can also indicates by the streamlines over the interceptor missile surface at different moment. Those results show a strong transient effect that must be considered when designing control algorithms for pulsed-jet reaction control systems.

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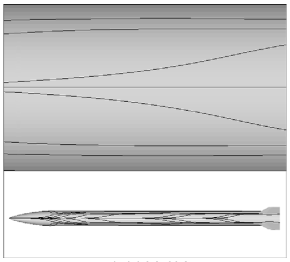
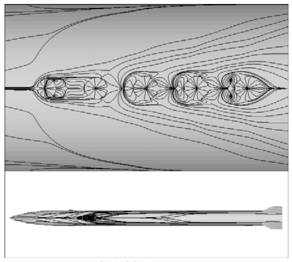

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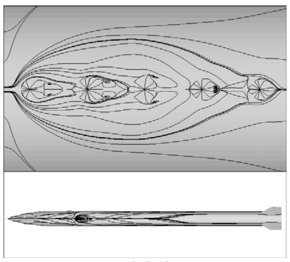
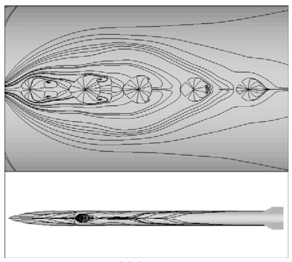

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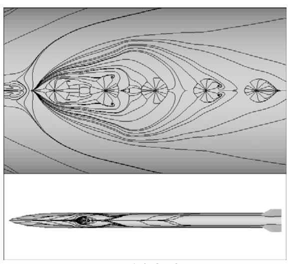
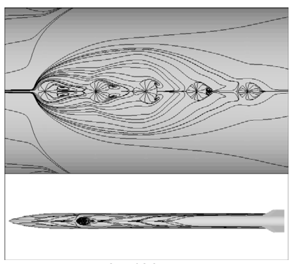

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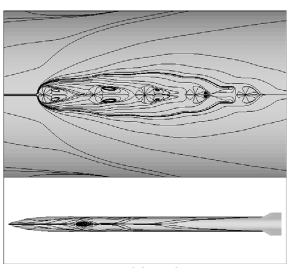
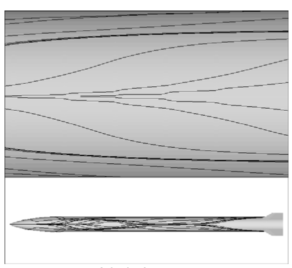
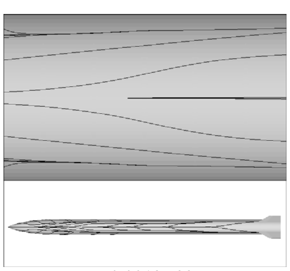
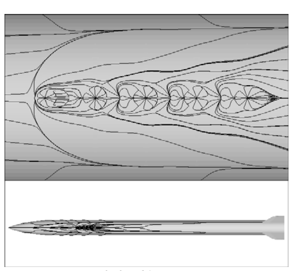



t= 28.559 ms   t= 30.479 ms

Fig.12 The stream lines over the wall and around nozzle exit for condition of 10km, M=3.0, α=20 degree

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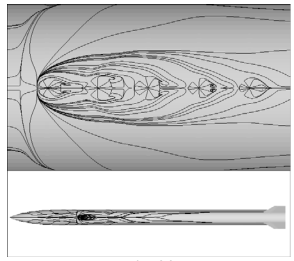
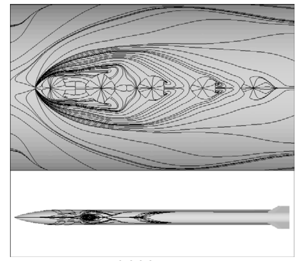

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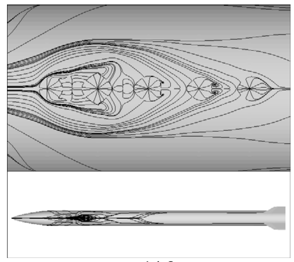
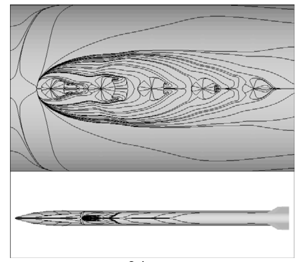

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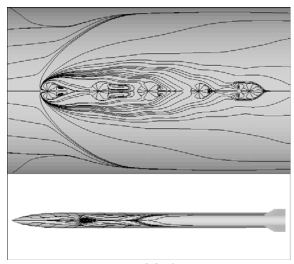
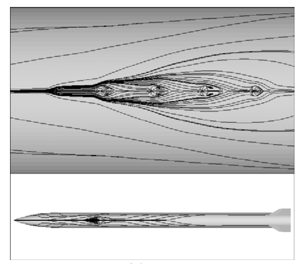

t= 28.4 ms   t= 30 ms

Fig.13 The stream lines over the wall and around nozzle exit for condition of 10km, M=6.0, α=20 degree