Numerical Characterisation of Jet-Vane based Thrust Vector Control Systems

M.S.R. Chandra Murty and Debasis Chakraborty[*]

Directorate of Computational Dynamics, Defence Research and Development Laboratory, Hyderabad-500 058, India
[*]E-mail: debasis_cfd@drdl.drdo.in

ABSTRACT

Computational fluid dynamics methodology was used characterise jet vane based thrust vector control systems of tactical missiles. Three-dimensional Reynolds Averaged Navier-Stokes equations were solved along with two-equation turbulence model for different operating conditions. Nonlinear regression analysis was applied to the detailed CFD database to evolve a mathematical model for the thrust vector control system. The developed model was validated with series of ground based 6-Component static tests. The proven methodology is applied to a new configuration.

Keywords: Jet vanes, CFD, nonlinear regression analysis, thrust vector control

1. INTRODUCTION

At the initial stage of missile launching, when the speed is not very high, the control and stability requirements of the missiles are met by thrust vector control (TVC) system. The TVC system re-orients the direction of thrust vector and provides necessary lateral force for quick change of flight path. Among many TVC systems (secondary injection of gas/liquid into the nozzle gas flow, the flex nozzle, jet vane, jet tabs, etc.), jet vane system is preferred for tactical missiles[1] due to its small torque, small space requirements, and the capability to control pitch, roll, and yaw simultaneously[2,3].

The basic principle of providing control forces using vanes is the same as lift generation of supersonic wing at an angle of attack. As the vane is deflected at a typical angle to the exhaust gas, an oblique shock increases the surface pressure on the windward side whereas expansion reduces surface pressure on leeward side of the vane. The pressure difference between the windward and leeward sides of the vane provides a force normal to the chord of the vane. Its two components (i) Lift (side force) - useful to control the missile, and (ii) Drag - resulting in thrust loss. The smaller is the ratio of the thrust loss to the side force, the better is the performance.

Jet vanes are exposed to hot exhaust gas of the rocket nozzle, and with temperature as high as 3000 K and velocities up to Mach 3.5 that exert extreme mechanical and thermal loads on the vane. The degree of erosion on the vane surfaces directly affects its ability to directionally control the thrust vector of the missile. As erosion reduces the vane area, the lift and side forces provided by the vane reduce with time. Hence, due to complexity of modelling of erosion, the characterisation of jet vane is mostly done through experimental[4] and semi-empirical methods[5-6].

Traditionally, experiments took major role in TVC development procedure of conventional missile. With the advent of powerful parallel computers and advanced numerical methods, CFD tools are increasingly being used in the design and development of the jet vane TVC. The literature on the numerical simulation of the jet vane flow field is very limited. Rogers[7], *et al.* conducted numerical studies of jet vane flow field using upwind flux difference splitting Navier Stokes code. Sung and Hwang[8] used commercial software to study the aerodynamic characteristics of jet vane arranged in X-formation within TVC shroud. These studies revealed that when erosion of jet vane is less than 1 per cent of the cross-section of the vane, the simulated aerodynamic characteristics matches with the experimental results. Chandra Murty[9], *et. al.,* have presented CFD based jet vane TVC characterisation of a tactical missile. A comprehensive regression analysis was done with CFD database to arrive at a mathematical model to estimate the forces generated by vanes depending on the chamber pressure and vane deflection angle. The mathematical model may be incorporated into OBC of the missile that generates TVC control and actuation signals based on trajectory requirements. The developed model was validated extensively for a number of ground tests and flight tests for different duty cycles of vane deflections. In the present work, CFD based methodology has been used to characterise a new TVC system of a tactical missile.

