DEVELOPMENT OF CFD BASED SPLIT BODY METHODOLOGY FOR MISSILE AERODYNAMICS ESTIMATION

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ABSTRACT

Accurate estimation of the missile aerodynamic coefficients at the design stage is of great importance in predicting design configuration aerodynamic performance parameters. In order to determine aerodynamic characteristics of the missile configuration, significant number of Computational Fluid Dynamics (CFD) solutions are needed. Nevertheless, performing CFD analyses are expensive and require high computational power. In this study, a new approach named as "split body method" for the estimation of missile aerodynamic coefficients in an accurate and efficient manner is introduced. In this method, estimation of the interference effects between the missile body and tail fin panels with limited number of CFD analyses is achieved. For this purpose, the missile body is divided into four equal quadrants each with a separate zone name and the tail fin panel in each quadrant is set to different deflection angle. In this way, individual interference between each tail fin and quarter body can be calculated for any flight condition. Thus, the split body solution allows us to extend the results of these four quadrants which will be used in various combinations of panel deflections for estimating missile aerodynamic coefficients. After a validation study of the CFD analysis tool with Tandem Control Missile, the methodology was tested in different combinations of panel deflection angles for the same missile configuration. The results of this study indicate that the split body method (SBM) is successful for the estimation of missile aerodynamic coefficients.

INTRODUCTION

A standard cruciform missile configuration consists of a fin set with four panel surfaces. Convention of the panel numbering from rear view is shown in Figure 1. For such a standard missile configuration, the aerodynamic coefficient estimation can be made utilizing wind tunnel tests, semi-empirical codes, CFD analyses and flight tests. Semi-empirical codes are cheapest but they are inaccurate, wind tunnels are expensive and limited; on the other hand,

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CFD is less expensive and most accurate computational solution [Usta, 2015]. Therefore, it is preferable to use CFD based aerodynamic coefficients in intermediate design phases.
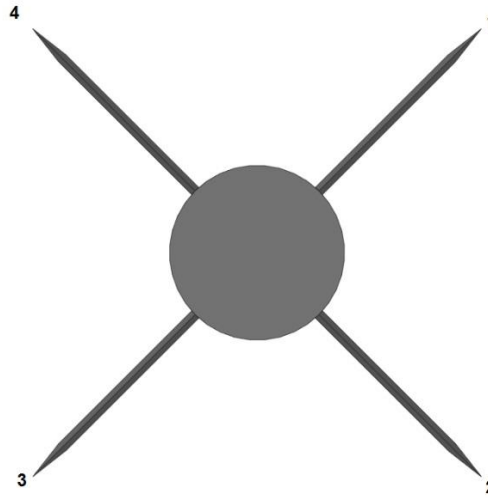

Figure 1 Panel Numbers Viewing from the Missile Base (Rear view)

CFD solutions require a lot of computational resources. Hence, it is highly desired to be able to extend a limited number of solutions. A study based on periodicity was conducted for extending wind tunnel results by Kim, D. in database generation [Kim, 2018]. It is asserted in this paper that a database generation method can be developed with a smart selection of the flight conditions for CFD run points and modification of the solid model zones.

In a standard CFD analysis, the missile body is modelled as a single zone as shown in Figure 2. In this paper, instead of single body zone, the body is split to four equal parts as shown in Figure 3 each with its own panel of influence.
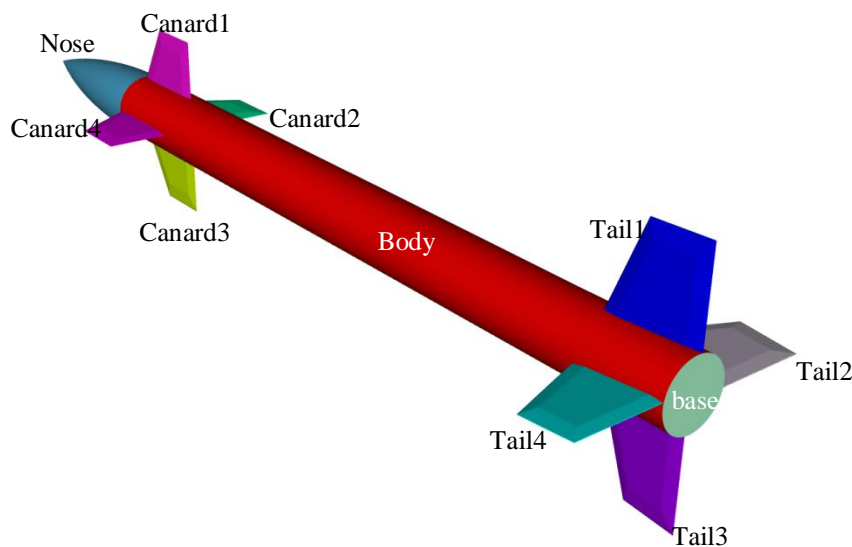

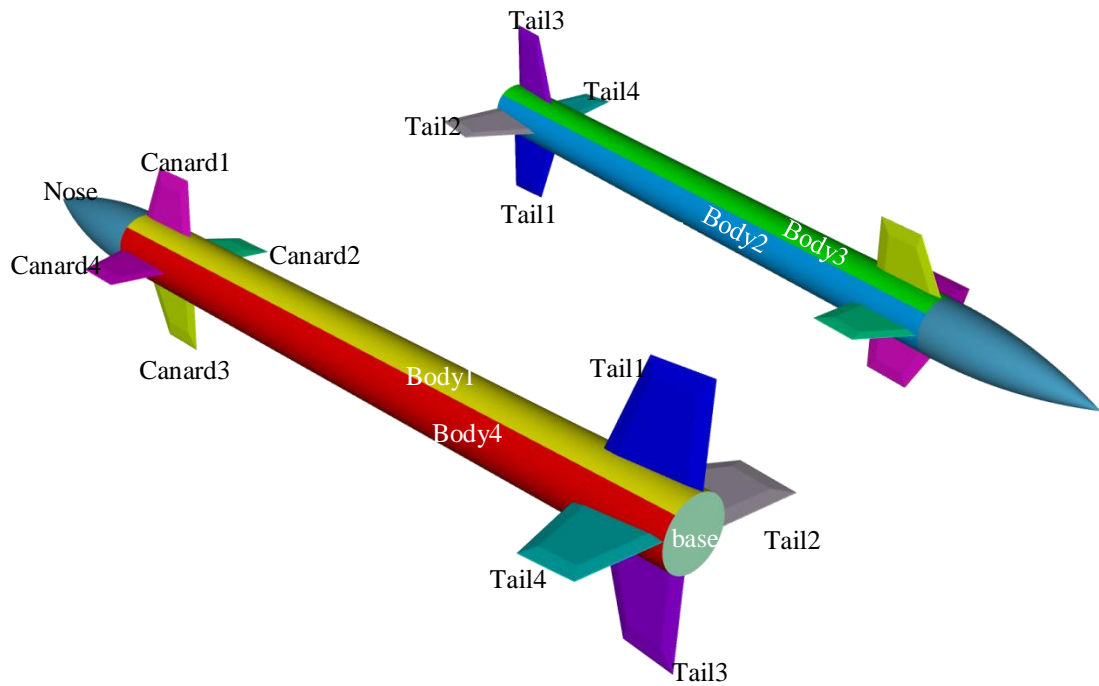**Figure 2** Conventional TCM Geometry

Figure 3 Components of the TCM Geometry with Body Surface Split Into Four Pieces

The region of influence for a cruciform missile body can be defined in four quadrants and each quadrant is assumed to be the region of influence for the containing panel. Each control panel is deflected by different angles. For a single Mach number and angle of attack case, aerodynamic roll angle is swept from 0° to 360° with 22.5 intervals. These limited CFD analysis results are used to extend for different combinations of panel deflections by means of split body methodology (SBM). In this way, it is possible to generate aerodynamic database which includes any combination of discrete input parameters.

