초음속 유도탄의 측추력기 작동시 풍동실험을 위한 CFD 해석 연구

Computational Investigation of Similarity Law and Wind Tunnel Testing for Side Jet Influence on Supersonic Missile Aerodynamics

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Computational study has been undertaken to investigate the aerodynamic influence of side jet on a supersonic missile and to find a similarity condition between the flight condition and the wind tunnel testing. Tasks were performed to validate the existing Raytheon test body with side jet, to simulate the flow inside the supersonic wind tunnel, and to compare the flow fields between the missile in free flight and that in the wind tunnel. Then sub-scale model of body-tail configuration was analyzed to estimate the influence of the side jet on the missile components. It is found that the influence of side jet is not as significant on the tail region as on the body surface and a simple algebraic formula for aerodynamic coefficients accounting for the side jet as a point force may be cautiously utilized in setting up control logic.

1. Introduction

For the rapid and abrupt maneuver, side jet or lateral jet thrust generators have been adopted to recent tactical missile development programs in several countries. In this paper, as a part of preliminary research, the influence of the side jet thrusters on the basic aerodynamic performance of the missile body has been investigated with CFD analysis results. At first, we proposed the typical flow field description for ogive-cylinder with jet eruption at the forebody part including validation cases. Wind tunnel test using model equipped with the side jet simulator will be indispensible for the construction of 6-DOF aerodynamic model. Apart from the basic aerodynamic wind tunnel tests without secondary jet involvement like side jet, these experiments require more constraints for appropriate simulation of jet interaction phenomena and the different aerodynamic model is required for the analysis of measured data. Therefore, some of the wind tunnel modeling results were reviewed to confirm similarity laws satisfied between flight condition and wind tunnel condition. The simplest algebraic model for normal force and pitching moment coefficients was suggested and compared with CFD results. We improved the model performance with introduction of the jet effectiveness factors for each coefficient and the extraction processes of the factor for the variation of altitude, jet position, and number of simultaneously activated jets were described independently.

2. Computational Results

2.1 Body Alone Calculation

The CFDS, termed as the Characteristic Flux Difference Splitting, numerical method for the three-dimensional Navier-Stokes has been applied to various complex flows and validated over the past few years [Ref.1]. Employing the CFDS code, the Raytheon test case of Mach 3 flow over a simple ogive-cylinder body with side jet has been computed and the

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RAYTHEON VALIDATION - SIDE JET EFFECT
(M=3.0, H=20Km, AOA=20°, T/qS=1)

Normal Force Coeff.

	ADD	Reytheon	Exp.
Tare	4.17	3.73	4.36
Upward Side Jet	3.15	2.77	3.37
Downward Side Jet	4.80	4.56	4.64

Fig.1 Raytheon case analysis results

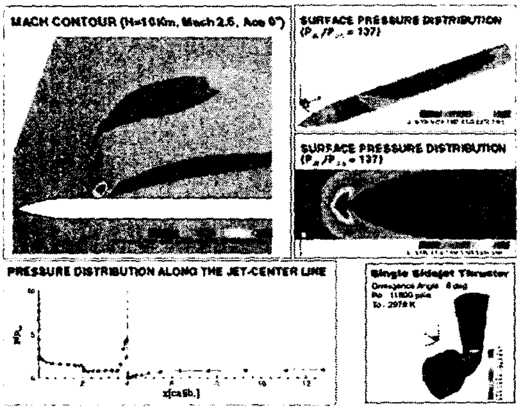

Fig.2 Typical results for body alone analysis

results are tabulated in terms of normal force coefficient to capture the side jet flow topology over missile configuration. The agreement between the presently computed and the available test data is slightly better with our results even with the first-order spatial accuracy than the Raytheon results. As shown in Fig.1, the influence of flow angle is quite severe on the effectiveness of side jet. When the jet is injected into the shock layer, only 30 percent of the side force can be effective for the aerodynamic control. In contrast, the currently proposed missile system employs multiple side jets located on the nose section. The location on the missile body as well as performance of single side jet thruster are depicted in Fig.2. A typical flow condition is given in the same figure. The exit flow condition of the side jet thruster is obtained from a separate simulation and shows a very severe pressure condition [Ref.2]. The ratio of the upstream pressure to that in the exit plane is 137, for example at the cited condition. This ratio will increase as the flight altitude goes up and eventually pose a difficulty in conducting wind tunnel test. Fig.2 also presents Mach contours in the symmetry plane when the side jet is turned on, showing a big bow shock and barrel shock, among others. Both the pressure contours on the body surface and the wall pressure distribution illustrate severe changes in the pressure field.