2. SYSTEM DESCRIPTION

Jet vane TVC system mounted in X configuration on the rear of the missile is shown in Fig. 1. Primary objective of the TVC is to direct the missile into the line-of-attack from its vertical launch within short warning time. Validated CFD methodology was applied on this new configuration and we have evolved a nonlinear TVC mathematical model that is to be integrated into OBC control logic.
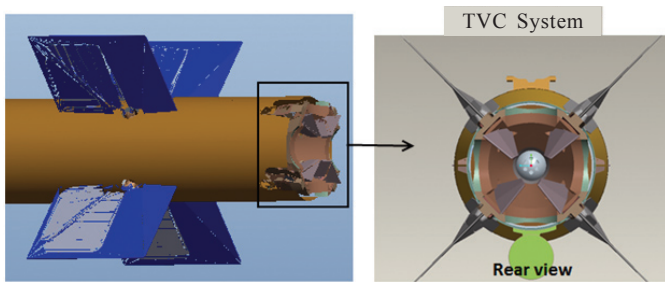
Figure 1. Schematic of the missile rear section.

3.   SOLUTION METHODOLOGY

The commercial CFD software Ansys[10] Fluent 14.5 was used in the present analysis. Density based coupled solver with first-order upwind Roe scheme[11] was considered for discretisation of inviscid fluxes. First-order schemes are found to be adequate in the estimation of overall parameters like pitch/roll forces, and moments etc. for jet vane applications[9]. Temporal discretisation was achieved, by a first-order, implicit Euler scheme. Turbulence was modelled using k-ε turbulence model along with wall functions. Computational domain consists of rocket motor blast tube, nozzle, TVC and external domain covering free stream up to about 2 m in all directions. Commercial grid generator[12] ICEMCFD 14.5 was used to generate unstructured grid in the computational domain. Typical computational grid is presented in Fig. 2. Necessary care was taken in placing the first gird point on the wall boundaries to maintain proper wall y^+ values. Grid spacing near the walls was about 3 micron (wall Y^+ = 1 to 60) while for the far region it was about 10 mm. More elements were clustered around the jet vanes to account for large gradients in flow variables. Nearly 2.9 million grid points were used in the domain which are adequate to capture all the relevant features of the flow, as shown in the grid-independence results presented later. At inflow of blast tube, rocket chamber conditions were imposed. Total pressure was varied between 4 MPa to 14 MPa for different cases, total temperature was fixed as 2944 K. Plume gas specific heat, dynamic viscosity, thermal conductivity, and molecular weight were given as 1870.9 J/Kg K, 9.5133 x 10^{-5} Ns/m^2, 0.27542 W/mK and 25.12, respectively. External free stream boundaries were given atmospheric. No slip, adiabatic wall condition was imposed on all walls. Maximum residual $(= \varphi_j^{n+1} - f\left(\varphi_j^{n+1}, \varphi_j^n\right)) < 10^{-4}$ is taken as convergence criterion.
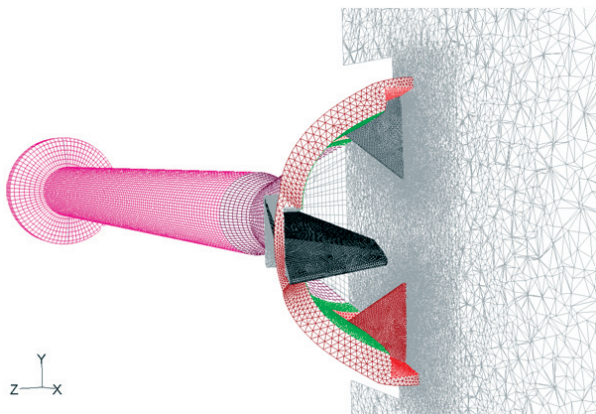
4.   RESULTS AND ANALYSIS