Geometry and Test Conditions

The missile geometry used in this study is Tandem Control Missile (TCM) with T3 tails and C4 canards which is given in Figure 5 [Blake, 1985] and the axes system used in this study is given in Figure 4.
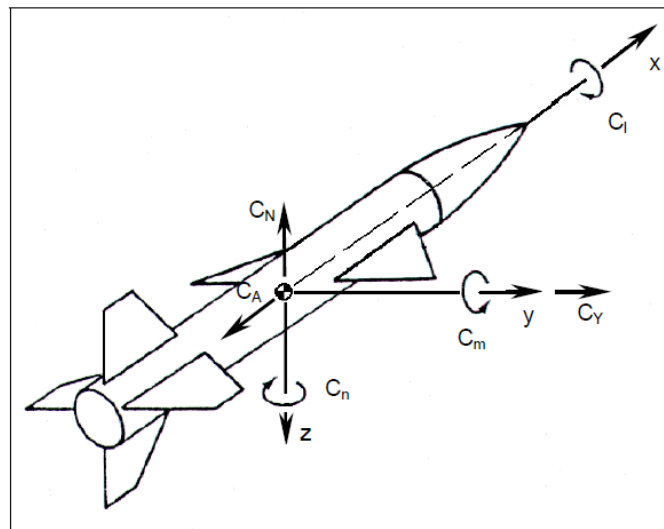

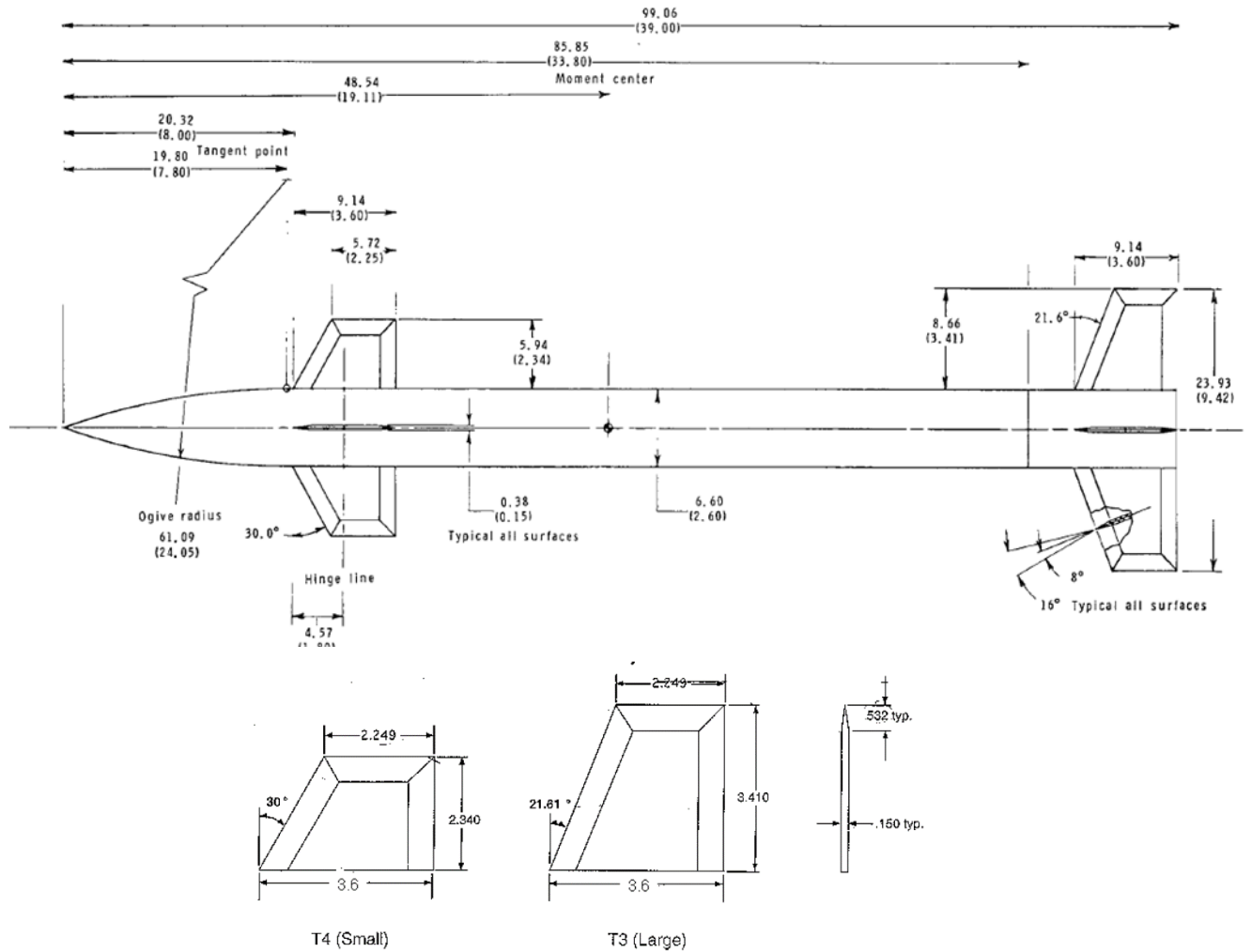**Figure 4** Axes system and Direction of the Forces and Moments

Figure 5 TCM Geometry Details [inches and cm]

Numerical Method

Solid model and computational domain are created by using GAMBIT and TGRID commercial programs. CFD++ is used as the CFD solver. Steady analyses are performed to obtain aerodynamic coefficients. Flow field is modeled at 1.75 Mach number for different angles of attack, using Realizable k-ε turbulence model.

Validation Results

In order to validate CFD methods used in this study, CFD analyses are carried out at ϕ=0 M=1.75 and angle of attack from α=0° to α =20° and compared with wind tunnel results. Wind tunnel test conditions are given on Table 1.

Table 1 Wind Tunnel Test Conditions

M	1.75
Re$_d$	2x10^5 per feet

Change of normal force and pitching moment coefficients with respect to angle of attack are represented in Figure 6 and Figure 7 respectively.
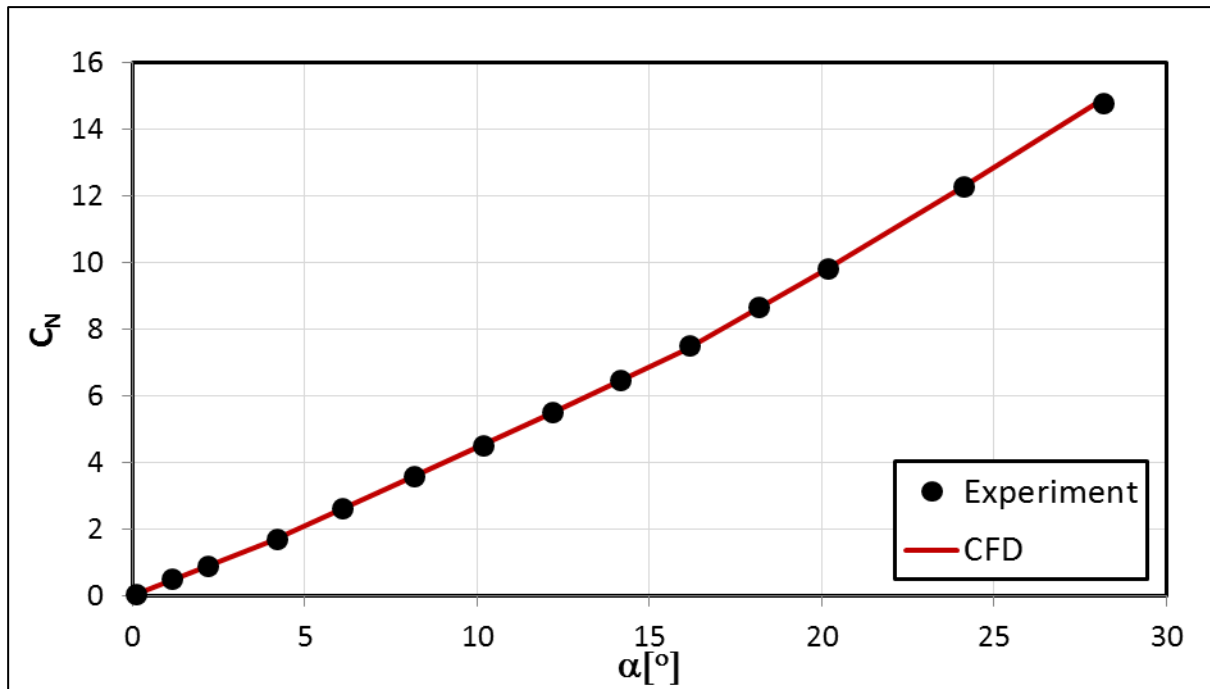
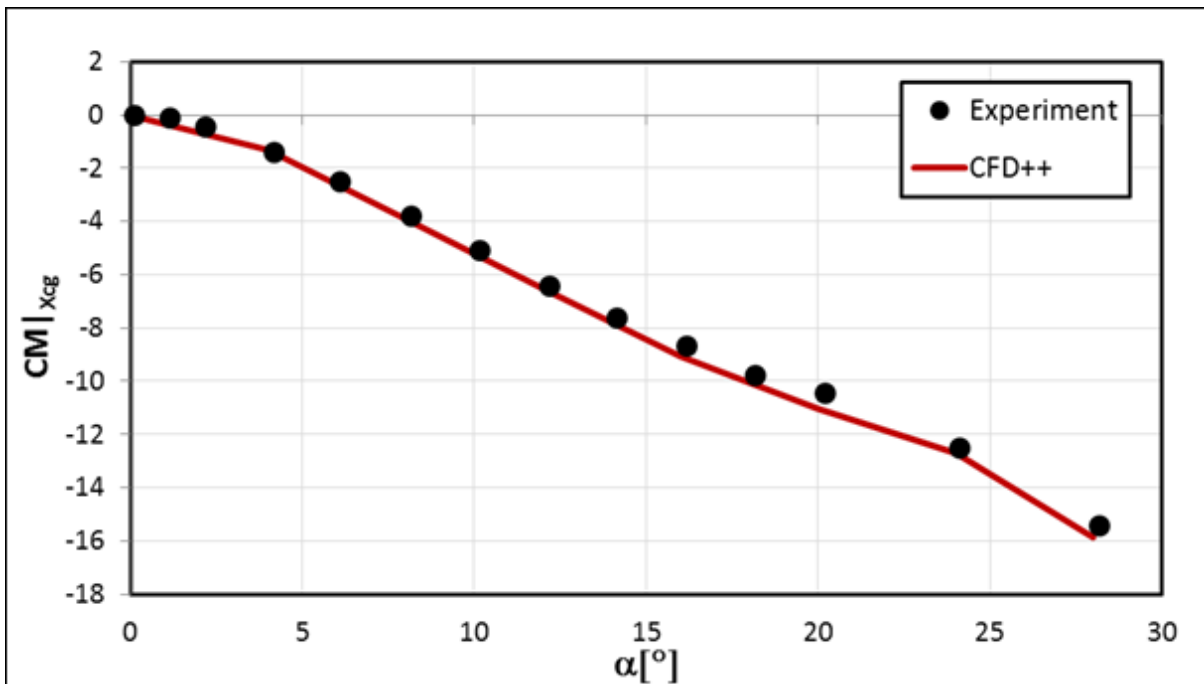**Figure 6** Normal Force Coefficient with Respect to Angle of Attack (M=1.75, ϕ=0)

