Numerical Analysis and Design Optimization of Lateral Jet Controlled Missile

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Summary Numerical parametric study of the lateral jet controlled missile has been performed. The behavior of the normal force and the pitching moment characteristics have been investigated through the numerical analyses for the different jet flow conditions, angle of attacks, circumferential jet nozzle locations and spouting jet angles. Based on the results of the aerodynamic analyses of the supersonic flow around lateral jet controlled missile for various jet and flow conditions, pitching moment and normal force are selected as the objective and constraint functions, and the flight Mach number, the angle of attack and the spouting lateral jet angle are selected as the design variables. By implementing the genetic algorithm for the global optimum, and the response surface method, the design optimization of the lateral jet controlled missile is performed to find out the most effective flight conditions for the missile control.

Introduction

Existing fin controlled missiles have delayed response time and limitations on maneuvering at low velocity or high altitude because they are controlled by the moments produced at the control surfaces that need high dynamic pressure. On the other hand, the lateral jet controlled missiles have short response time and high maneuverability even at low velocity and low-density area. Therefore, the lateral jet attitude control has been a preferred concept as a new missile defense system [1].

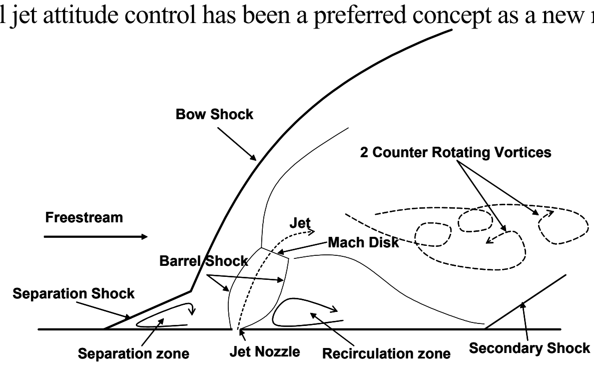


Fig. 1 Complicated flow structure around jet nozzle

As shown at Fig. 1, the aerodynamic characteristics of a lateral jet are complicated because of the local shock-shock interaction [2]. By the separation shock and bow shock interaction, a high-pressure region is formed in front of the lateral jet nozzle, and a low-pressure region is generated behind the jet nozzle because of the suction effect by lateral jet. Therefore, normal force loss and pitch down moment is generated at the jet nozzle, which locates at the center of gravity of the missile. These phenomena are affected by the jet nozzle arrangement, the jet configuration parameters and the jet flow characteristics such as jet spouting angle, jet thrust, jet nozzle location, and jet nozzle shape [1,3]. Therefore, for the effective lateral jet controlled missile design, the influence of those parameters must be studied thoroughly.

In this study, three dimensional Navier-Stokes computer code (AADL3D) was developed and validated for the analysis of the complex lateral jet flow characteristics. The paper will investigate the effect of several jet flow conditions, angle of attacks, circumferential jet nozzle location and spouting jet angle by comparing the normal force coefficient and the moment coefficient. Also, based on the results of the aerodynamic analyses of the supersonic flow around lateral jet controlled missile for various jet and flow conditions, a numerical design optimization study for the effective flight condition is performed.

Aerodynamic Analysis Method

For the analysis of complex flow phenomena around the lateral jet controlled missile, a three-dimensional Navier-Stokes computer code, AADL3D, is developed for the unsteady, compressible flow. Roe's FDS(flux difference splitting) scheme is implemented for the spatial discretization with the MUSCL for higher order extension. The minmod limiter is used to remove solution oscillations. Central difference scheme is used for the calculation of viscous flux term and fully implicit LU-SGS scheme is employed for time integration. Spalart-Allmaras one equation turbulence model is implemented on the AADL3D code for relatively rapid computational time.

