TECHNICAL NOTE

WIND TUNNEL INVESTIGATION OF TYPICAL STRATEGIC MISSILE CONFIGURATION AT HIGH ANGLE OF ATTACK

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Abstract

The present wind tunnel investigation is a part of a project studying the effectiveness of flat fin control on short-range strategic missile at high angle of attack. As a part of this program, the longitudinal aerodynamic coefficients were computed analytically and were compared with estimates obtained through wind tunnel testing. Wind tunnel tests were conducted over a range of angle of attack from -15° to +45° at a free stream speed of 60m/s. Aerodynamic coefficients were generated for various missile configurations. These coefficients were then compared with the estimates obtained analytically. It was conjectured that, at high angle of attack, vortices shaded by the body interact with the local flow near the fins and drastically alters the stability characteristics of the missile. The subject missile has a small hemispherical nose as compared to most of the missiles having conical or ogival nose. For such a configuration sufficient theoretical/experimental data are not available. Thus, it was important to generate longitudinal aerodynamic data for the range of angle of attack upto which the theoretical model can be used to evaluate the aerodynamic stiffness of the missile. Such a model structure is required for postulating aerodynamic model in estimation algorithm, used for parameter estimation from flight data of the subject missile.

Nomenclature

A_{fin} = area of fin
A_p = planform area
A_{ref} = reference area
C_{dc} = cross flow drag coefficient
C_l = rolling moment coefficient
C_m = pitching moment coefficient
C_N = normal force coefficient
$C_{Nf(B)}$ = normal force coefficient of fin in presence of body
C_x = axial force coefficient
C_y = side force coefficient
d = diameter of missile
$(K_2\text{-}K_1)$ = Munk's factor
$K_{B(f)}$ = interference factor of body due to presence of fin
$K_{f(B)}$ = interference factor of fin due to presence of body
M = Mach number
M_n = cross flow Mach number
S_{ref} = maximum reference cross-sectional area
X_{cg} = distance of center of gravity from nose
X_{cp} = distance of center of pressure from nose
V_∞ = free stream velocity
α = angle of attack
α_f = angle of attack seen by fin
δ = tail deflection angle
η, η_0 = drag proportionality factors

Introduction

A base line missile under development is considered for evaluation of its flight performance. This missile is intended to represent a typical tail controlled missile. Typically, short range strategic missiles are expected to reach a predefined height within a shortest possible time, and then cruise for some duration before engaging a target using commanded accelerations as dictated by the desired guidance and control law. The first requirement demands large turning rate of the missile. Since during this phase, booster will be on, part of this turn rate will be obtained from thrust and part from the normal force generated by the missile at a particular angle of attack. To utilize the part of the thrust and lift force (for this turning), it is necessary to introduce angle of attack to the missile. The control fins at the rear end of the missile can appropriately be, deflected to generate the required angle of attack. Since during this phase no guidance and control are operative, tail deflection has to be pre-programmed as a function of time to generate required angle of attack. The second requirement of maintaining a level cruise at a chosen

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height, demands missile to attain adequate angle of attack to balance the weight of the missile. Here again, the tail control deflection has to be pre-programmed to generate adequate angle of attack to produce desired lift. To meet the third requirement of following the guidance law, the missile has to be configured in such a manner, that it generates sufficient acceleration per unit tail deflection to be able to steer the missile towards the target as dictated by the guidance law.

A strategic missile with terminal guidance needs to have a high level of maneuverability at the terminal end. In aerodynamic sense this means that the missile should have marginal static stability at the operational angle of attack. The missile under study does not have wing as lifting surface and during terminal phase thrust is not available, thus most of the lift is to be generated by the cylindrical body alone. The cylindrical body at high angle of attack, generates complex vortex pattern to add non-linearity to the flow [1]. The fin attached to the rear end of the missile frequently falls in the vortex sheet created by the body. Interaction of these vortices with the flow near the fin alters the lifting characteristics significantly. More importantly, physical phenomena governing this interaction is not well understood or modeled [1]. Further at high angle of attack, the body is expected to shed asymmetric vortices, this drastically alters the flow field at high angle of attack, around the missile, resulting in appreciable side force and yawing moment. Available theoretical methods find it difficult to predict this behavior accurately and thus wind tunnel testing remains to be the best source to capture the flow non-linearities and their effect in force and moments experienced by the missile [2].