Figure 7 Pitching Moment Coefficient with Respect to Angle of Attack (M=1.75, ϕ=0)

METHOD

The Split Body Method enables the calculation of aerodynamic coefficients for combinations of panel deflections at full factorial of flight conditions. In this method, results of a limited number of CFD solutions with different magnitude panel deflection angle in each quadrant are required. The limited number of CFD solutions having the coefficients in each quadrant are used as foundational basis. In the foundational CFD solutions, each panel has different panel deflection angle (2.5°, 5°, 10°, 7.5°) in each quadrant of the missile configuration. For this model, CFD analyses are carried out at full factorial design space of six (6) angle of attack , sixteen (16) aerodynamic roll angle and one (1) Mach number as shown in Figure 8

and listed. As for the non-deflected solution, number of aerodynamic roll angles reduced from sixteen to only three (0°, 22.5°, 45°) as shown in Figure 9 since the values of the aerodynamic coefficients at remaining aerodynamic roll angles (67.5 to 337.5) can be obtained considering the symmetry conditions. The flight conditions corresponding to the figures are tabulated in Table 2.
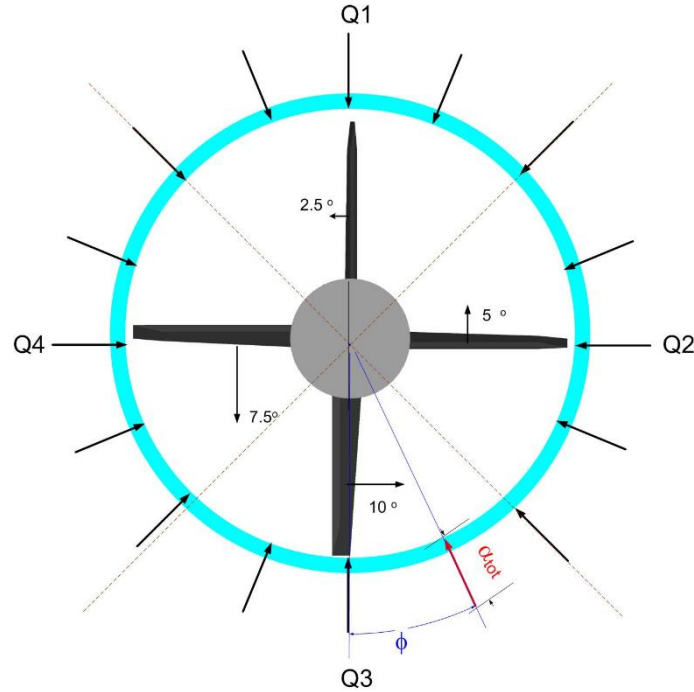

Figure 8 Sweep of the Aerodynamic Roll Angle for Discrete Panel Deflections
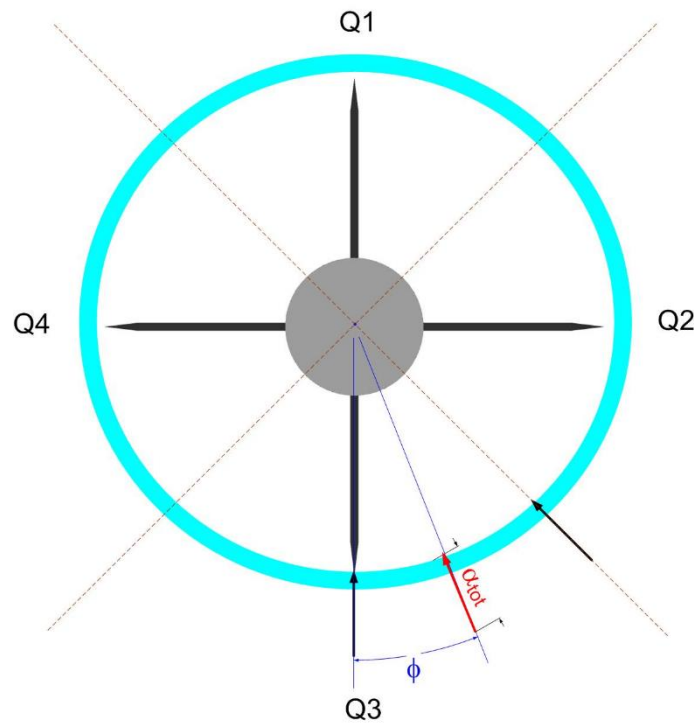

Figure 9 Sweep of the Aerodynamic Roll Angle for Non-Deflected Panels

The Split Body Method works based on dividing the solution to the quadrants. The orientations of the quadrants are changed with axes transformations and the split solutions are merged to obtain new combinations of panel deflection sets.

The coefficients of the foundational deflected and non-deflected fin solutions at all quadrants (Q1, Q2, Q3, Q4) shown in figures Figure 8 and Figure 9 are obtained from the CFD solutions separately. The limited number of CFD solutions for the deflected and non-deflected panels needed for calculations are named "Foundational CFD Analyses" and the results for each quadrant are named as "Foundational Case". By combining deflected and non-deflected solutions for separated zones with the superposition of the values for each quadrant and the axes transformations, the calculations from the foundational case are extended to find aerodynamic coefficients for any combination of discrete deflection angles. The extended solutions which are not in the foundational CFD analyses and calculated by using corresponding "Foundational Case" at each quadrant are named as "Derived Case".

The grid generation and CFD model preparation are performed for the cases shown in Figure 8 and 9 . Then, the foundational CFD analyses for flight conditions tabulated in the Table 2 are executed.

Table 2 Foundational CFD Analyses for Database Generation

	Deflected CFD Solutions	Non-deflected CFD Solutions
Mach	1.75	1.75
α_{tot} **(°)**	0,4,8,12,16,20	0,4,8,12,16,20
ϕ **(°)**	0.0,22.5,45.0,…,337.5	0.0,22.5,45.0
δ_1 , δ_2 , δ_3 , δ_4 **(°)**	[2.5,5,10,7.5]	[0,0,0,0]

The components of the conventional missile configuration CFD model consists of the nose, body, canard1-4, tail1-4 and base as shown Figure 2. Implementing the SBM for the conventional cruciform missile configuration splits body zone into four parts causing increment in the number of the zones of CFD model as shown in Figure 3.

The nose is not split into four part since it is located upstream according to the tail panels and will not be affected by the panel deflections due to nature of the supersonic flow. In addition, base is not split due to its negligible overall effect.

