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Cfd Analysis of Mechanical Thrust Vectoring Control (TVC) of Missile

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Abstract:- **This paper explains the amount of thrust vectoring obtained using jet type of Thrust Vectoring Control (TVC) system. A new thrust vectoring component is suggested and validated with available experimental data. The methodology entails the design of three dimensional nozzle using two input design parameters followed by descretisation of control volume and simulation through ZNPL PUNS solver. Grid independence test was carried out for basic nozzle case (nozzle with no TVC component). Taguchi design technique for design optimization was adopted. Nine cases were simulated for varying position of TVC component in a direction normal to nozzle axis i.e. nozzle exit blockage along with clearance between TVC component and nozzle exit plane along the axis downstream. The optimised cases were selected through post processing and analysing the solution in perspective of nozzle wall pressure forces and TVC efficiency parameters.**

***Keywords*—Thrust Vectoring Control (TVC); C-D Nozzle; Annulus Plate; CFD**

I.INTRODUCTION

Thrust vector control comprises of controlling the missile thrust force. The present research covers the thrust vectoring design process for nozzle thrust vectoring flow parameters. The mechanical thrust vectoring has a high rate of reliability compared to other thrust vectoring techniques. Two-dimensional thrust vectoring with jet tab as an obstacle is analysed and validated with available experimental two-dimensional TVC results. A new 3D thrust vectoring component was suggested. An annulus plate as a TVC component was used as an alternative to jet tab plate. Annulus plate is placed at the exit section of the nozzle. Plate moves in a direction normal to the nozzle axis. This motion blocks the nozzle exit passage and directs the flow in direction away from the nozzle axis. The deflected flow renders the thrust opposite to the gas flow. Also, the annulus plate is displaced along nozzle axis downstream. This parameter is considered to analyse the effect of gas leakage on clearance between nozzle exit and annulus plate position as a design constraint. Mechanical thrust vectoring is still used due to its reliability effectiveness. Mechanical types of TVC systems are still commonly used. They are applied in the tactical as well as large calibre rockets and missiles. Over the past decades, researches of the mechanical TVC systems have become of great interest [1] Nozzle shadowed ratio and expansion ratio are the most important TVC system design parameters. Pressure in the recirculation between at and nozzle exit plane largely depends on the distance between position of annulus plate and nozzle. Nozzle exit plane as jet tab moves downstream, pressure wave moves downstream and vice versa. [3] Taguchi design method is used for parameter analysis and optimisation. [5]

The essential parameter analysed is the asymmetric pressure distribution on the interior nozzle wall divergent cone of the conical nozzle. This pressure distribution is responsible for vectoring of the nozzle in the direction normal to nozzle axis.

Thrust vectoring is useful when aerodynamic control surfaces are ineffective i.e. at low speeds and high altitudes. Jet tabs, movable nozzle, nozzle dome deflectors are frequently used in tactile missiles. The selection of jet tab concept is mainly due to the minimum moment of control hinge resulting in the least weight of components as compared to other mechanical TVC systems. [4]

Three-dimensional thrust vectoring analysis of missile C-D nozzle is analysed by taking two-dimensional nozzle design parameters. Also, thrust vectoring nozzle is designed in proportion with nozzle exit radius. Thrust vectoring nozzle tab in two-dimensional geometry is replaced by an annulus plate as a thrust vectoring component geometry design suggestion.

Thrust vectoring nozzle is analysed by adopting Taguchi design technique. [8] for optimising the set of thrust vectoring parameters. The thrust vectoring geometry configurations are designed with a gap for structural and functional reasons such as hinge motion of TVC component, thermal expansion.

II.METHODOLOGY

1. Validation of 2D TVC with experimental data
2. Referencing the 2D TVC system parameters for 3D TVC system design
3. 3D CAD modeling and TVC system design
4. Taguchi design 3X3 matrix for optimization
5. CFD calculation
6. Validation of analytical axial and lateral direction thrust with numerical solution
7. Selection of best suitable TVC configuration analysing results for effective TV

Throat height (mm) = 78
Exit Plane Height (mm) =115.7
Expansion Ratio= 2.2
Convergence Ratio=7.5
Curve Radius at Throat= 50.7
Exit Mach number =2.3

The passage of supersonic flow over the obstacle, a recirculation zone is created which leads to the separation of boundary layer and oblique shock wave in supersonic stream. The boundary layer separation further leads to supersonic flow deflection and thus generation of shock wave. The disturbed flow produces asymmetric pressure distribution on the interior nozzle walls, which produces a component of pressure force perpendicular to nozzle axis i.e. side force. This force component is used as a flight control force on the propelled fight vehicle.