2.2 Flow Simulation inside W/T

A key question to perform wind tunnel test is to establish a similarity law for the side jet conditions between the flight and wind tunnel models. A good starting point can be referenced from the works by Champigny et al. [Ref.3]. From the paper, the single most important similarity parameter may be the ratio between the upstream pressure and pressure at the jet exit plane. To prove this point, four cases were computed for a body-alone configuration; two were for the body in flight condition and in wind tunnel; each of which with and without side jet. Numerical results are presented in Fig.3 in terms of pressure contours, showing four cases. The results are summarized in the table 1, comparing normal, pitching moment coefficients and centers of pressure for the four cases. Moment center is at nosetip and negative sign for moment means nose-down moment. Unit for Xcp is the caliber from nosetip. It should be noted that the typical flight point is at Mach 2.6, while the wind tunnel block is designed for Mach 2.3, presenting slight difference. Also the aerodynamic coefficients match closer with side jet on than off. Despite some difference in jet-off case, these results confirm the similarity notion between the wind tunnel and flight simulations as long as the ratios of flow parameters between the upstream and the jet exit plane are matched. The similarity parameters are i) static pressure ratio, ii) momentum flux ratio between free stream and jet exit plane.

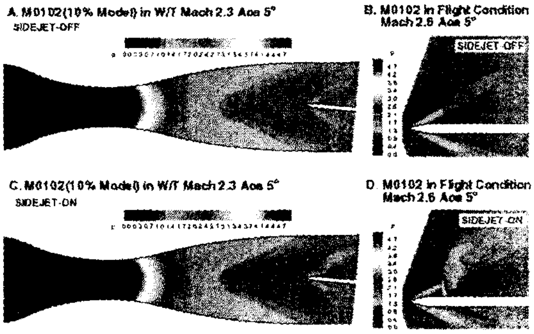

Fig.3 Pressure contours for 4 cases

	Jet Off		Jet On	
	A(W/T)	B(Flight)	C(W/T)	D(Flight)
CN	0.34	0.27	0.59	0.54
CM	-1.14	-0.62	-3.01	-2.77
XCP	3.35	2.30	5.10	5.13

Table 1. Calculated aerodynamic coefficients

Body-tail configuration is placed inside the M=2.3 tunnel to see the effect of the side jet on the full body as well as components of the model. Objectives are to compare the flow fields with and without side jet on the body and to quantify the side jet influence on the aerodynamic coefficients. Fig.4 presents Mach contours in the symmetry plane. The model scale is 10% and the ratios of pressure, velocity and density between the upstream and the jet exit plane are taken from the flight condition corresponding to 10Km altitude. Changes in normal and pitching moment coefficients are tabulated in table 2. From this point, moment center for all the cases in this paper is at 9.5caliber from nosetip. Due to the pressure cancellation effect, the normal force coefficients show only 1% difference. However, the pitching moment yields 22% difference for the body-tail configuration. Normal force coefficients on the body experience only 2% difference, while the pitching moment faces 120% difference when the jet is activated. On the other hand, the tail region undergoes only less than 5% difference both the normal force and pitching moment coefficients, because the jet is placed on the nose section and far from the tail control surface. This may help reduce the number of wind tunnel tests by allowing only a few body-tail combinations.