Estimation of accurate values of the force and moment coefficients, is of paramount importance to pre-program the tail deflection to achieve the desired trajectory and evolve efficient control law to implement guidance command. At the initial design stage, approximate analytical methods are routinely used to freeze the initial parameters of the design. Moore et. al [2] have suggested approximate methods to estimate aerodynamic coefficients for such configurations. To refine the design parameters, wind tunnel testing is routinely done and theoretical values are updated. In this study, available theoretical methods [2-4] have been applied to estimate aerodynamic coefficients and are compared with the estimates obtained through wind tunnel testing. It is generally observed that the estimates obtained using theoretical methods matches excellently as long as angle of attack is small. However, it shows gross deviation from estimates (obtained via wind tunnel testing) in and around high angle of attack regime (above 10°). For the particular case, it is found that theoretical methods are good enough for initial estimates upto 10°. Beyond 10° the aerodynamic model must be corrected using estimates obtained through wind tunnel testing.

Theoretical Methods

The aerodynamic coefficients were estimated using Ref. [2-4]. There are many non-linearities that occur in the weapon aerodynamics. The ones that have most influence on the body alone are angle of attack, Mach number, cross flow and Reynolds number.

The body normal force coefficient can be expressed as sum of both linear and non-linear contribution as represented below[2],

$$C_{N\,body} = C_N\,(linear) + C_N\,(non\text{-}linear) \quad (1)$$

where linear term is approximated using Munk Factor (K_2-K_1) [3-5] as

$$C_N\; linear = 2*(K_2 - K_1) \quad (2)$$

C_N (non linear) is a cross flow term on drag force experienced by an element of circular cylinder of same diameter in a stream moving at the cross component of the stream velocity $V_\infty \sin \alpha$. The cross flow term is primarily created by the viscous effects of the fluid as it flows around the body, often separating and creating a non-linear force coefficient. The non-linear force coefficient is modeled using the following expression [2]

$$C_{N'}\,(non\text{-}linear) = \eta C_{dc}\,(A_p/A_{ref})\,Sin^2\alpha \quad (3)$$

where $\eta = (1-\eta_0)/1.8\, M_n + \eta_0$ and A_p and A_{ref} are the planform and reference area respectively, and M_n is cross flow mach number (M sin α). The drag proportionality factor, η, is the ratio of cross flow drag of a cylinder of finite length to one of infinite length and is obtained using Ref. [2].

Fin Alone Normal Force Coefficient

The fourth order equation for the fin alone normal force was found to be most accurate for all angle of attack [2]. The fin alone normal force coefficient is thus expressed as

$$C_{N,fin} = a_0 + a_1\,\alpha_f + a_2\alpha_f^2 + a_3\alpha_f^3 + a_4\alpha_f^4 \qquad (4)$$

where $\alpha_f = |\alpha + \delta|$ and δ, is the fin setting angle. The constants a_0 to a_4 were evaluated using Ref. [2].

Fin Body and Body Fin Interference

There are two primary types of interference $K_{f(B)}$ and $K_{B(f)}$. These are interference factors associated with normal force of the fin in the presence of the body and additional normal force on the body as result of fin being present due to angle of attack. Mathematically,

$$K_{f(B)} = C_{Nf(B)}/C_{N,fin} \qquad (5)$$

and defined as ratio of normal force coefficient of fin in presence of body to that of fin alone at δ = 0 deg. The ratio of additional body normal force coefficient in the presence of fin to fin alone normal force coefficient at δ = 0 deg. The mathematical model along with procedure to estimate these two ratios are presented in detail in Ref. [2]. The normal coefficient for the complete body and fin incorporating interference factors can be written as

$$C_N = C_{N,body} + C_{N,fin}.\,(K_{f(b)} + K_{B(f)}).\,A_{fin}/S_{ref}$$

The total center of pressure of the missile is estimated using the following relation

$$Xcp,missle = (C_{N,linear}\,X_1 + C_{N,nonlinear}.\,X_2 + C_{N,fin}.X_3)\,/$$

$$(C_{N,linear} + C_{N,nonlinear} + C_{N,fin}) \qquad (7)$$

where,

X_1 = Center of pressure of nose linear loads

X_2 = Center of pressure of non-linear load. The non-linear center of pressure shifts with angle of attack.

X_3 = Center of pressure for fin, is assumed to be at the quarter chord point. It's variation with angle of attack has been neglected.