During the estimation of the aerodynamic coefficients of each quadrant for any derived flight condition, the following procedures are applied to obtain similar relative flight condition in the foundational case. Firstly, "relative panel roll angle", defined as the difference between the positional panel angle and aerodynamic roll angle, is calculated for each panel in the derived case as shown in Figure 10. Secondly, for each of the panels in the derived case, corresponding panel having same deflection angle is found from the foundational CFD analyses. Then, to obtain the same "relative panel roll angle" for the foundational case, the "relative panel roll angle" of the derived case is subtracted from the corresponding panel roll angle in the foundational case. Finally, the force and moment coefficients calculated from corresponding quadrants of the foundational case are transformed into the axes of the derived case and sum up together to find the total forces and moments.
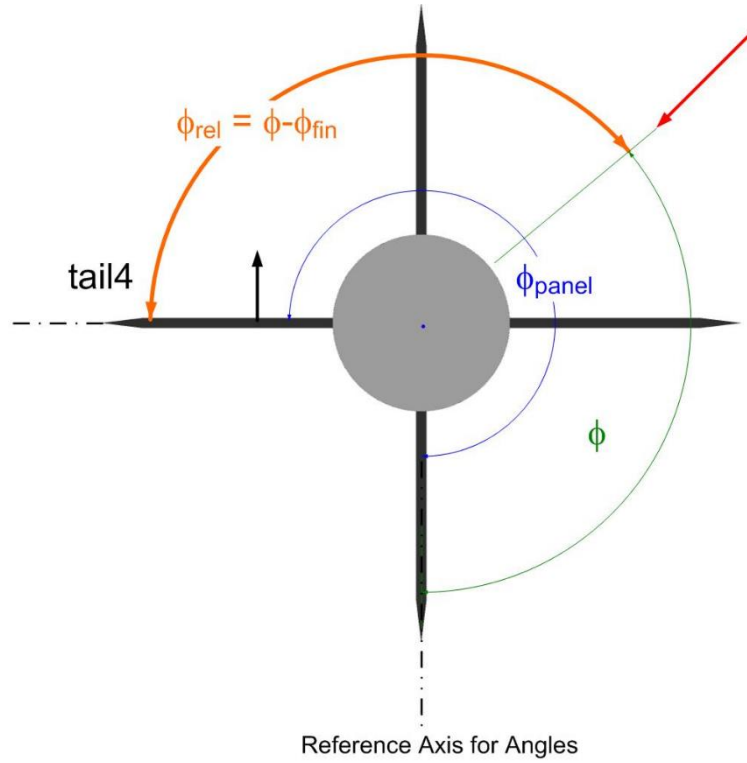
Reference Axis for Angles

Figure 10 The aerodynamic roll, positional panel angle and relative panel roll angle drawings

C_N : Normal Force coefficient
C_Y : Side Force Coefficient
C_A : Axial Force Coefficient
C_l : Roll Moment Coefficient
C_m : Pitching Moment Coefficient
C_n : Yaw Moment Coefficient

For 14 components (nose, base, body1-4, canard1-4, tail1-4) shown in the Figure 2 Conventional TCM Geometry the following formulation for the forces and moments are formulated:

$$C_X = \sum_{q=1}^{4} \left(\sum_{i=1}^{14} \left(C_{X_{\emptyset_{relative}}}^{comp_i} \right)_q \right)$$

$C_{X_{\emptyset_{relative}}}^{comp_i}$ is the corresponding force component in the foundational axes to the C_X direction in the derived axes for the component "i", at quadrants q=1 to 4.

In the formula, the coefficient C_x calculated can be one of the followings:

$$C_X = C_N, C_m, C_A, C_Y, C_l, C_n$$

RESULTS

A sample case is selected for calculation of the aerodynamic coefficients by Split Body Method (SBM). Flight conditions for the case are listed in Table 3:

Table 3 Flight Conditions and Panel Deflection for the Sample Case

	Deflected CFD Solutions
Mach	1.75
α_{tot}	0,4,8,12,16,20
ϕ	0.0,22.5,45.0
$\delta_1 , \delta_2, \delta_3, \delta_4$	[5,5,5,5]

According to the SBM, for each quadrant in the derived case there should be an equivalent flow quadrant in the foundational CFD analyses in terms of the panel and body interactions and it is called the foundational case corresponding to the derived case. The pressure contours for the derived case are shown in below figures together with the corresponding foundational case having the equivalent region of influence. For example, in Figure 11, Q2 from foundational case is corresponding to the quadrant Q1 in derived case. The relative panel roll angle is the same for the tail2 in Q2 of the foundational case, with tail1 in Q1 of the derived case. Therefore, similar pressure contours are expected in these equivalent quadrants. In figures, panel upper surface correspond to the surface where the arrows are pointing out and the lower ones are the opposite surface of the fin panel.
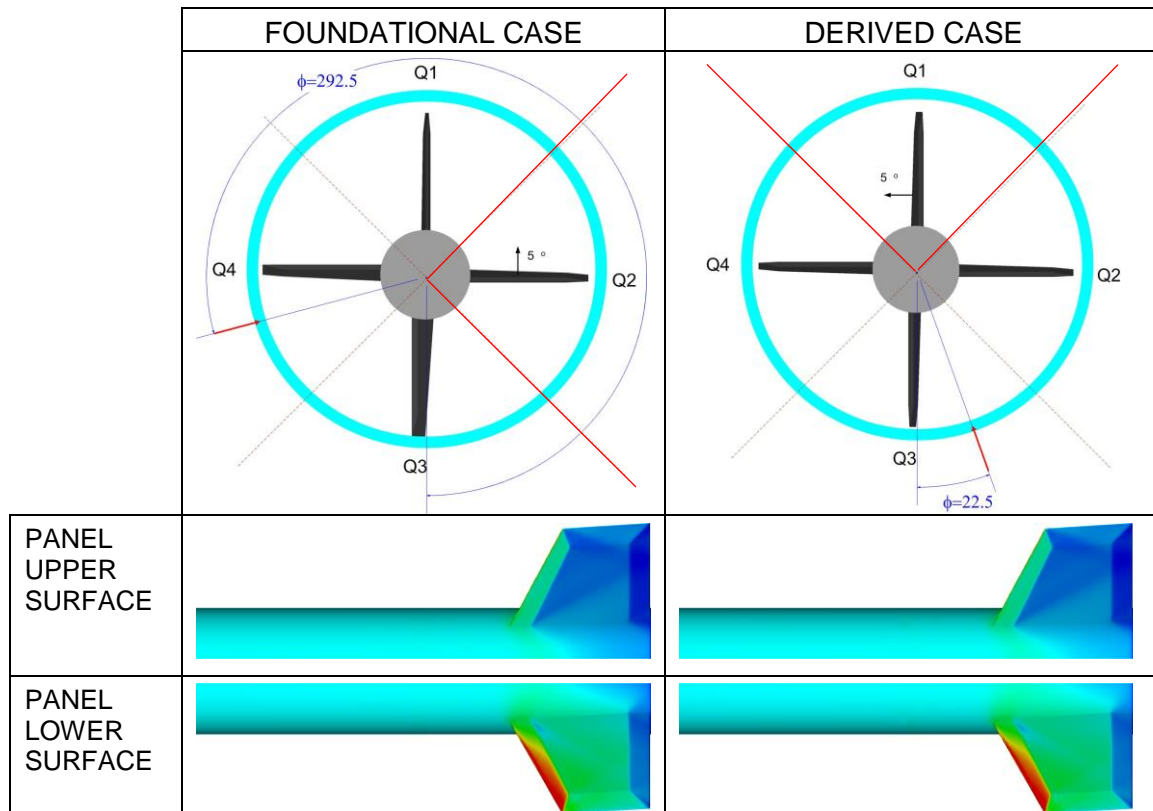

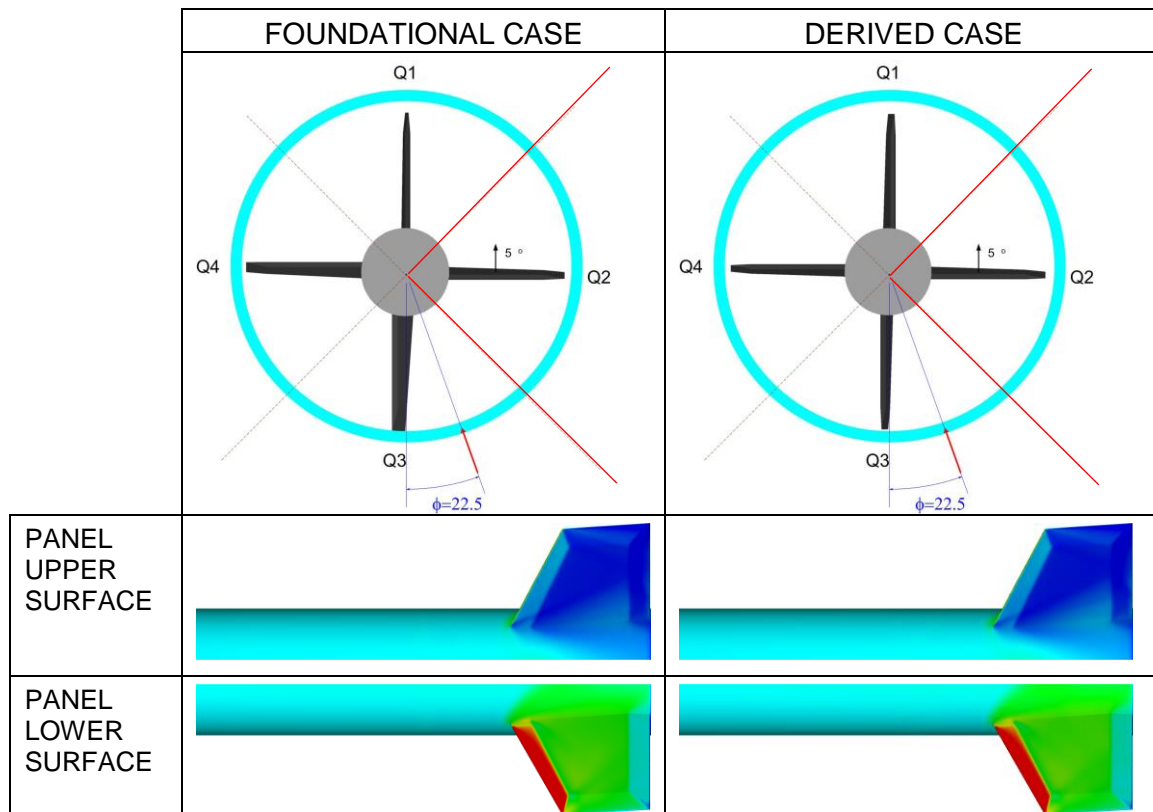**Figure 11** Location and Pressure Contours of the Derived Case [tail1] and Equivalent in Foundational Case [tail2]