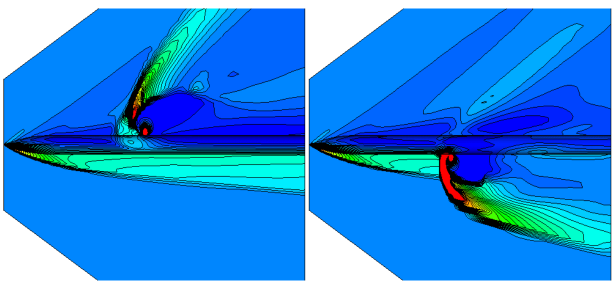
Validation of the numerical approach

To validate the accuracy of the code for the three-dimensional missile shape with both angle of attack and lateral jet, the analyses results of AADL3D code are compared with the existing calculation results and the wind tunnel experimental data of B. Srivastava[3]. Free stream Mach number and the Reynolds number are 2.97 and 8.2×10^5, respectively. Comparison is performed for five test cases. The experimental conditions of each case are summarized at Table 1.

Table 1 Experimental condition[3]

Test Case	C_T	Angle of Attack	Jet Location
1	1.0	20°	leeward jet
2	1.0	20°	windward jet
3	4.0	20°	leeward jet
4	4.0	20°	windward jet
5	jet off	20°	-

Figure 2 shows C_p contour at the symmetry plane of Cases 3 and 4. It shows distinctly different barrel shock and bow shock shapes and different flow phenomena around the jet nozzle. In the case of jet located at the windward side, the flow separation region in front of the jet nozzle is reduced and the vortices bent by freestream are wrapping around the missile body. Moreover, the propagated vortices to the down stream hit the missile body, hence, another high-pressure region is generated. AADL3D results are compared with the Raytheon calculation and experimental results at Table 2. AADL3D has better normal force prediction than ref. 3.



(a) Case 3 (b) Case 4

Fig. 2 C_p contour at the symmetry plane

Table 2 Normal force coefficient comparison

Test case	C_N (Raytheon Exp.)	C_N (Raytheon Calc.)	C_N (AADL3D)
1	3.37	2.77	3.20
2	4.64	4.56	4.52
3	0.21	-0.19	0.25
4	7.33	7.27	7.35
5	4.36	3.73	4.15

Grid system selection

The missile configuration for the case studies is simple tangent ogive-cylinder body without fin, as shown at Fig. 3. To increase the computational efficiency, a grid system, which is coarse but can guarantee solution accuracy, is selected by investigating the convergence rate and the converged solutions of several grid systems.

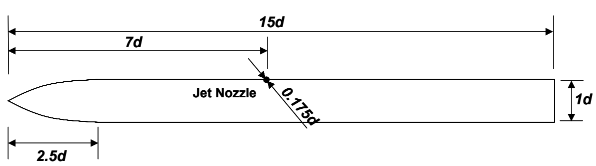


Fig. 3 Missile configuration for the case studies

The freestream Mach number was 2.6 and jet Mach number was 2.04. $P_{ratio}(P_{jet}/P_{freestream})$was 45.7 and the Reynolds number was 6.63×106. From the result of Fig. 4, the 95×34×33 grid system has been selected, and the grid system is shown at Fig. 5.

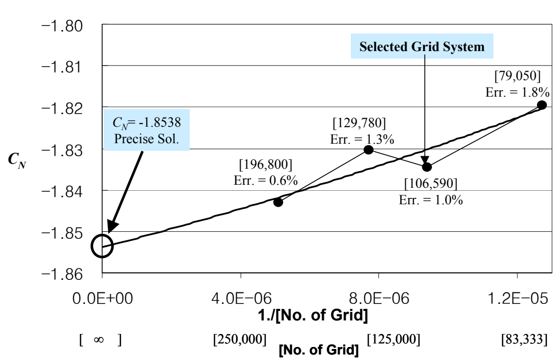


Fig. 4 The result of grid density test

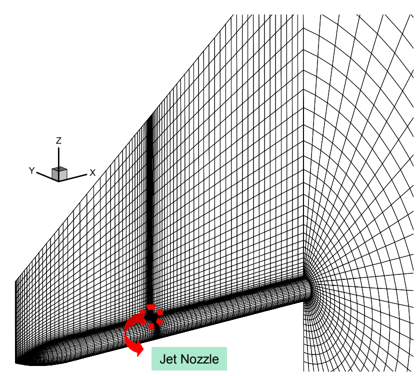


Fig. 5 Selected grid system (95×34×33)