The essential parameters used for study of gas flow process are:

1. Pressure distribution on interior wall of nozzle
2. Reciculation zone shape and position
3. Shock wave shape and position

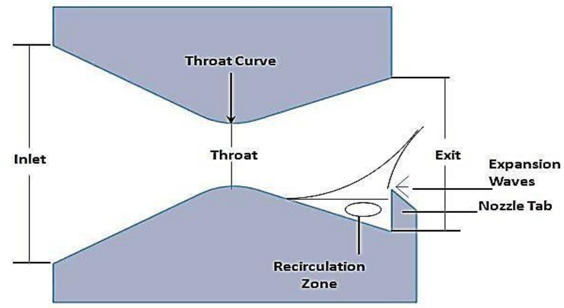

Figure 1: Physical Model illustrating nozzle flow with jet tab

The final geometry is validated with configuration details as:

1. No Obstacle in the flow
2. Obstacle in the flow with Offset

Ratio=10% of Rexit, Tab Gap=0 mm, [1]

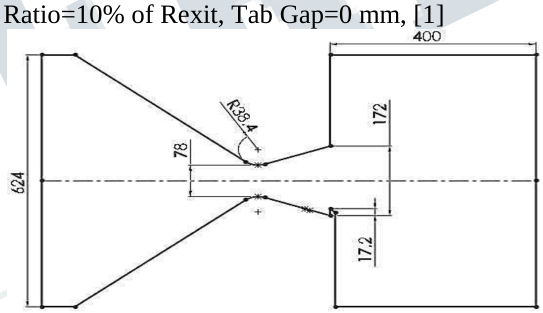

Figure 2: Two dimensional geometry applied in CFD calculations

III. 2D CFD Calculation

The 2D nozzle geometry with structured meshing is used for flow domain as shown in fg. The divergent cone near wall mesh elements is increased to capture the intense vortices. The vortices are mainly generated due to flow interference due to obstacle at the exit. The boundary layer height of wall neighbour cell is y+ ~1.

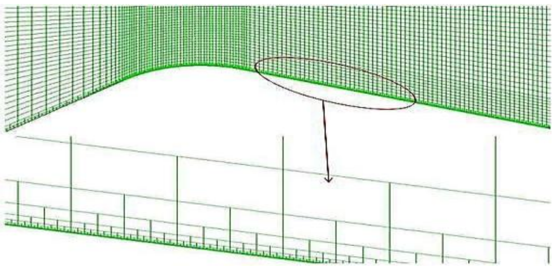

Figure 3: Two dimensional domain with mesh and boundary layer refinement

The thickness of boundary layer is less than 0.5mm which is achieved using adaptation technique in Flunt . The near wall cell is divided into 5 cells. The SA model is used as the best fit for the given application [1].

Main aspect of 2D simulation was to determine the pressure distribution on lower divergent wall of nozzle. This was due to the pressure wave generation causing pressure forces on nozzle wall as studied in available experimental data. These pressure forces lead to vector the thrust. Therefore, the solution is studied by considering Static Pressure distribution parameter Vs. Linear Distance from nozzle throat on lower divergent wall.