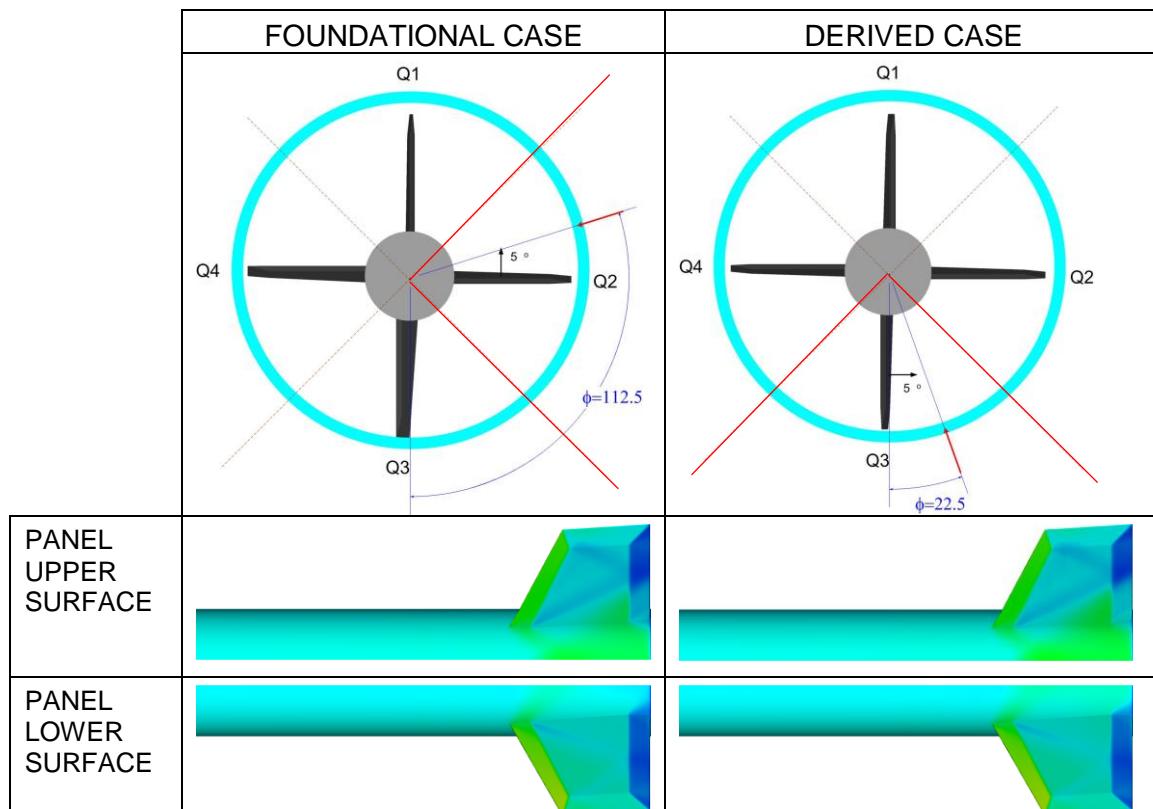**Figure 12** Location and Pressure Contours of The Derived Case [tail2] and Equivalent in Foundational Case [tail2]

Figure 13 Location and Pressure Contours of the Derived Case [tail3] and Equivalent in Foundational Case [tail2]
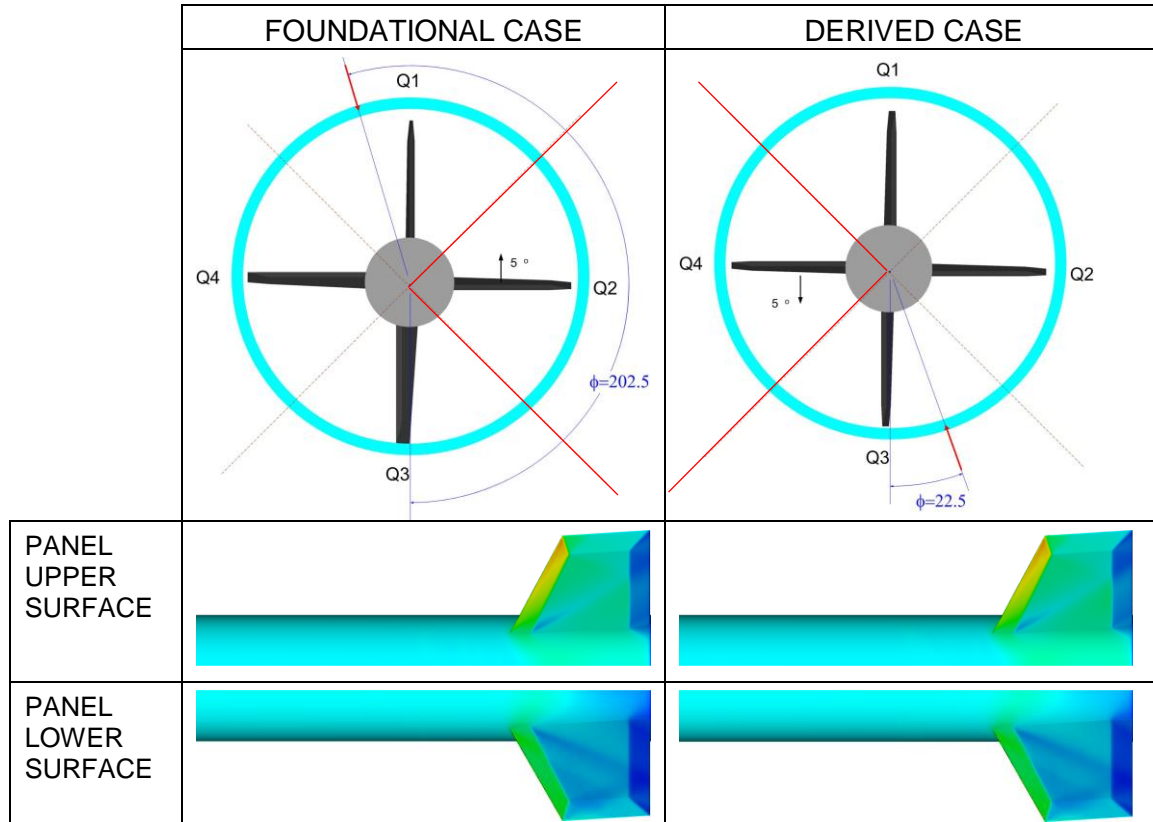
Figure 14 Location and Pressure Contours of the Derived Case [tail4] and Equivalent in Foundational Case [tail2]

It is clearly seen that the pressure contours for both foundational and derived case are very similar for the panels with the same deflections in different orientations. It can be said that fins at 5° deflection are not affected significantly by neighbor fins and body-fin interferences are very similar. Assuming that up to 10 degrees the panels won't be affected by the neighbor fins, the aerodynamic coefficients of the fins for foundational case can be used to estimate aerodynamic characteristic of the models with different fin deflection combinations.