Case Studies of Lateral Jet Controlled Missile

Analysis conditions and nomenclature definition

For all calculations, the analysis condition of freestream flow is same as the grid system selection case and the atmospheric condition is that of the 10km altitude. To find out the effect of the jet flow characteristics on the missile attitude control, the different pressure ratios and the jet Mach number variations cases are selected and Table 3 summarizes the jet flow conditions of each case and angles of attack of those cases were set to zero. Furthermore, to find out the freestream-jet angle effect, case studies have been performed for the different angles of attack, the circumferential jet locations and the spouting jet angle. Table 4 represents each analysis condition.

Table 3 Jet flow conditions for case 1 ~ case 6

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
P_{ratio}	**150**	**300**	**450**	150	150	**850**
M_{jet}	**1**	1	1	**2**	**3**	**1**
$\dot{m}_{jet}$ [kg/s]	14.04	28.08	42.12	28.08	42.12	79.56
C_T	2.323	4.653	6.983	6.401	13.196	13.196

Table 4 Analysis conditions for each case

	a) Angle of attack effect					b) Jet location effect				
	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16
P_{ratio}	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7
M_{jet}	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
M_∞	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
α	**-20°**	**-10°**	**0°**	**10°**	**20°**	10°	10°	10°	10°	10°
ψ	90°	90°	90°	90°	90°	90°	90°	90°	90°	90°
θ_{jet}	180°	180°	180°	180°	180°	**0°**	**45°**	**90°**	**135°**	**180°**

	c) Spouting jet angle effect							
	Case 17	Case 18	Case 19	Case 20	Case 21	Case 22	Case 23	Case 24
P_{ratio}	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7
M_{jet}	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
M_∞	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
α	0°	0°	0°	0°	0°	0°	0°	0°
ψ	**30°**	**45°**	**60°**	**75°**	**90°**	**105°**	**120°**	**135°**
θ_{jet}	180°	180°	180°	180°	180°	180°	180°	180°

The missile configuration is nondimensionalized by the missile diameter, *d*. Force, moment and other nomenclatures are defined at Fig. 6. Missile surface is divided into four regions with respect to the center of gravity, and the normal force and moment distribution at each region were compared.

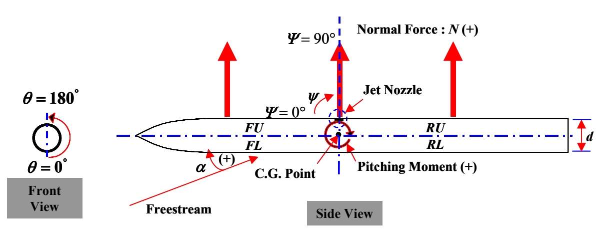
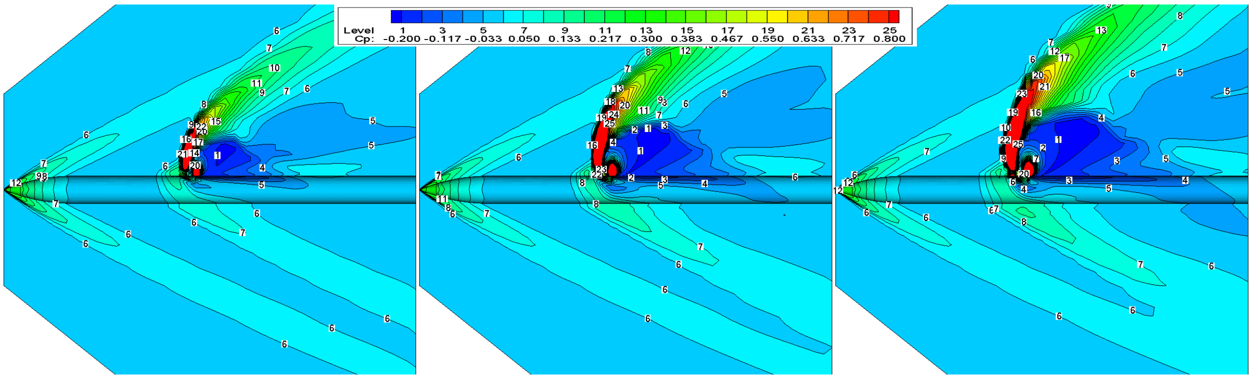