Results of 2D Analysis

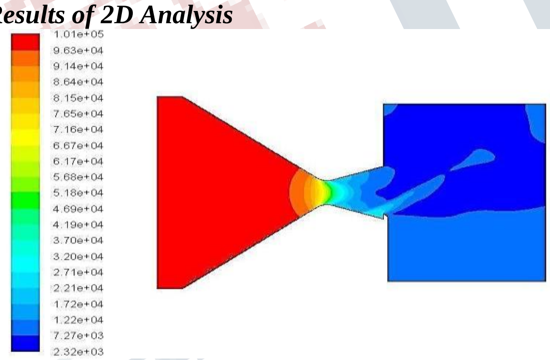

Figure 4: Pressure contour plot showing pressure wave generation

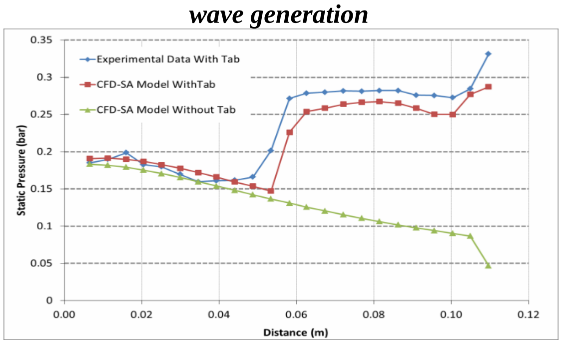

Figure 5: Plot of Static Pressure Vs. Distance from throat centre

Comparing CFD results and experimental data reveal that greater resolution is acceptable near the flow separation point and wall near nozzle tab. These two zones show the largest disagreement with experimental data. Results show that two vortices are created in nozzle divergent section. One is located just after the separation zone which has high pressure levels up to 0.28 bar. The other vortex is at the interface of nozzle wall and tab with pressure levels up to 0.25 [1]bar due to stronger viscosity effects. This high-pressure zone influences the thrust of the nozzle.

The tab deflects the flow downstream influencing the thrust loss. The loss in thrust compared to no obstacle configuration is 196.27(N). Recirculation zone or plateau pressure region has pressures values of 26178 Pa with recirculating velocities of
325 m/s. It can be concluded that SA Model choice is acceptable. The shockwave separation point and further region where there is a disagreement of experimental results with CFD results suggest that mesh refinement is required on the lower wall up to tab height. Secondly, the experimental wall has higher friction than the inviscid CFD wall

IV. 2D TO 3D CONVERSION

Important/Influential parameters taken from the 2D analysis are used to design the 3D TVC control system to study the flow characteristics in real life ambience. The key feature of the 3D nozzle is that the design of the thrust vectoring nozzle is based on only two important input parameters i.e. Throat Radius and Expansion Ratio. The output i.e. the other nozzle design parameters are Mach number, Nozzle Pressure Ratio (NPR), Flow Deflecting Plate Thickness, Plate annulus, Nozzle Exit Plane Blockage, Gap between annulus plate and Nozzle exit plane.

$Ac3D=Ac2D$ $\propto d3D=\propto d2D$

$\in 3D=\in 2D$ $Rc3D=Rc3D$

3D Nozzle geometry parameters

Expansion Ratio or Area Ratio= 2.2, from the given relation we get nozzle exit diameter=115.7mm.The TVC system is designed with reference to the nozzle exit Radius which comprises of missile nozzle and TVC component design in order to reduce the number of TVC geometry design parameters. Plate

Chamfer is provided to minimize the mass of the plate as an initial design perspective.

Outer Radius (mm) =81
Inner Radius (mm) =57.85
Plate Thickness (mm) =6
Chamfer (Degree) =45

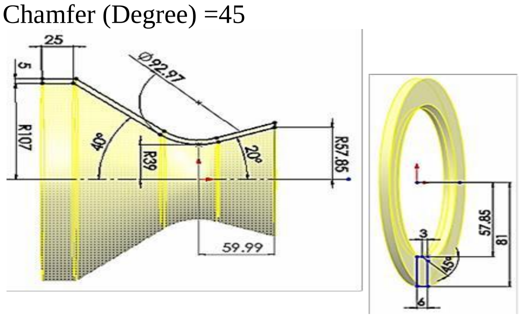

Figure 6: Three dimensional nozzle model with TVC Component

In the present study, the available parameter is Area Ratio, from which other parameters viz. Mach number and Nozzle Pressure Ratio are calculated. The geometries are prepared for variable nozzle exit plane blockage. This parameter is studied to understand flow deflection against TVC component's vertical plane motion which

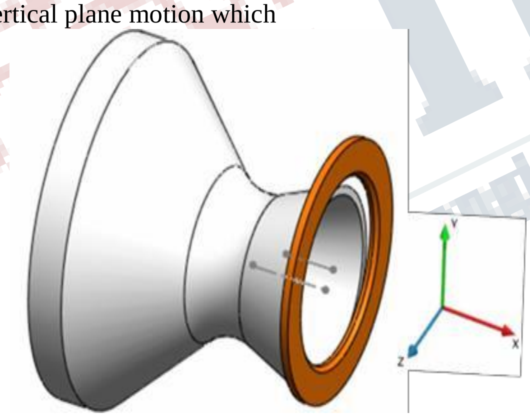

Figure 7: Nozzle and TVC component three dimensional configuration

eventually leads generation of variable pressure forces on nozzle wall. The other studied parameter in TVC system is clearance between exit plane and TVC component (annulus plate) to design and define the optimised position of TVC component. Therefore the two parameters viz. clearance and Blockage are analysed in combination with each other for optimized blockage and clearance.