Total moment coefficient has been obtained by taking moment about the missile center of gravity.

$$C_{m,c.g}. = (C_{N,fin}.\,(X_1\text{-}X_{cg}) + (C_N.(X_2\text{-}X_{cg}) +$$

$$C_{Nfin}.\,(X_3\text{-}X_{cg}))/d \qquad (8)$$

Model and Test Conditions

The model used for this experiment is presented in Fig.1. It has hemispherical nose and length to diameter ratio of around 8. The model is composed of three modules: one for nose, one for the mid-section and finally, one for the tail section of the model. The fitment and model mounting arrangement is schematically presented in Fig.1. The complete full scale model was placed in between two vertically located turn tables in the test section. A fitment was fabricated to hold the model rigidly between these turn tables. To avoid interference due to wake formation by the fitment, the model was positioned at a sufficiently large distance from the vertical element of the fitment. A six component balance was installed inside the model to measure the forces and moments. The tunnel was stabilized at a wind speed of 60m/s and data acquisition system was switched on to acquire data for three missile configurations namely, body-alone, body with fins at different positive and negative setting angles. Before every run, a dry run (no-wind) was carried out to estimate the bias error, if any. The raw data acquired were then processed to obtain force and moment coefficients namely, axial force coefficient, C_x, normal force coefficient, C_N, pitching moment coefficient, C_m, etc. respectively.

Result and Discussion

The force and moment coefficients were obtained by processing wind tunnel data. The wind tunnel raw data was processed, corrected for bias and then converted into

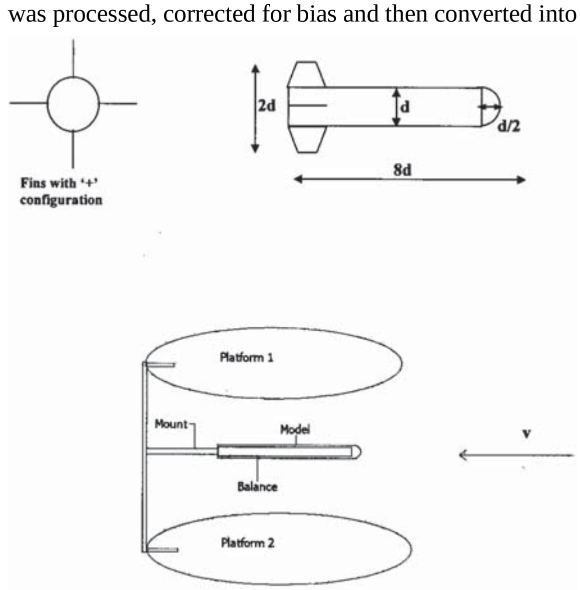

Fig. 1 Schematic of the model and the fitment used in wind tunnel testing

Table-1 : Comparison of wind tunnel and theoretical estimates of normal force coefficient for body alone and body with fin at δ = 0º, -10º

Alpha, Deg.	Body Alone		Body and Fin at δ = 0º		Body and Fin at δ = -10º	
	Theoretical	Wind Tunnel	Theoretical	Wind Tunnel	Theoretical	Wind Tunnel
-15	-1.0261	-0.97323	-1.5258	-1.2869	-1.5184	-1.3801
-10	-0.56284	-0.51578	-0.94077	-0.8899	-1.0016	-0.97491
-5	-0.21944	-0.25778	-0.4308	-0.49837	-0.55982	-0.51546
0	0	0.12023	0	-0.09825	-0.19722	-0.28287
5	0.21944	0.22187	0.4308	0.40483	0.21019	0.13138
10	0.56284	0.55578	0.94077	0.82968	0.56284	0.79674
15	1.0261	0.96654	1.5181	1.3465	1.4299	1.2271
20	1.6015	1.3659	2.1564	2.0447	2.1316	1.8027
25	2.2848	1.6143	2.8571	2.1246	2.8939	2.0677
30	3.0483	1.8262	3.5927	2.4409	3.6879	2.3512
35	2.5464	2.2399	3.0105	3.204	3.1539	3.0214
40	3.0184	2.7712	3.3718	3.8027	3.5588	3.6635
45	3.4924	3.028	3.7118	4.3538	3.9376	4.1373

non- dimensional form to get aerodynamic coefficients, C_x, C_y, C_N, C_m, C_n, and C_1. Wind tunnel data for three-missile configurations, body alone, body with fins at zero setting in '+' configuration (Fig.1) and body with fins at different positive (down) and negative (up) fins setting angles were analyzed. During the process of data generation, all these three configurations were tested for varying angle of attack ranging from -15° to 45°.