Fig. 6 Nomenclature definition

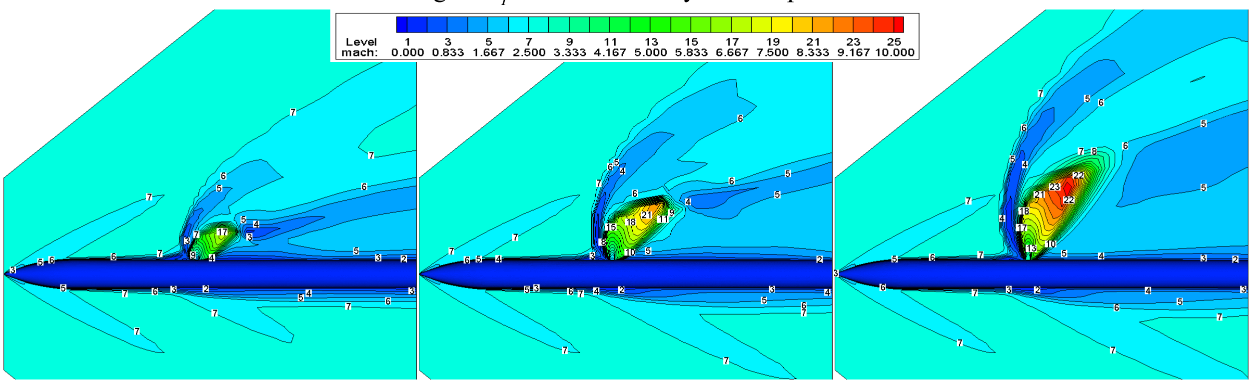
Jet flow condition effect

For the different pressure ratios and the jet Mach number variations, the normal force and the moment coefficients of a missile body are compared to find out the effect of the jet flow characteristics on the missile attitude control. Fig. 7 compares the pressure contours of Case 1, 2 and 3 and Fig. 8 compares the Mach number contours of Case 1, 4 and 5. From these two figures, different shape changes of barrel shock can be observed; bigger barrel shock for higher pressure ratio and steeper barrel shock for higher jet Mach number. Table 5 and Fig. 9 show the normal force and pitching moment results.



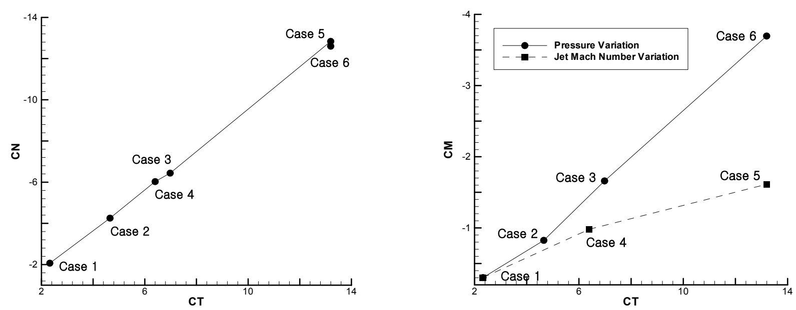
(a) Case 1($P_{ratio} = 150$) (b) Case 2($P_{ratio} = 300$) (c) Case 3($P_{ratio} = 450$)

Fig. 7 C_P Contour at the symmetric plane



(a) Case 1($M_{jet} = 1$) (b) Case 4($M_{jet} = 2$) (c) Case 5($M_{jet} = 3$)