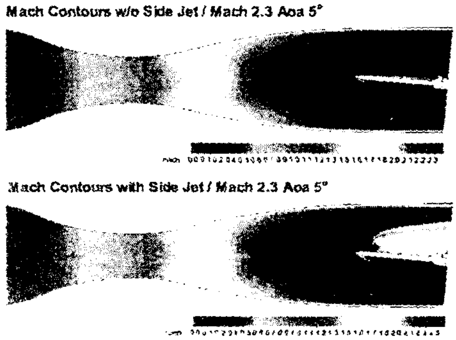

Fig.4 Mach contours for 10% Model with/without side jet

		Jet-Off	Jet-On	Variation
<a> Body-Tail	Cz	0.988	0.996	+0.8%
	Cm	-2.71	-3.31	-22%
<b> Tail Only	Cz	0.409	0.427	+4.5%
	Cm	-3.09	-3.22	-4.2%
<c> Body Only	Cz	0.580	0.569	-1.9%
	Cm	0.384	-0.085	-122%

<b> 'Tail Only' means 'Tail influenced by Presence of Body'
<c> 'Body Only' means 'Body influenced by Presence of Tail'
Therefore, '<a> = <b>+<c>' relationship is maintained for Cz and Cm of each column.

Table 2. Aerodynamic coefficients for body-tail configuration

2.3 Aerodynamic Model for Side Jet

Primary aim of side jet analysis is to provide 6DOF aerodynamic module including the aerodynamic effect of side jet. However, the influence is likely a function of flight Mach number, altitude, angle of attack, orientation of jet, tail deflection and the number of side jets operated at one time. As a primitive aerodynamic model to account for side jet effect, the normal force and pitching moment coefficients may be written as:

$$C_N = C_{N_{W/O\,JET}} + \frac{T_{SINGLE\,JET}}{q_{REF}\,S_{REF}} \quad (1)$$

$$C_M = C_{M_{W/O\,JET}} + \frac{T_{SINGLE\,JET}}{q_{REF}\,S_{REF}}\frac{L_{JET}}{L_{REF}} \quad (2)$$

where T is the single side jet force. Now, aerodynamic coefficients obtained based on the simple algebraic formula above and from CFD results of Section 2.2 are compared to comprehend how much the difference might be. In the case of Mach 2.3, altitude 10km, normal force shows 2.7% and pitching moment reveals 8.5% difference between CFD and simple formula (Table 3).

	Jet Off	Jet On	
	CFD	CFD	Eq.(1),(2) Model (Difference with CFD)
CN	0.988	0.296	0.288 (-2.7%)
CM	-2.71	-7.18	-6.57 (+8.5%)

Table 3. Point-force modeling result comparison with CFD result

After further CFD simulations and wind tunnel tests, empirical formula which accounts for the effect of side jet force may be devised as:

$$C_N = C_{N_{W/O\,JET}} + k_{CN}\,N_{JET}\frac{T_{SINGLE\,JET}}{q_{REF}\,S_{REF}} \quad (3)$$

$$C_M = C_{M_{W/O\,JET}} + k_{CM}\,N_{JET}\frac{T_{SINGLE\,JET}}{q_{REF}\,S_{REF}}\frac{L_{JET}}{L_{REF}} \quad (4)$$

$$where,\ k_{CN} = f(a, Mach, H, N_{JET}, \phi_{JET}) \quad (5)$$

$$k_{CM} = g(a, Mach, H, N_{JET}, \phi_{JET}) \quad (6)$$

Sections below thus explore effect of side jet on aerodynamics with the purpose of shedding more light on determination of the empirical factor k above.

2.4 Altitude Effect

Effect of altitude on flow topology as well as aerodynamic coefficients are simulated at Mach 2.3. The dominant parameter is the pressure ratio between the jet exit pressure to the free stream pressure. The four altitudes are 5, 10, 15 and 20km for which the pressure ratio corresponds to 67, 137, 300 and 657, respectively. Objectives are to see how big the bow shock becomes and how extensively the aerodynamic coefficients become affected with increasing altitude. In Fig.5 the Mach contours in the symmetry plane including the side jet are compared among the four cited altitudes. As was expected the bow shock due to the interaction of the Mach 2.3 free stream and the side jet increases its size as the altitude goes up. The side jet effect on the aerodynamic coefficients as the flight altitude increases has been compared for different altitudes. The result suggests that the empirical factor is close to 1.0 as the altitude increases and that the high altitude may be modeled by the empirical formula given in Eq.(3),(4) in the planning stage. Variation of