C_N Vs Angle of Attack, α for Body Alone

For body alone, Fig. 2 shows that C_N vs α variation is nearly linear in the range of -10° to 10°. Theoretical values of C_N for different values of angle of attack computed using Eq. (1) are presented in Table-1. Column 2 and 3 of Table-1 list the numerical values of body alone normal force coefficient C_N obtained through the theoretical and wind tunnel methods. It can be observed that within the α range of -15° to 15°, the estimated value of the coefficient compare well with the wind tunnel estimates. Beyond 20° the difference between C_N estimated by the theoretical and wind tunnel methods widen significantly. This was expected as the theoretical methods used, is not accurate enough to capture the effect due to shedding of vortices by the body at high angle of attack. Modification of fin effectiveness is primarily due non-linear interaction between body vortices and fin.

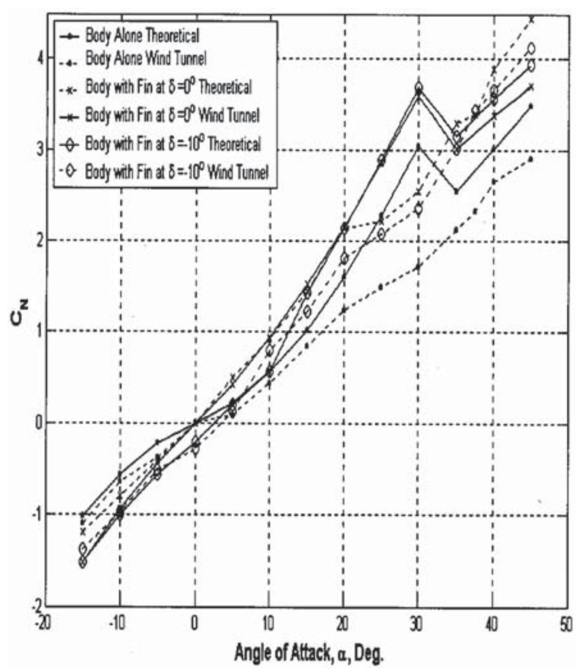

Fig. 2 Comparison of wind tunnel theoretical estimates of normal force coefficient for body alone and body with Fin at δ = 0°, – 10°

C_N vs Angle of Attack, α at $\delta = 0°$

Figure 2 shows that C_N vs α is almost linear till α =10°, and then non-linear contribution is almost as much as the linear contribution till α = 20°. Referring Fig.2 and Table-1 (column 4 and 5), it can be observed that at α = 20°, there seems to be break in the trend and a new non-linear behavior is observed. At α =10° and δ = 0°, the wind tunnel and theoretical values of C_N are 0.829 and 0.9407 respectively. Also, the wind tunnel and theoretical values of C_N for body alone are 0.55578 and 0.56284 respectively. These numerical values will be compared next with the measured values at different α and δ combination.

C_N vs α at $\delta \neq 0°$

Figure 2 shows a comparison between theoretical and wind tunnel estimates of normal force coefficient C_N, as a function of angle of attack for non-zero fin setting angle of δ = -10°. Table-1 (column 6 and 7), lists the numerical value of C_N as function of angle of attack for typical fin setting of -10°.

Referring Fig.2, it can be seen that it has trend and variation with α similar to the one observed for δ = 0°. The measured C_N at α =10º and δ = -10º was 0.797 where as computed values is 0.5628. One would expect that at this combination of α and δ, fin contribution to C_N is zero and C_N would have value equal to that for body alone at α = 10º i.e. C_N=0.555. However, the measured value is actually comparable to 0.829 measured for body plus fin at α =10º. It is known that for long slender bodies, flow separation and shedding of trailing vortices begin from body at some distance from the nose of the body and this vortex would interact with fins to generate normal force. This we believe explains the observed value of C_N. It may be noted that at 10º, there was no generation of side force. Thus, the additional force experienced by the missile is attributed to the interaction between body vortex fin and not on the asymmetric shedding vortices. Further force measurement were carried at α sweep for δ=-20º, -25º, -30º, etc. As in the case of α=10º and δ=-10º, the combination of (α = 20º and δ = -20º), (α = 25º and δ = -25º), (α = 30º and δ = 30º) shows that the measurement value of C_N greater than that for body alone at the corresponding α. Here again it seems to confirm our earlier conjecture that vortex flow is responsible for additional C_N. In an overall way, the variation of C_N with α for all these δ settings are similar in character as discussed for δ = 0º case.