Fig. 8 Mach number Contour at the symmetric plane



(a) C_N *vs.* C_T (b) C_M *vs.* C_T

Fig. 9 C_N, C_M *vs.* C_T plots

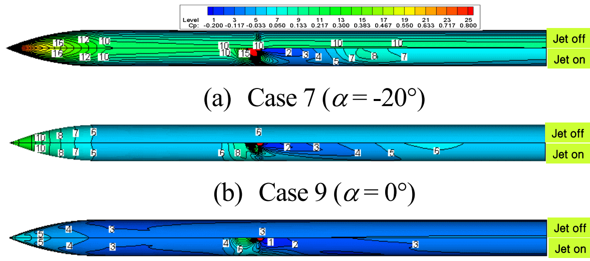
Table 5 The results of calculations (jet pressure variation effect)

	C_T	C_N	$C_{N_{FU}}$	$C_{N_{FL}}$	$C_{N_{RU}}$	$C_{N_{RL}}$	C_M	$C_{M_{FU}}$	$C_{M_{FL}}$	$C_{M_{RU}}$	$C_{M_{RL}}$
Case 1	2.323	**-2.067**	-0.236	0.099	**0.426**	-0.034	**-0.302**	-0.162	0.053	**-0.701**	0.508
Case 2	4.653	**-4.254**	-0.376	0.144	**0.689**	-0.058	**-0.825**	-0.224	0.084	**-1.511**	0.827
Case 3	6.983	**-6.440**	-0.470	0.205	**0.903**	-0.095	**-1.660**	-0.330	0.156	**-2.533**	1.046
Case 4	6.401	**-6.028**	-0.373	0.118	**0.661**	-0.032	**-0.981**	-0.187	0.059	**-1.686**	0.833
Case 5	13.196	**12.837**	-0.436	0.122	**0.641**	0.032	**-1.613**	-0.197	0.059	**-2.077**	0.602

The results show that the normal force is almost proportional to the jet thrust but the behavior of the moment is different between jet pressure increased case and the jet Mach number increased case. The increased jet thrust by increasing jet Mach number produces less pitch down moment than the same thrust with increased jet pressure. Therefore, increasing jet Mach number is more advantageous than increasing jet pressure ratio in order to obtain higher jet thrust while maintaining minimum pitch down moment. Furthermore, Table 5 shows that most of the normal force loss and the pitching moment generation are taken place at the low-pressure region behind the jet nozzle.

Angle of attack effect

Figure 10 compares surface pressure contours with jet-off case. At α = -20°, the generated vortex is bent by the freestream, and it sweeps the missile surface, as a result, vortex prevents the downward freestream hits the missile surface. Therefore, strong bow shock effect caused by downward freestream velocity component is vanished above upper rear body surface, and more large low-pressure region is formed compared to jet-off case. Figure 11 shows angle of attack effect results. A negative angle of attack (windward jet) causes a relatively big normal force loss and pitch down moment compared with the positive angle of attack case (leeward jet).

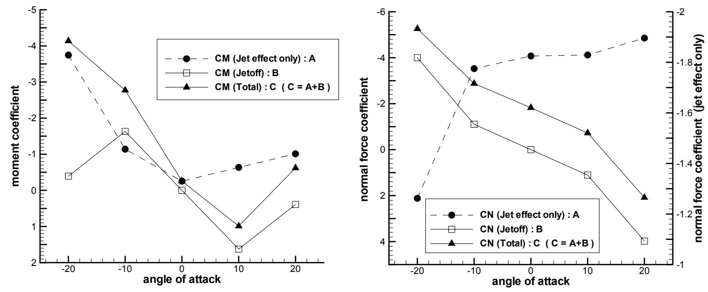


(a) Case 7 ($\alpha = -20°$)

(b) Case 9 ($\alpha = 0°$)

(c) Case 11 ($\alpha = 20°$)

Fig. 10 C_P contour on the surface



(a) C_N *vs*. angle of attack (b) C_M *vs*. angle of attack

Fig. 11 C_N, C_M *vs*. angle of attack plots

Circumferential jet location effect

Figure 12 shows surface pressure comparison and Fig. 13 shows the results. Greater normal force loss and pitching down moment were generated when jet nozzle is located at θ=0° than θ=180°. However, maximum normal force and minimum pitching down moment were generated when jet nozzle is located at θ=90° because of the largest high pressure region on the rear body upper surface behind the nozzle, which contributes to the increase of the normal force and to decrease of the pitching down moment, due to the strong bow shock by freestream (Fig. 12), and another low pressure region at the opposite side of the nozzle due to the bent jet by freestream. Hence, the lateral jet should be operated with concerning these varying aerodynamic characteristics.