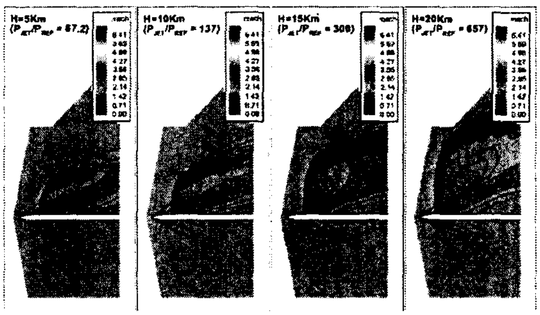

Fig.5 Mach contours for various altitude conditions

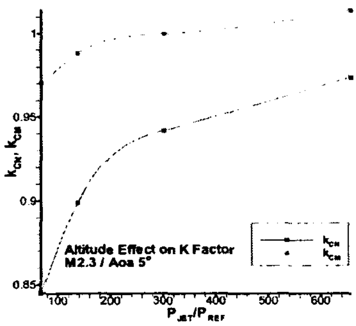

Fig.6 Jet effectiveness factor, k vs. altitude

the k factor as a function of altitude, or pressure ratio, is plotted in Fig.6, both for CN and CM. It further implies that we may skip high altitude wind tunnel simulation close to 20 km high, which has been a source of concern in light of wind tunnel preparation for the second chamber. Especially, the k factor for the pitching moment is close to 1.0 above 10km altitude. The k factor for normal force shows more dependency on altitude than the moment coefficient.

2.5 Jet Position Effect

Now, one of the ideas is to operate the side jet at any circumferential location on the missile as shown in the upper left corner of Fig.7. It means we need to examine the effect of the position of the jet on 6-DOF aerodynamic coefficients. We need to know whether rolling moment, yawing moment and side force are generated when the side jet is erupted asymmetrically in any circumferential direction. Fig.7 shows pressure field change on the body surface as a result of jet eruption in the lateral plane. To show the extent of the wall pressure change due to the jet, the wall surface is split open and made flat. When the side jet is activated in the leeward direction, changes on the body pressure is milder compared to that is in the windward direction. It is noted that the bow shock shape is not symmetric but is tilted toward the leeside.

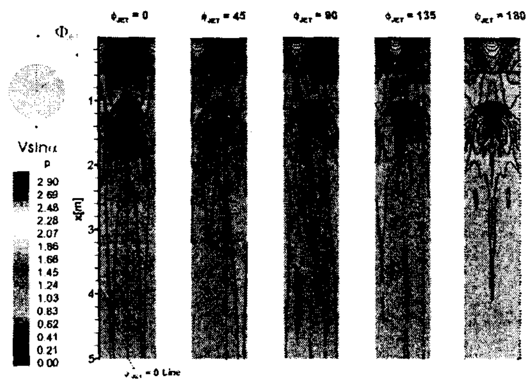

Fig.7 Unfold surface pressure contour for various jet positions

More importantly, five of 6-DOF components except the axial force coefficient are calculated when the jet is located at 0, 45, 90, 135 and 180 degrees on the cross-sectional plane. The flight condition is at Mach 2.3, altitude 10km and 5 degrees of angle of attack. The order of magnitudes of the normal and side force is about the same, while that of pitching and yawing moments is also the same. Therefore the off-plane forces are generated when the jet is turned on at non-pitch plane locations. However, rolling moment is not affected by the jet and remains zero regardless of the jet position. The order of magnitude for rolling moment for this body-alone at relatively low angle of attack case is negligible, but the values for the high angle of attack cases or body-tail configuration cases are still uncertain. Based on the solutions above, the k factors are extracted and plotted in Fig.8. If there is no interference effect on the pressure field by jet eruption, k factors must be coincide exactly with cosine function. The deviation from cosine function possess the quantitative interference effect.