The force and moment coefficients calculated by Split Body Method (SBM) and Computational Fluid Dynamics (CFD) for the sample case are compared in following figures.
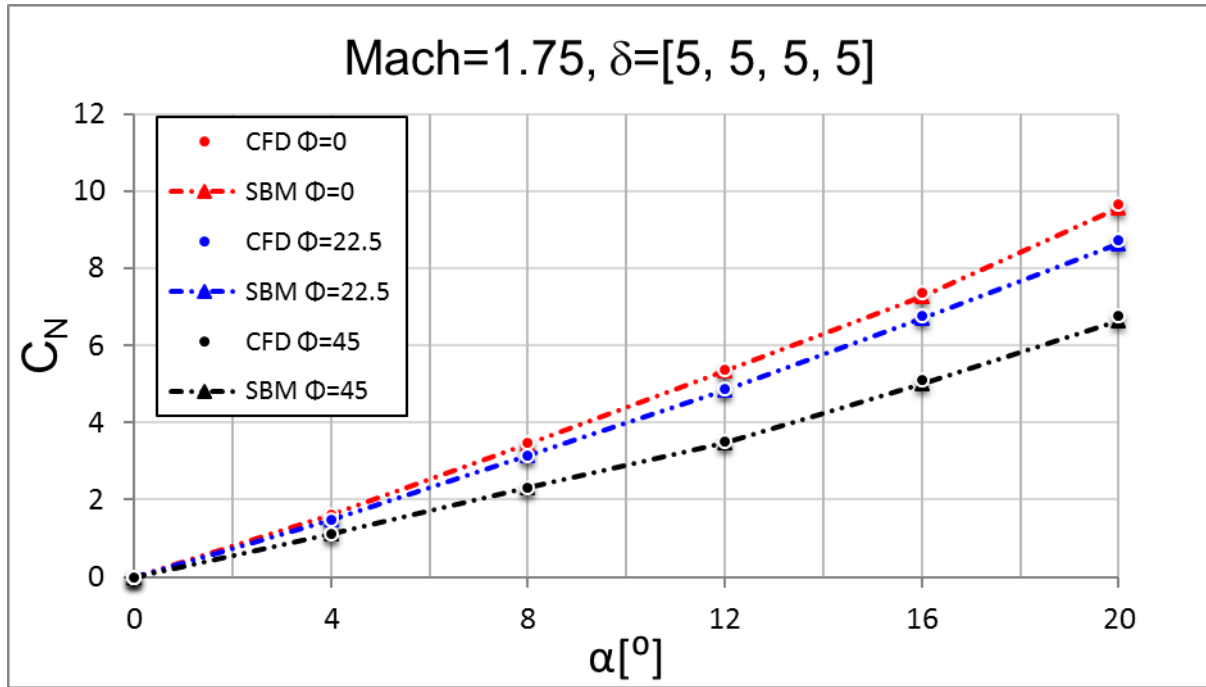
Figure 15 Normal Force Coefficient of TCM with Angle of Attack for the Sample Case
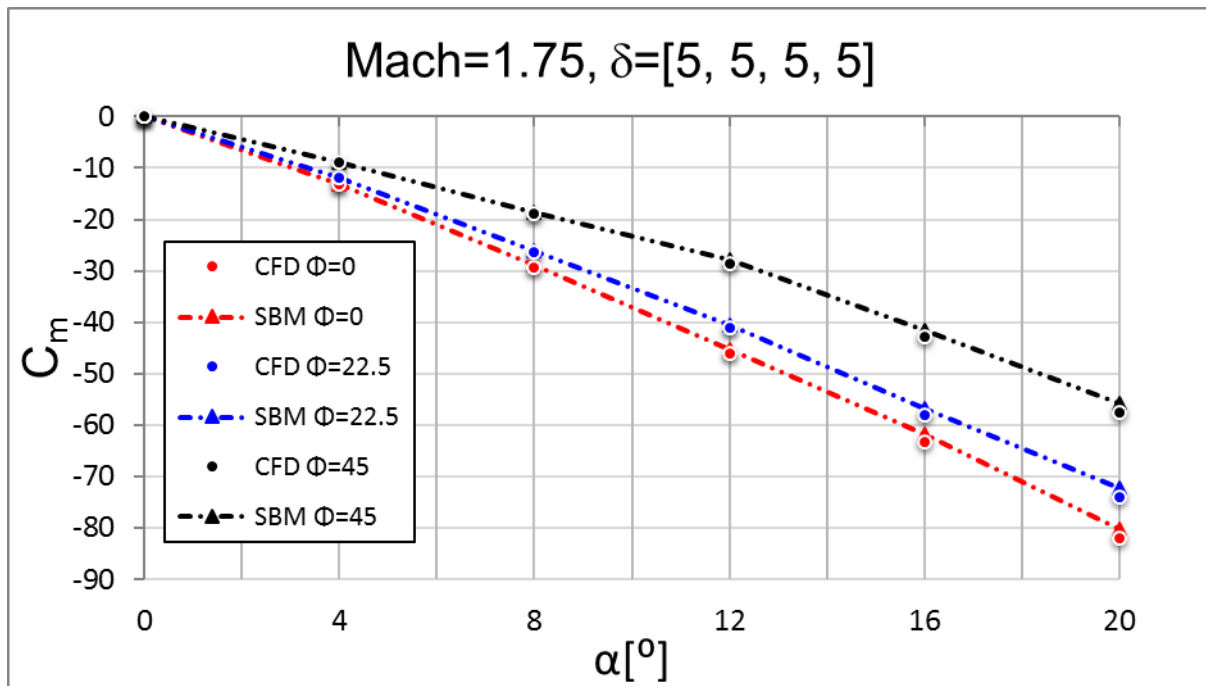

Figure 16 Pitching Moment Coefficient for TCM with Angle of Attack for the Sample Case
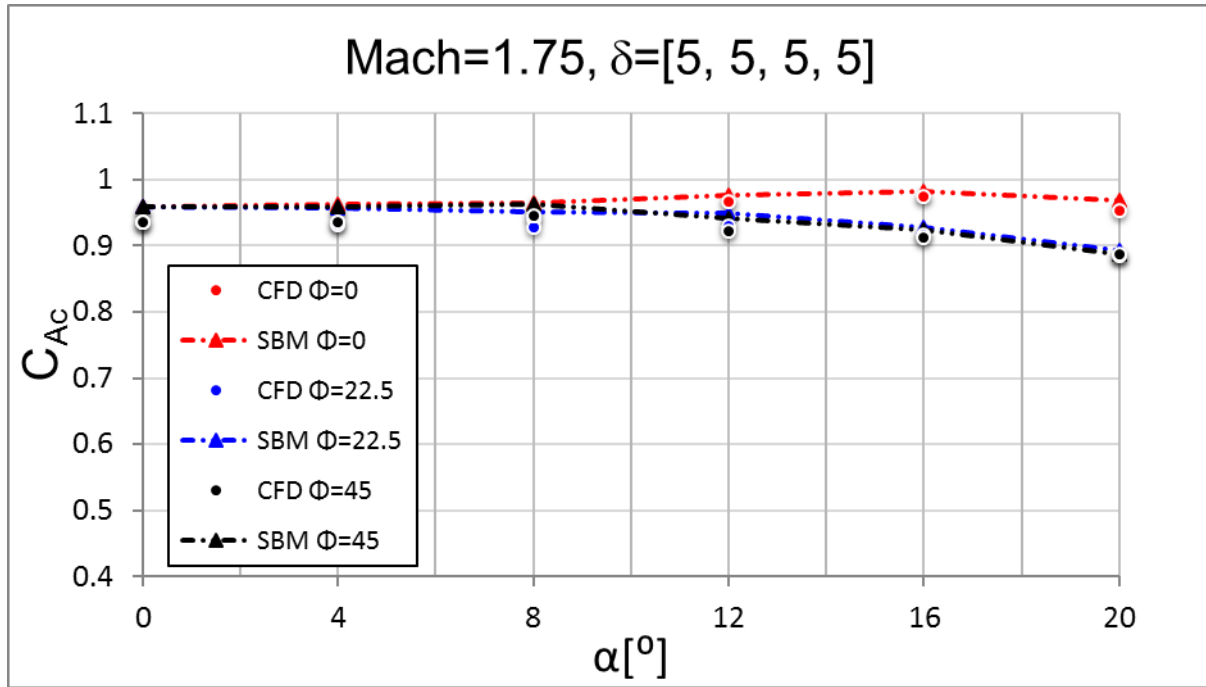
Figure 17 Axial Force Coefficient of TCM with Angle of Attack for the Sample Case
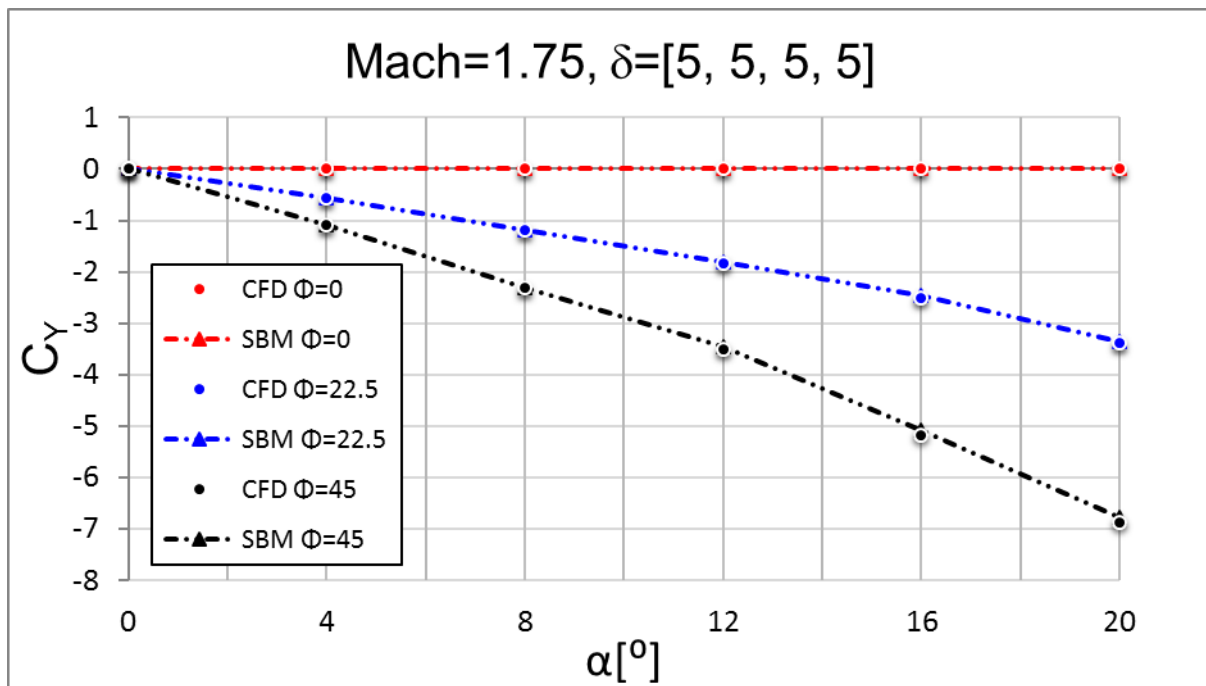