The Pitching Moment

There are few interesting trends observed in the estimates of C_m obtained through wind tunnel testing. For body alone, Fig. 3 shows that the variation of C_m with α is increasing almost linearly upto α=10º and then non-linearly till α= 30º, beyond which C_m decreases. It was noted earlier that the normal force (body alone) increases with α to even beyond α=30º. This would suggest that the decrease in C_m is due to shift of center of pressure closer to center of gravity. The remaining text discusses and analyses the pitching moment variation with respect to angle of attack for various configurations.

C_m vs α for $\delta = 0º$

Figure 4 presents C_m vs α for δ = 0º and δ= -10º. The corresponding trim points, for δ = 0º and δ = -10º, are approximately at α = 0º and α = 10º. The slope of C_m vs α curve at these trim points are negative and hence the subject missile is statically stable at these trim points. However, as α varies between 10º to 30º, the missile almost become insensitve to angle of attack as far as additional generation of moment is concerned. This shows that for such a cylindrical body with hemispherical nose, the center of pressure of the cylindrical body is almost at 50% of the body length. The center of gravity being almost at 53% of the body length, makes the net moment due to body lift almost zero. Thus, $C_{m\alpha}$ and $C_{m\delta}$ are nearly equal (as these are due to fin only). Since at trim C_m =0, one can write,

$$0 = C_{m\alpha}\,\alpha + C_{m\delta}\,\delta$$

and hence,

$$(\alpha)_{trim} = -\frac{C_{m\delta}}{C_{m\alpha}}\,\delta$$

Therefore, it can be expected that α_{trim} will be approximately equal to fin deflection, δ for such a missile.

Referring the Fig. 3, it can be seen that δ = 0º, δ = -10º the missile trims approximately at α = 0º and 10º respectively. The C_m vs α graph shows, that the missile is statically stable about the equilibrium point. However, as

α varies between 10º to 30º, the missile almost become insensitive to α as far as moment generation is concerned. It was pointed out that body alone contribution increases till α = 30º and then drops off. The reason for achieving low aerodynamic stiffness in the range of 10º < α < 30º seems to be a result of well designed tail size and its location. For efficient maneuvering, it is desirable that the missile has low or almost zero stiffness, in the range of α that is likely to be during the maneuver. The C_m contribution from the fin and body are made to cancel each other. The C_m (negative contribution) due to fin increases as α increases but so also body configuration increases with α. In the present configuration, it is ensured that both contributions cancel each other. This is achieved for a value of α upto 30º. However, as mentioned earlier for α > 30º, the unstable contribution to C_m due to body drops off and thereby the net C_m again is increasingly negative as α increases, and missile regains its aerodynamic stiffness.

C_m vs α for δ < 0º

Figure 3 further shows, C_m vs α for δ = -10º. It is noted that the missile trims at approximately $\alpha \approx$ 10º. The missile is statically stable at α = 10º. For α = 10º, δ = -10º, one would expect C_m to be equal to values of body alone, if the fin experienced no normal force. But as pointed out earlier, the shed vortex flow from body seems to give rise to normal force on fins and this in turn, will create a nose down C_m. As α increases, the vortex flow at the corresponding α would pass over the fin increasing distance and less and less normal force would be induced. However, increase in α will increase the fin contribution of C_N due to increase in angle of attack seen by the fin. These two effects seem to add to increase C_N with α in such a way that the negative C_m produced is more in magnitude as compared to the positive C_m due to body in the α values varying between 15º to 30º. The difference in body and fin contributions remains a constant in the range of 15º < α < 30º. In this range it is observed that change in C_m with α is almost zero. However, this should not be seen as case of neutral stability. Stability should be investigated at the equilibrium point (C_m = 0). At C_m = 0, all the configuration have adequate static stability ($C_{m\alpha}$ < 0). Also it is noted that at α = 10º, the negative C_m due to fin and positive C_m due to body exactly cancel each other, providing the condition (C_m = 0) for α = 10º and δ = -10º. Beyond 30º, again due to drop off in body contribution, the overall C_m becomes increasingly negative with α and thus makes the missile more stiff aerodynamically.