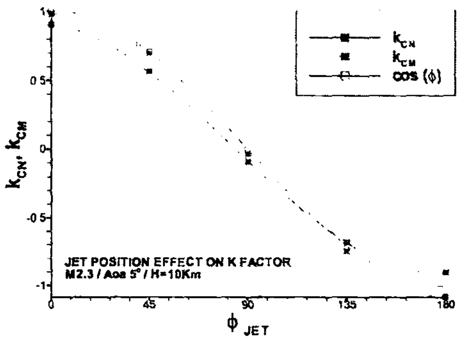

Fig.8 Jet effectiveness factor, k vs jet position angle

2.6 Multiple Jet Effect

Since in actual flight scenario, multiple jets may be utilized at any time, in this section the effect of multiple jets on flow topology and aerodynamics coefficients is investigated. Of particular concern is whether the jet strength remains the same or lose its effectiveness when multiple jets are operated. As test cases, single jet, longitudinal dual jets, transversal dual jets, quadruple jets have been analysed. As shown in Fig.9, interference phenomena between jet exits generate very complex flow structure. For these cases, proposed model performance has been compared. Table 4 shows the CFD results with point-force model(Eq.(1),(2)) estimation and improved model(Eq.(3),(4)) with jet effectiveness factor, k estimation results. In summary, simple point-force model produces 10-20% of average difference with CFD results. But improved model shows good agreement within 5% of difference except transversal dual jet case. Relatively large discrepancy in case 2T and case 4 is caused from the after C.G.-portion of the pressure variation and this problem could be modeled some empirical methods.

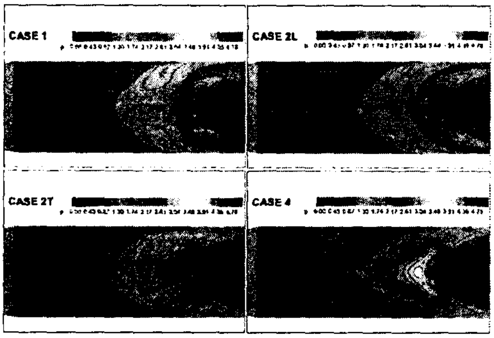

Fig.9 Surface pressure distributions near jet exit region for multiple jet activated cases

CASE I.D.		CFD		Eq.(1),(2) Model		Eq.(3),(4) Model	
		Jet Off	Jet On	Jet On	Difference	Jet On	Difference
CASE 1	CN	0.35	-0.82	-0.78	23%	-0.82	0.0%
	CM	1.73	-4.13	-4.38	5.6%	-4.13	0.0%
CASE 2L	CN	0.35	-1.60	-1.87	17%	-1.59	0.63%
	CM	1.73	-9.83	-10.5	6.8%	-10.0	1.7%
CASE 2T	CN	0.35	-1.63	-1.83	12%	-1.56	4.3%
	CM	1.73	-10.5	-10.3	1.9%	-9.82	6.5%
CASE 4	CN	0.35	-3.66	-4.05	11%	-3.50	4.4%
	CM	1.73	-22.2	-22.4	0.90%	-21.5	3.2%

Table 4. Modeling result for multiple jet cases

3. Conclusion

Computational study and analysis have been undertaken to aid in planning wind tunnel tests including side jet thruster. Conclusions may be drawn as follows:

1) Current CFD code has been tested for the existing test case and results show good agreement between computation and available data.

2) Similarity law between the flight condition and wind tunnel test has been examined when the side jet is turned on.

3) The side jet influence on the components of body-tail configuration is examined, showing large influence on the body yet small influence on the tail section at angle of attack 5 degrees.

4) Empirical formula accounting for the side jet yields aerodynamic coefficients within tolerable accuracy compared to the CFD results for the Mach 2.3, altitude 10km condition.

5) Further test and simulations are needed to warrant reliable empirical formula for the side jet at off the pitch plane and high AOA.

References

[1] Hong, S. K., Bardina, J., Lombard, C. K., Wang,D. and Codding, W., "A Matrix of 3-D Turbulent CFD solutions for JI Control with Interacting Lateral and Attitude Thrusters," AIAA 91-2099, Sacramento, June 1991

[2] 홍승규, 성웅제, "Side Jet 발생기의 유동특성에 관한 해석," 한국전산유체공학회지, 제6권, 제3호, 2001. 9

[3] P. Champigny and R. G. Lacau, "Lateral Jet Control for Tactical Missiles," AGARD R-804, June 1994