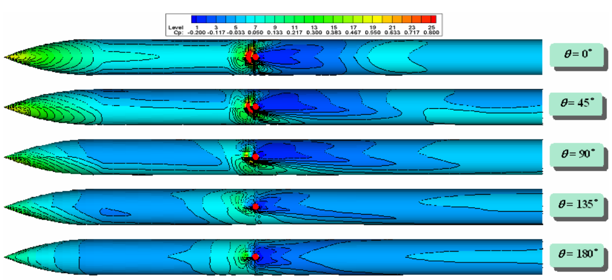
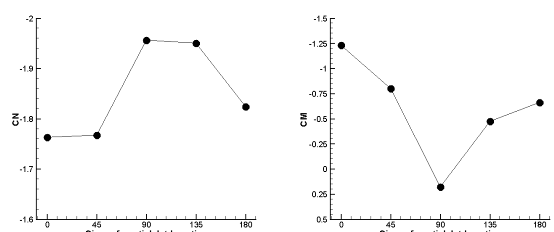


Fig. 12 C_P contour on the surface

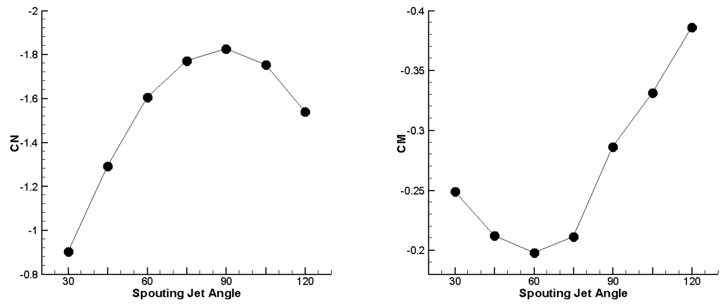


(a) C_N *vs*. θ (b) C_M *vs*. θ

Fig. 13 C_N, C_M *vs*. circumferential jet location

Spouting jet angle effect

Figure 14 summarizes the results of the spouting jet angle effect. Pitching down moment is decreased as the spouting jet angle is inclined forward. However, when the spouting jet angle is inclined forward excessively(below 60° in this study), pitching down moment is increased again. Normal force becomes maximum when ψ=90° and is decreased as spouting jet angle is inclined forward or backward because the jet thrust is decreased by cosine law. Therefore, the pitching moment can be minimized by selecting proper spouting jet angle while satisfying required normal force for attitude control.

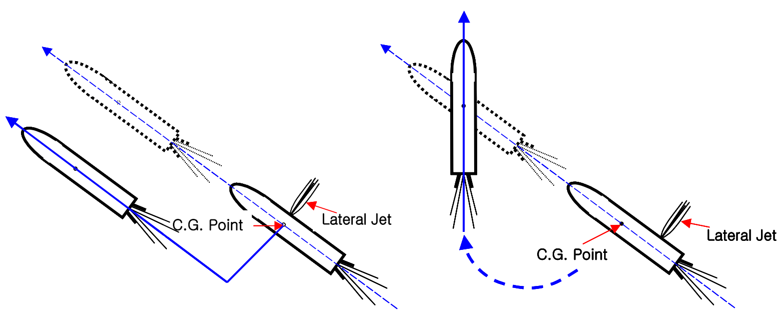


(a) C_N *vs.* ψ (b) C_M *vs.* ψ

Fig. 14 C_N, C_M *vs.* spouting jet angle

Optimal Design of the Lateral Jet Controlled Missile

There are two kinds of missile attitude control types using lateral jet(Fig. 15). First, by locating the jet at the center of gravity of the missile, a transition movement of missile can be obtained without any pitching moment generation. The other type is to control the missile attitude using the pitching moment generated by the jet located at a certain distance from the missile center of gravity. In this study, the first type, a lateral jet locates at the center of gravity, is considered. Therefore, generation of the pitching moment is negative effect to the missile control and should be diminished.