In order to optimize TVC system, Taguchi optimization technique is adopted.

$$\text{Blockage Ratio} = h/R_{exit} = (10,20,30)\% \text{ of } R_{exit}$$

$$\text{Clearance Ratio} = \delta/R_{exit} = (0,10,20)\% \text{ of } R_{exit}$$

Mesh and Domain

A spherical domain around the nozzle exit and TVC component is chosen as the atmosphere. The sphere diameter is taken 10 times the nozzle exit diameter. To visualise the gas flow leakage through clearance, domain placed behind the nozzle exit.

The mesh refined at the nozzle exit proximity region from one end of the domain to other to capture the plume of nozzle.Prism layers are used on the nozzle interior wall as well as on the TVC component to capture the boundary effect at nozzle exit. Mesh size(total number of cells) for all cases is in the range of 0.8 million to 1.2 million. Mesh quality of all surface meshes was maintained equal to and greater than 0.2 and positive volume meshing quality number.

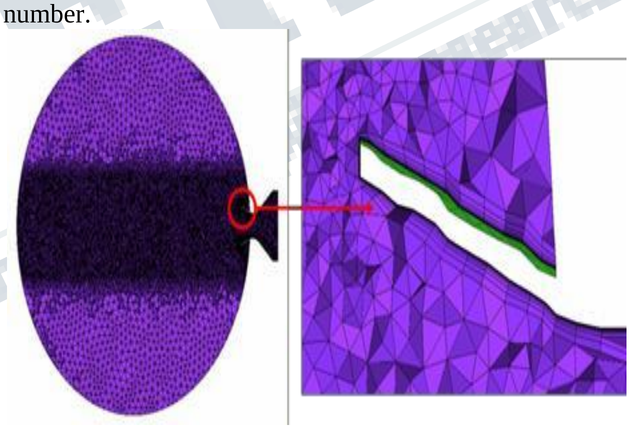

Figure 8: Unstructured grid details at symmetry plane with prism layers of TVC system domain for CFD calculation

V. BOUNDARY CONDITIONS

The spherical domain was considered as the atmospheric condition and pressure, temperature corresponding to sea level condition are given in Table 1the nozzle interior wall was defined as no-slip boundary condition.

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Table 1: Boundary conditions

Boundary Condition Type	Pressure (Pa)	Temperature(K)
Nozzle Inlet	1266562.5	617.4
Farfield	101325	300

Grid Independence Test:

Table 2: Results of Grid Independence tests conducted for basic nozzle case

Total Cell Number	Boundary Layer Cell Levels	Nozzle Axial Thrust (N)	Resultant Nozzle Exit velocity (m/s)
762330	10	6532.68	755.49
1069565	15	6539.94	756.31

Basic nozzle configuration grid independence test was carried out to understand solution variation with increased number of cells. The results are shown in table 2.

VI. SIMULATION MATRIX

Table 3: Taguchi Design simulation matrix used for optimisation of TVC parameters

Case	% (h/R_e)=□	%(□/R_e)=σ
1	0 (0 mm)	10 (5.8 mm)
2		20 (11.6 mm)
3		30 (30 mm)
4	10 (5.8 mm)	10 (5.8 mm)
5		20 (11.6 mm)
6		30 (30 mm)
7	20 (11.6)	10 (5.8 mm)
8		20 (11.6 mm)
9		30 (30 mm)

VII. SOLVER

Table 4: Solver details for CFD calculations

Type of Fluid Flow	Mono-phase(Standard Air Properties)
Type of Flow Model	Steady RANS(Viscous)
Numerical Scheme	Density Based Compressible Solver
Turbulence Model	Spallart- Allamaras
Turbulence Quantities	Eddy Viscosity with 0.1
Wall Function	No Wall Function
Time Stepping	Implicit
Gradient Calculation	Greens Theorem
Scheme Order	Second Order
Numerical Scheme	HLLC

Analytical Thrust Calculation:
Thrust for basic nozzle case (No TVC component) was calculated using the formula given below:

$$T = \dot{m} \times Ve + (Pe - Patm)Ae$$

Numerical Thrust Calculation:
The thrust on nozzle exit plane was calculated using area weighted average considering two parameters i.e. Velocity and Pressure on nozzle exit plane.
Analytical Thrust(N)= 7809.62
Numerical Thrust(N)= 6532.66
%Error= 16.35

VIII. RESULTS AND DISCUSSION

The 10 simulations consisting basic nozzle case were run for CFD calculation of TVC system. The residues were dropped by 3 orders. Following are the graphically illustrated results of ten TVC system configurations.