Computed side force obtained from two different grids (namely 2.9 million and 5.5 million) are compared in Table 1. Very close agreement of results between the two grids demonstrate the grid independence of the results and 2.9 Million grids is taken as baseline grid to carry out the remaining parametric simulations. Different CFD studies were performed for various combinations of chamber pressures and vanes deflections. Mach number contours for different vane deflection angles (β/βmax = 0.42, 0.625, 0.83, and 1.04) are shown in Fig. 3. With the increase in vane deflection angle, plume was getting more and more distorted. Maximum Mach number was estimated around 4 occurring in the plume expansion region and Nozzle exit Mach number was 3. Complex flow structure was observed near the jet vane flow field, particularly when the trailing edges of adjacent jet vanes were closer. Three-dimensional interactions of oblique shocks originated from vanes leading edge is presented through Mach number contour plot in Fig. 4. Shock interaction and reflection into the plume region is clearly observed. For a fixed chamber pressure of 110 ksc, the surface pressure distribution on jet vanes for vane deflection angles of (β/β$_{max}$ = 1.04) is presented in Fig. 5. Non-uniformity in the surface pressure is attributed to the shape of the jet vane as well as flow expansion/compression near the jet vane root cavity. The pressure difference between the windward and leeward surfaces provides the net side force. Under large vane deflections, flow decelerates on windward through an oblique shock. Rapid expansion of flow on leeward side was also seen in Mach contour plot across jet vanes (Fig. 4).

5.   DEVELOPMENT OF ENGINEERING CORRELATIONS

Characterisation of TVC system involves many parameters viz., chamber pressure, jet vane angles, rotational offset angle, etc. Enormous combinations of these parameters can exist; therefore it is impractical to perform CFD simulations/ ground test for all the combinations. A mathematical model is generated for TVC forces and moments which can be used

Table 1.   Comparison of computational grids

Grid No.	Size, cells	Side force, F_z/F_{max}
Grid-1	2.9 Million	0.420
Grid-2	5.5 Million	0.419
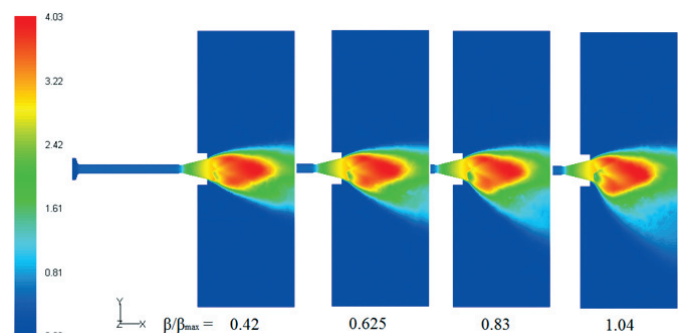
Figure 3.   Contours of Mach number for different vane angle deflection configurations.
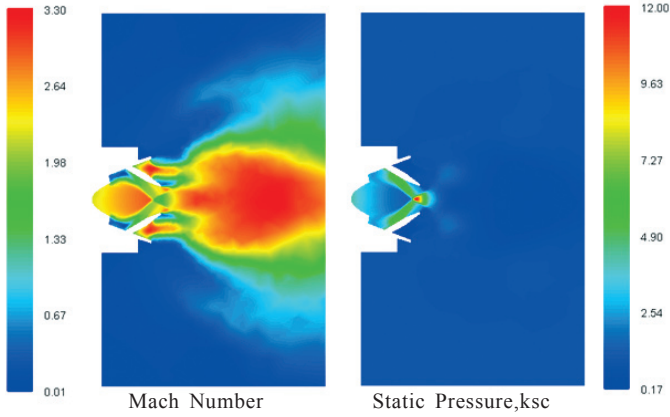

Figure 2. Computational grid.