(a) Using normal force (b) Using moment

Fig. 15 Missile attitude control using lateral jet

Based on the results of the parametric study, a numerical design optimization study for the effective flight condition is performed. First of all, the design problems are formulated by defining the design variables and the design constraints. By incorporating the proven optimization and approximation techniques, the design optimization at the altitude of 10km is performed. Pitching moment and normal force are selected as the objective and constraint functions, and the flight Mach number, the angle of attack and the spouting jet angle are selected as the design variables. GENOCOP III[4], a genetic algorithm is used to obtain the global optimum, and the response surface method[5] is employed.

The optimization formulation is as follows;

Minimize

$$\boldsymbol{F}(\vec{\boldsymbol{X}}) = \left| \boldsymbol{C}_{\boldsymbol{M}_{total}} \right|$$

Subject to

$$\boldsymbol{g}(\vec{\boldsymbol{X}}) = \boldsymbol{C}_{N_{10G}} - \boldsymbol{C}_N \le 0$$

Where

$$\vec{\boldsymbol{X}} = \left\{ \alpha, \quad \psi, \quad \boldsymbol{M}_{freestream} \right\}$$

$$-20 \le \alpha \le 20$$

$$30 \le \psi \le 90$$

$$2 \le \boldsymbol{M}_{freestream} \le 4$$

The $\boldsymbol{C}_{N_{10G}}$ represents normal force coefficient required to obtain initial 10G acceleration for the missile transition without respect to drag. The assumed missile weight is 500kg, jet Mach number is 2.0 and P_{ratio} is 150. The missile shape is the same as the shape for the case study.

The optimization strategy using response surface is shown at Fig. 16.

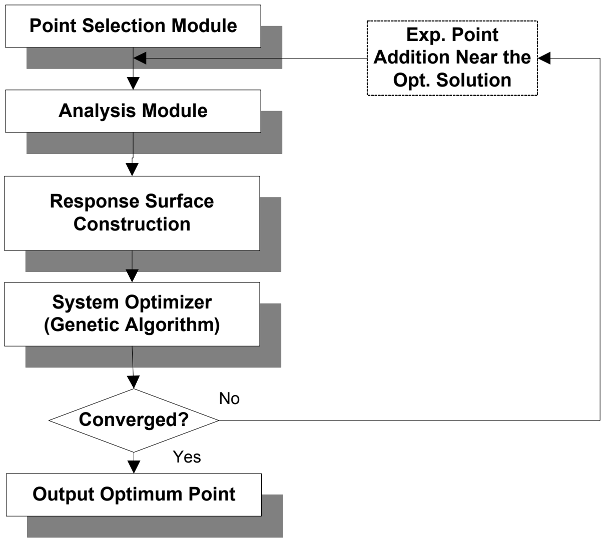


Fig. 16 Optimization strategy

Conclusions

The normal force was almost proportional to the jet thrust and there has been thrust loss because of shock interactions. However, the moment was not only a function of jet thrust, but also of the jet pressure and the jet Mach number.
The nonlinearity of the normal force and pitch down moment according to the angle of attacks has been confirmed. Especially, negative angle of attack (windward jet) case shows greater normal force loss and the pitch down moment. θ = 90°). Also, existence of least pitching moment point was identified through the case study of the spouting jet angle effect. The low-pressure region behind the jet nozzle contributes more greatly to normal force loss and pitch down moment generation than the high-pressure region. Therefore, for the efficient lateral jet attitude control system design, it is identified that the study on reducing the low-pressure region is required. Based on the results of case studies, the design optimization of the lateral jet controlled missile is performed to minimize the pitching moment while satisfying the normal force constraint using genetic algorithm and response surface method.

Acknowledgement

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