Figure 18 Side Force Coefficient for TCM with Angle of Attack for the Sample Case
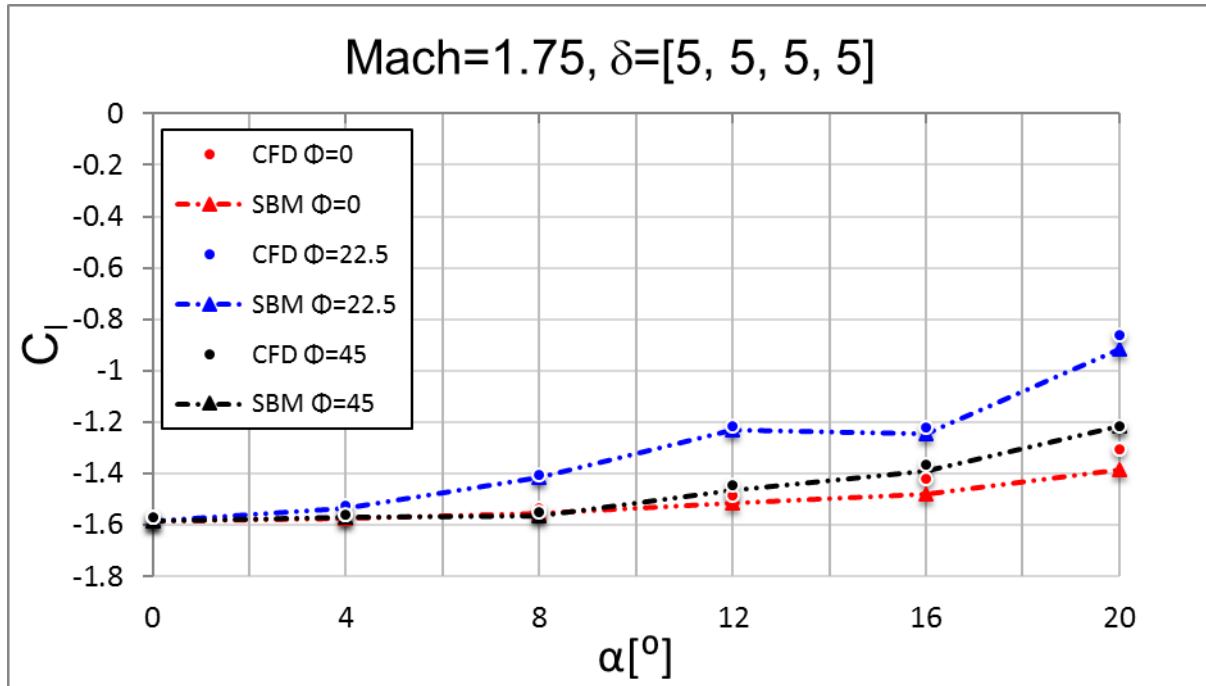
Figure 19 Rolling Moment Coefficient for TCM with Angle of Attack for the Sample Case
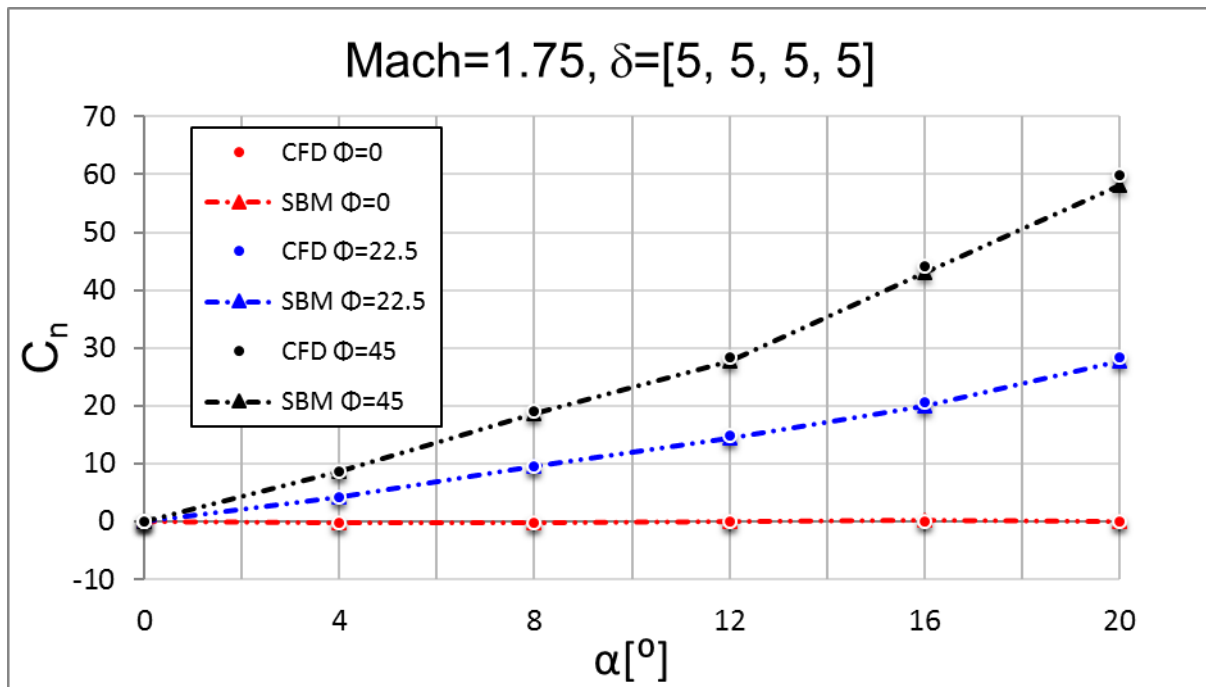

Figure 20 Yawing Moment Coefficient for TCM with Angle of Attack for the Sample Case

Comparing the sample case CFD results in Figure 15-20 with the values calculated by SBM method for the force and moment coefficients, it can be seen that the values are in good agreement except small differences in axial force. The difference in the axial force is estimated to be due to the base surface being not split.

For validating the method in other deflection cases three other deflection sets are selected (Table 4) and aerodynamic coefficients are calculated using both SBM and CFD. The results of all the force and moment coefficients were given for the sample case. For validating the method in other panel deflection cases, only C_N values are presented in Figure 21-23.