For δ = -20º, -25º and -30º, it is again observed that $\Delta C_m \equiv 0$ but not so emphatically. For example, Fig. 4 for δ = -20º shows that $C_{m\alpha}$ in the range of 20º < α < 30º is changing from negative at α = 20º to positive at α = 25º and to negative again for α = 30º. If fluctuations were assigned to experimental errors, and $C_{m\alpha}$ value is averaged out for 20º < α < 30º, the C_m vs α would again show loss of aerodynamic stiffness in this range of angle of attack, α Beyond α = 30º, as explained earlier, net C_m starts to build up to more and more negative values and missile regains its stiffness. Also, as observed for α = 10º, δ = -10º combination, the α = 20º, δ = -20º combination also shows trim condition (C_m = 0) is achieved.

A less than obvious similar trend can be observed by closely studying Fig. 4 that shows C_m vs α for δ = -25º. Here again, for 25º < α < 30º, the C_m vs α curve seems to

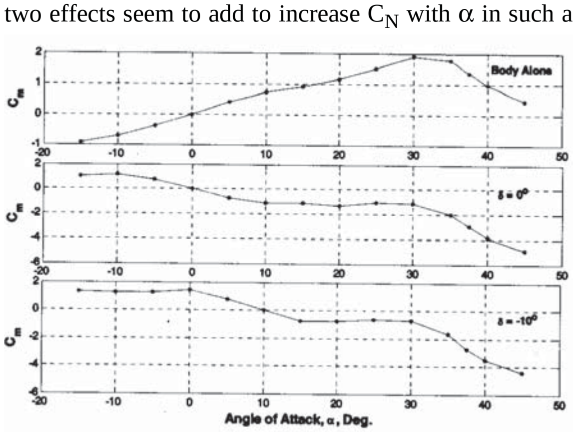

Fig. 3 Pitching moment coefficient Vs. angle of attack for body alone and body with fin at $\delta = 0°, -10°$

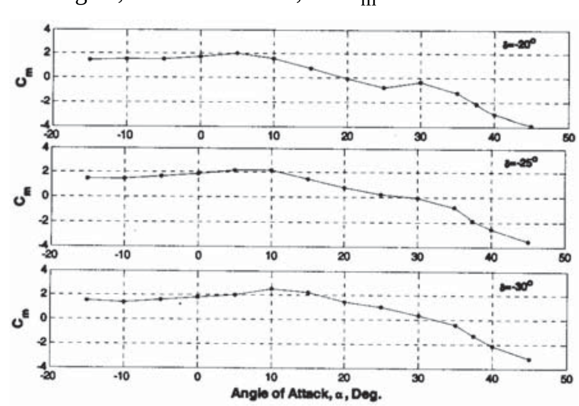

Fig. 4 Pitching moment coefficient Vs. angle of attack for body with fin at $\delta = -20°, -25°, -30°$

relatively flatten out before again becoming negative for $\alpha > 30^o$. Also it is noted that for $\alpha = 28.5^o$, $\delta = -25^o$ combination, the trim condition ($C_m = 0$) is achieved. The similar trends can be seen for C_m vs α for $\delta = -30^o$. Here one would expect no loss of aerodynamic stiffness, as we are already at $\delta = -30^o$ and for $\alpha > 30^o$, the decreasing value of body C_m would not get cancelled by fin contribution and thus a negative $C_{m\alpha}$ is observed. Also, it is noted that unlike for other combinations of $\alpha = x^o$, $\delta = -x^o$ for $\alpha = 30^o$, $\delta = -30^o$ no trim ($C_m = 0$) is achieved, and a net small value of C_m is observed, and trim is observed at slightly high value of $\alpha = 32^o$.

Conclusion

The aerodynamic coefficients were generated by wind tunnel test conducted for the short range strategic missile. These coefficients were also computed using the available analytical methods and comparison were made for normal force coefficient, C_N which compares well with wind tunnel result for angle of attack range -10º to 10º. Further, the theoretical method fails to capture the phenomena of shedding of vortex by long slender body at high angle of attack. Also, theoretical method could not predict the resultant side force and yawing moment at this regime of α. Further, it appears to be a well-designed missile from operations point of view. The trim angle for the missile is achieved at angle of attack, $\alpha \approx -\delta$ (approximately equal), thus trim angle of attack can be obtained by simply deflecting the tail at negative magnitude of trim angle of attack.

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