Nozzle Axial thrust efficiency:
Nozzle exit thrust was calculated by taking nozzle exit plane axial velocity and pressure. The thrust efficiency was calculated by taking a ratio of thrust of every configuration to basic nozzle thrust (nozzle without TVC component).

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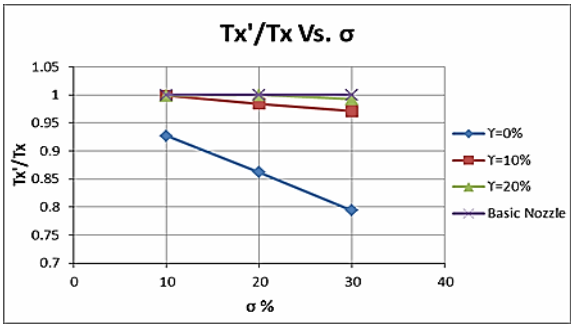

Figure 9: Axial Thrust efficiency Vs. Blockage ratio

The Axial thrust ratio was plotted against blockage ratio along with clearance ratio as shown in figure 9. It was found that case1 has lesser efficiency compared to a no TVC component case as the exit plane area was blocked along with no nozzle-TVC component clearance. Further increased blockage with constant clearance resulted in decreased efficiency (case 2 & 3). For Case 4, clearance was 10% which was similar to the no TVC component case. This showed that the efficiency was closer to the basic nozzle. For cases 5 & 6, efficiency decreased with minor gradient. It was observed for cases 7 to 9 that due to marginal clearance ratio of 20%, the TVC system acted as a basic case. Hence, cases 4 to 9 are significantly applicable in terms of axial thrust efficiency parameter i.e. without compromising axial thrust.

Pitch thrust or lateral thrust ratio:

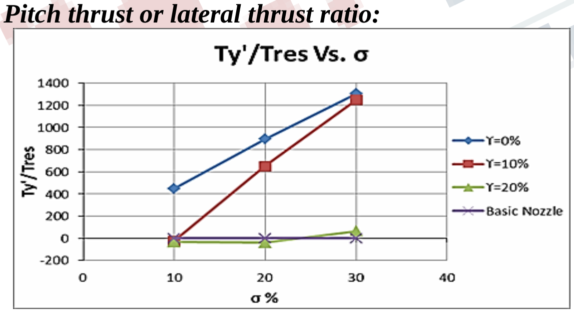

Figure 10: Lateral (Pitch thrust) Vs. Blockage ratio

Pitch thrust ratio is the measure of pitch thrust or lateral direction thrust with respect to nozzle resultant thrust. The Pitch thrust ratio was calculated against clearance and blockage ratio as shown in figure 10. Case 1 showed increased pitching compared to basic nozzle at γ=0% Further, thrust was linearly increasing for cases 2 and 3. When γ=10% for cases 4 to 6, zero lateral thrust was observed for case 4 and increased lateral thrust for case 6. It was observed that the Pitch thrust ratio increased linearly. When γ=20% for cases 7 to 9, no significant pitching was observed. This can be well explained as a clearance rendered the passage for leakage of the exhaust gases reducing effectiveness of lateral thrust.

Resultant Area Weighted Velocity (VR):

Resultant average velocity for basic nozzle was in the order of 740 m/s. The VR against σ was plotted in order to determine the exiting resultant gas