Figure 4. 3-D interaction of oblique shocks originated from vanes leading edge.
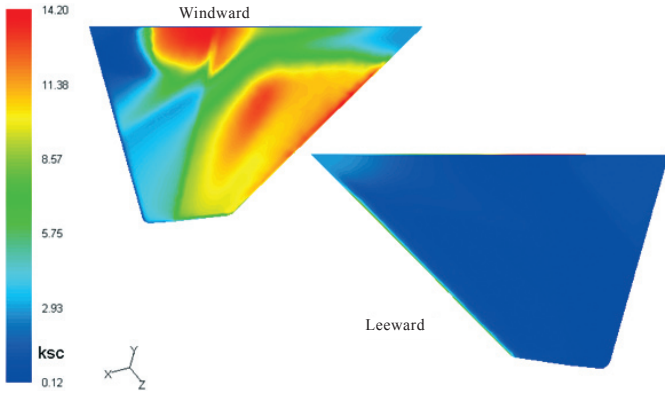
Figure 5. Surface pressure on vane for (β/β_{max} = 1.04) vane deflection angle.
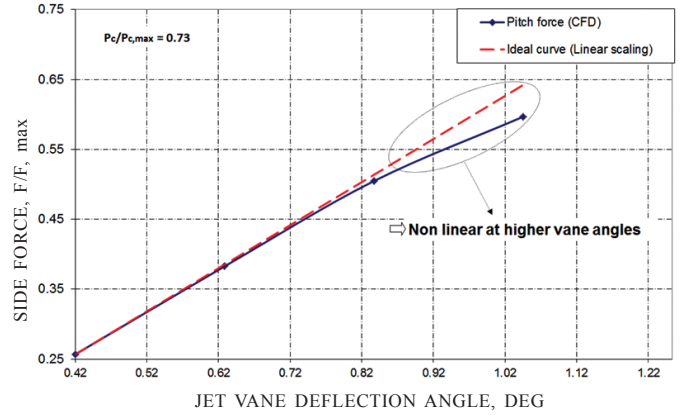

Figure 6. Variation of side force with vane angle for a fixed chamber pressure.
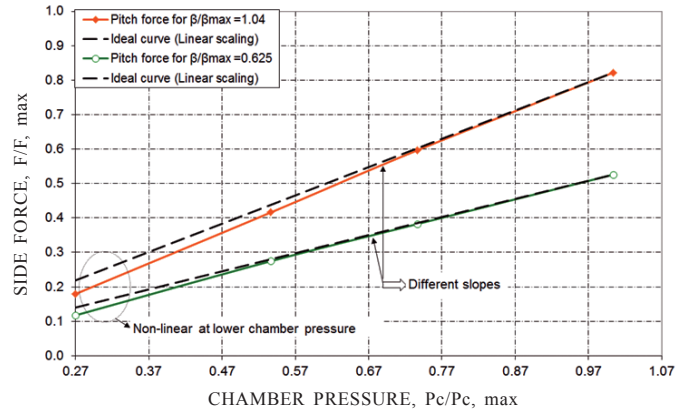
Figure 7. Variation of side force with chamber pressure for fixed vane angles.

in On Board Computer (OBC) of the missile, for generating actuator commands of vane deflections necessary for missile maneuver.

Figure 6 shows the variation of side force with vane angle for a fixed chamber pressure. Vane angle (β/β_{max}) is varied from 0.42 to 1.04 while keeping the rocket motor chamber pressure ($P_c/P_{c, max}$) as 0.73. A near-linear relationship between side force and vane angle (β/β_{max}) up to about 0.83 is obtained. Figure 7 shows the variation of side force with chamber pressure for a fixed vane angle. Vane characteristics at different vane angles show different slopes.

Large database is generated by CFD simulations for different chamber pressures, viz., ($P_c/P_{c, max}$ = 0.27, 0.53, 0.73 and 1.0) and vane angles i.e., (β/β_{max} = 0.42, 0.625, 0.83 and 1.04) A theoretical model is developed by performing nonlinear regression analysis[9] using CFD database. The model gives required side force/roll moment for any combination of chamber pressure, jet vane angles, and rotational offset angle. Table 2 presents model constants estimated from nonlinear regression analysis. Equations (1)-(4) were used to calculate yaw, pitch, and roll forces.

$$F^1_{Y,Z,R} = \frac{P_c^a \times \delta_e^b}{c} \qquad (1)$$

Subscripts *Y, Z* and *R* refer to pitch, yaw and roll configurations, respectively and P_c is rocket motor chamber pressure.