Table 4 Flight Conditions and Panel Deflection for the Validation Runs

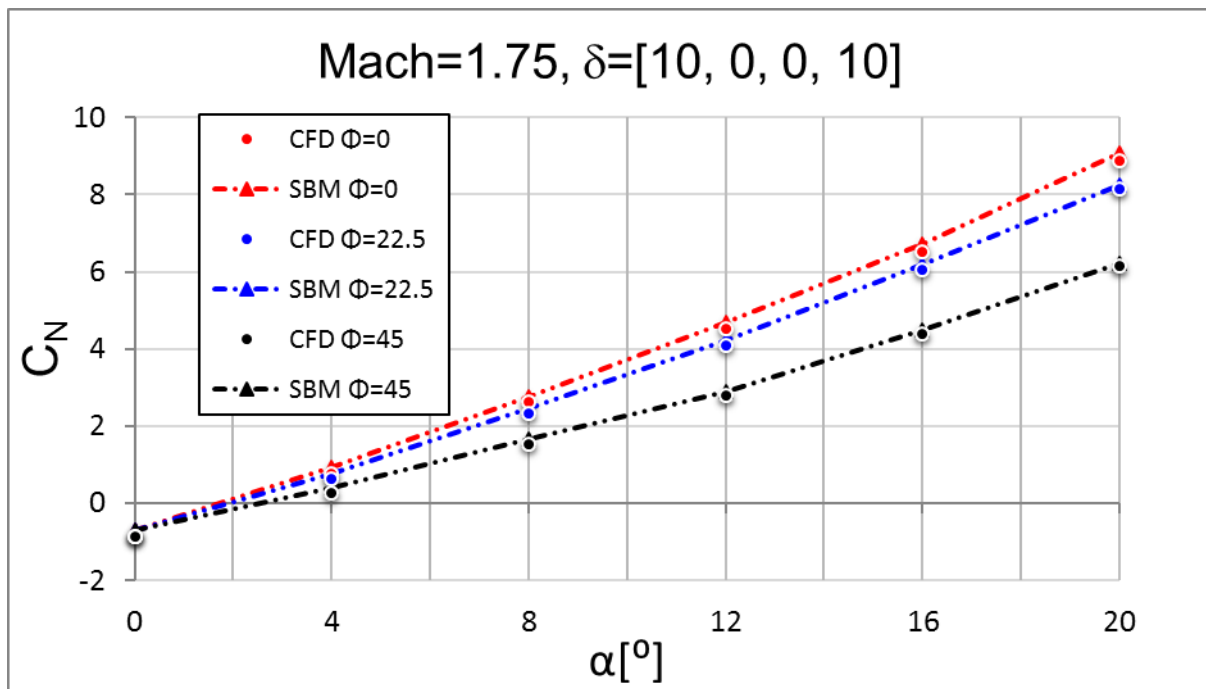|	**Deflected CFD Solutions**
$\delta_1, \delta_2, \delta_3, \delta_4$	[10,0,0,10]
$\delta_1, \delta_2, \delta_3, \delta_4$	[10,5,0,5]
$\delta_1, \delta_2, \delta_3, \delta_4$	[10,10,10,10]

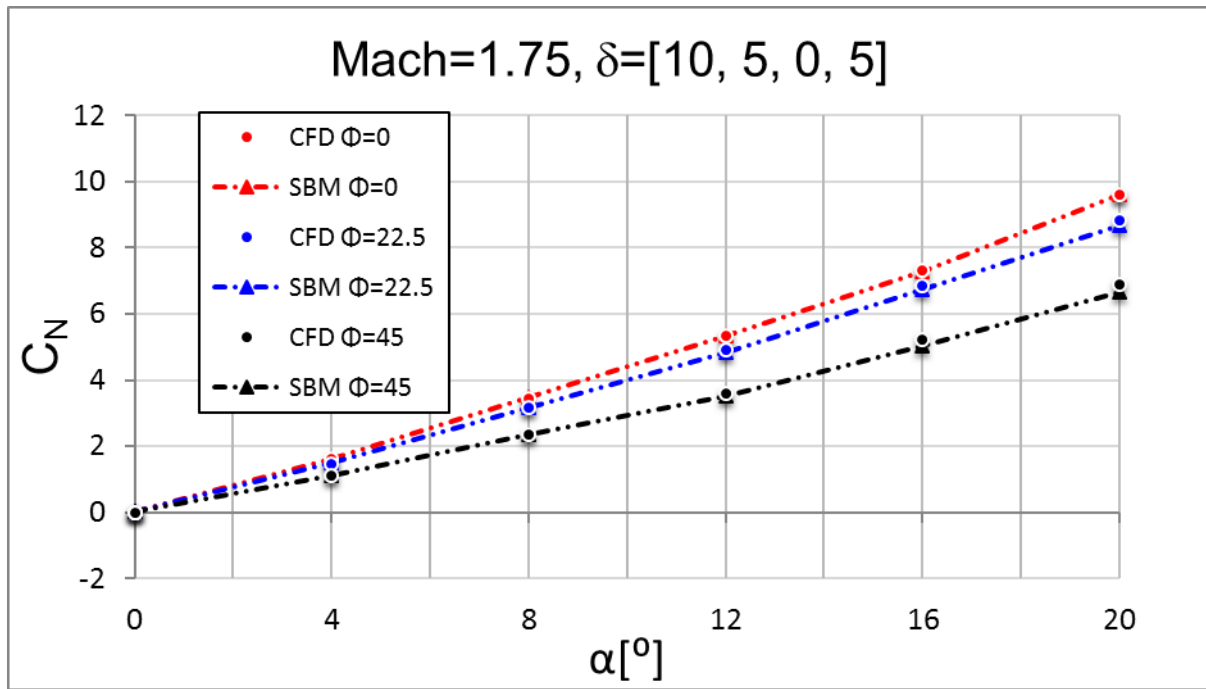**Figure 21** Normal moment coefficient for TCM with angle of attack for the case δ=[10,0,0,10]

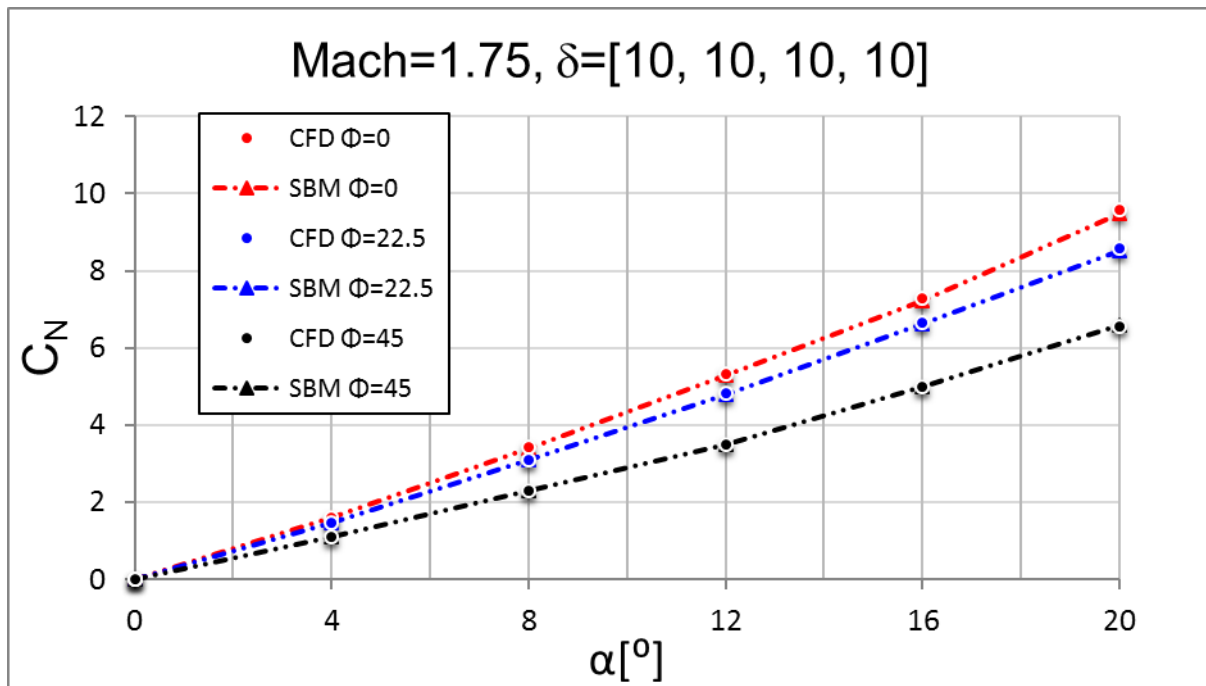**Figure 22** Normal moment coefficient for TCM with angle of attack for the case δ=[10,5,0,5]

Figure 23 Normal moment coefficient for TCM with angle of attack for case δ=[10,10,10,10]

In addition to the sample case, by observing the agreement of normal force coefficient values for the three other deflection cases in the figures 21- 23, it can be concluded that Split Body Method can successfully be employed to estimate aerodynamic coefficients of cruciform missiles.

CONCLUSION

- A new methodology called Split Body Method for calculating missile aerodynamic coefficients is developed. The methodology utilizes the similarity of the flow conditions in the quadrants with the same panel deflection of the cruciform missiles.

- The results of this study show that the SBM is successful for the estimation of aerodynamic coefficients with different combinations of panel deflections.

- Use of this method provides significant decrease in computational resource required for the mass generation of aerodynamic coefficients such as aerodynamic database.

- It is reasonable to assume that axial force calculated by the method gets better if the missile base is also split.

- The method further needs to be explored for the higher panel deflections, since the possibility of panel to panel flow interactions increase in that case.

References

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