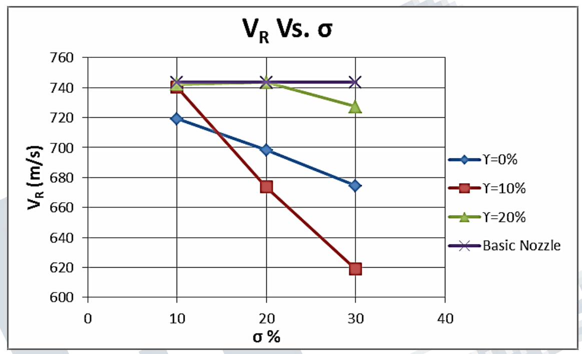

Figure 11: Resultant exit velocity Vs. Blockage ratio

velocity variations against varying configurations as shown in figure 11. This parameter entails the necessary resultant gas velocities responsible for nozzle resultant thrust. For γ=0% and σ=10%, VR is lower than basic case as the TVC component is attached to the nozzle exit with no clearance and further decreases with increased blockage. For the line γ=10%, VR decreases linearly. This was due to the exiting high velocity gases deflected in directions away from nozzle axis. For γ=20%, the nozzle shows similarities in resultant velocities with basic configuration up to σ=20% and further decreases as blockage influenced the flow to deflect away from nozzle axis.

Nozzle wall lateral forces:

The pressure waves generated due to blockage of nozzle exit plane were responsible for exerting the lateral forces on the nozzle interior walls. This forces are crucial parameters for pitching in order to vector the thrust. As shown in figure 12. no pitch was there for basic nozzle. As the blockage increased with constant γ for cases 1 to 3, increasing picthing force trend was obseved. Maximum picthing force was obseved for case3. For cases 4 to 6, pitch forces increased from zero upto a value which were below the constant clearance line(γ=0%). The gas leakage through clearance which minimised the pressure wave generation was responsible for

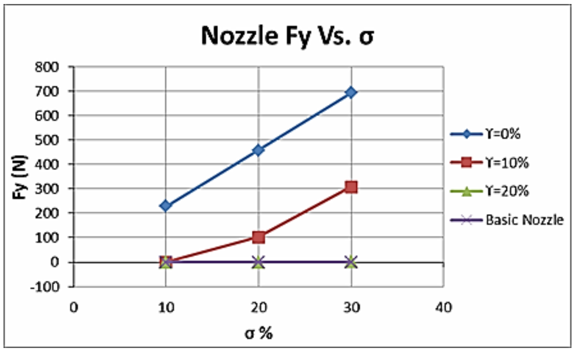

Figure 12: Lateral Nozzle wall Pressure forces Vs. Blockage Ratio

reduced nozzle pitch forces. For cases 7 to 9, almost zero magnitude of nozzle picth foces were generated due to significant clearance γ= against blockage.

Axial forces on TVC component:

The axial forces were computed onTVC component against σ and γ as shown in figure 13. The constant clearance lines show linear increased behaviour. The line γ=20% bears maximum magnitude of axial forces followed by the line γ=10% and γ=0%. As in the case s when γ the gases flow

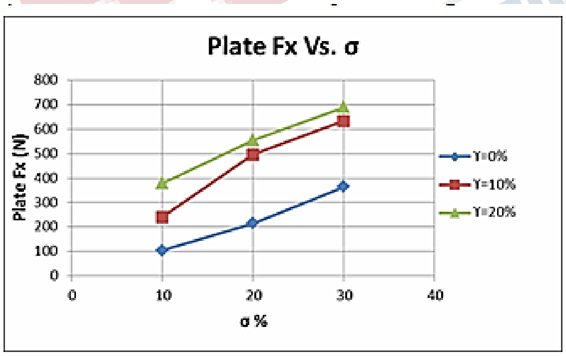

Figure 13: Axial gas loads on plate (TVC component) Vs. Blockage Ratio

above the recirculation i.e. the constant pressure zone generated due to blocked nozzle exit plane. This recirculation zone tends to deflects the flow laterally above the TVC component without significantly exerting axial forces. As the γ increases, pressure wave moves downstream, breaking the attached recircluation zone. This renders the nozzle downstream axial flow to exert the force with increased magnitude on the TVC component. For cases when γ=20%, no recirculation zones were generated as gases flow axially downstream upto the TVC component which explains the highest magnitude of axial forces.