Table 2. Model constants

Model constant	Predicted value
a	1.0952
b	0.8744
c	12.1235 (Yaw, Pitch), 6.3064 (Roll)

Effective Jet vane deflection angle δ_e is given by

$$\delta_e = \frac{(\xi_1 \times \delta_1 + \xi_2 \times \delta_2 + \xi_3 \times \delta_3 + \xi_4 \times \delta_4)}{4} \qquad (2)$$

a, b and c are model constants predicted using CFD based nonlinear regression analysis.

Net yaw force is given by

$$F_z = F^1_z \times \cos(\theta) + F^1_Y \times \sin(\theta) \qquad (3)$$

Net pitch force is given by

$$F_Y = F^1_y \times \cos(\theta) - F^1_z \times \sin(\theta) \qquad (4)$$

Net roll moment is given by

$$R = F^1_R \times r \qquad (5)$$

where *r* is centre of pressure location in radial direction (*Ycp*) = 41.4 mm.

5.1 Error Estimation for Correlation Against CFD Data

The correlations developed using nonlinear regression analysis have some standard data fitting errors. The error band

of the correlation need to be ascertained against experimental data and with CFD data as well. For all the simulations, the predictions using correlation and CFD data is presented in Table 3. A very important observation of the comparisons is that the correlations are deviating largely at lower chamber pressure ($P_c/P_{c, max} \sim 0.27$) and especially at higher vane angles ($\beta/\beta_{max} = 1.04$). The model constants in the correlations need to be refined with a series of wisely designed experiments. Nevertheless, it proves a basic structure of the theoretical model which will be helpful in the process of charactering the TVC system

Table 3. **Comparison of predicted side force between CFD and correlation**

Simulation no.	$P_c/P_{c, max}$	β/β_{max}	Side force (F/F_{max}), CFD	Side force, correlation	% Error
1	0.533	1.042	0.416	0.418	0.36
2	0.733	1.042	0.597	0.592	0.77
3	0.733	0.625	0.383	0.379	0.99
4	1.000	0.625	0.526	0.532	1.22
5	1.000	1.042	0.822	0.832	1.22
6	0.533	0.625	0.275	0.267	2.76
7	0.733	0.833	0.505	0.487	3.46
8	0.733	0.417	0.257	0.266	3.48
9	0.267	0.625	0.118	0.125	6.43
10	0.267	1.042	0.180	0.196	8.84

6. CONCLUSIONS

Jet vane thrust vector system of a tactical missile was numerically analysed by solving 3-D Reynolds Averaged Navier-Stokes equations along with k-ε turbulence model. Simulations are performed for different combinations of chamber pressure and jet vane angles. Various forces and moments like side/roll forces, moments, bending loads on vanes, hinge-moments, drag forces etc are predicted. Engineering correlations are developed by performing nonlinear regression analysis on CFD database. The model can predict yaw force, pitch force, and roll moment for a given chamber pressure and vane deflection angles. Theoretical model is agreeing well with CFD data except for lower chamber pressures and higher vane angles.

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CONTRIBUTORS

Mr M.S.R. Chandra Murty obtained his BTech (Mech Engg) from Regional Engineering College (REC), Warangal. He is currently working as Scientist, in Computational Combustion Dynamics Division, Defence Research and Development Laboratory (DRDL), Hyderabad. His areas of work include heat transfer and computational fluid dynamics related to aerospace propulsion.
 In the current study M.S.R. Chandra Murthy has done simulation planning, grid generation, simulations with different grids, chamber pressures and vane deflections, post processing of the results and preparation of the figures and draft manuscript.

Dr Debasis Chakraborty obtained his PhD in Aerospace Engg from Indian Institute of Science, Bengaluru. Presently, he is working as Technology Director, Computational Dynamics Directorate, DRDL, Hyderabad. His current interests are CFD, aerodynamics, high-speed combustion, and propulsion.
 In the current study Debasis Chakraborty has done overall planning and guidance of the work, review of results and preparation of the final manuscript.