Lateral forces on TVC component:

Lateral forces on TVC component against TVC component functionality was plotted as shown in figure 14. For γ=0%, the lateral forces on plates were increased against increasing blockage. This was due to the gas flow, with increased blockage, exerts pressure downward on TVC component. For γ=10%, the lateral forces were increased from σ=10% to σ=20%. Further up to σ=30%, the forces were reduced as significant direct gas leakage was occurred through clearance. This was due to the vortices generated below TVC component reducing lateral direction effect of the force. For case7, highest magnitude of lateral force was observed as flow was undeflected up to TVC component's position. This retained axial thrust which then was

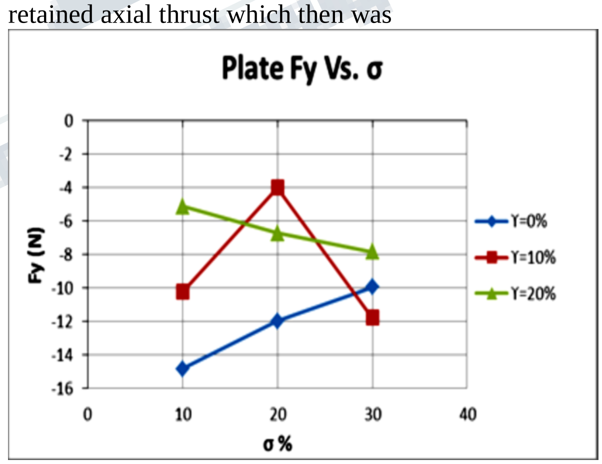

Figure 14: Lateral (Y directional) gas loads on Plate (TVC component) Vs. Blockage Ratio

responsible to exert lateral thrust when flow came in sudden contact with TVC component downstream. The forces show decreasing trend due to direct gas leakage and reduced magnitudes of axial thrust.

Thrust Vectoring Straight line mechanisms: The Scott-Russell exact straight line mechanism can be used for thrust vectoring. An actuator powers the

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linkages which are attached to an Annulus plate as a TVC component. In similar manner, bell crank lever mechanism can be used for thrust vectoring. In bell crank lever, the vertical plane motion of TVC annulus plate is not perfectly straight and follows a slight circular path. This is due motion of the lever about hinge. The optimized parameters can be set in mechanism and implemented in missile TVC system.

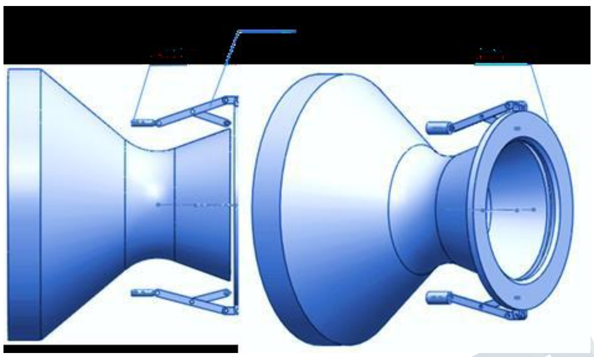

Figure 15: Exact Straight line Scott-Russell Mechanism

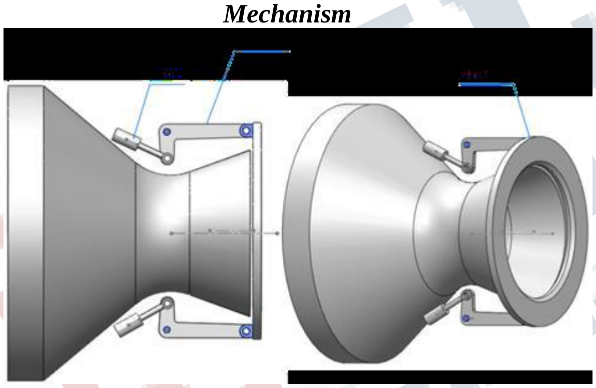

Figure 16: Approximate straight line Bell crank lever mechanism

IX. CONCLUSION

The Design, modeling and CFD analysis of thrust vector control system based on the generation of gas dynamic pressure forces on the nozzle wall is presented in this paper. The study deals with two and three dimensional hot flow tests. The two dimensional TVC model is validated with the experimental data based on nozzle wall pressure distribution. The three dimensional model is developed from the physical behaviour of two dimensional model. An alternative TVC component geometry has been suggested and analysed in place of Jet tab TVC. By adopting the Taguchi design technique, nine simulations were studied for varying TVC configurations in order to determine the optimised TVC configuration. The CFD Numerical results validated and found in good agreement with analytical results for basic nozzle case within margin of error. Grid independence tests for basic nozzle case show similar results.

Cases 5 and 6 i.e. gap 10% with 20% and 30% nozzle exit section blockage are the most relevant configurations. For other cases, thrust vectoring efficiencies and effectiveness are ineffective. To achieve thrust vectoring using suggested and analysed TVC component, two straight line mechanisms viz. Scott-Russell Mechanism and Bell Crank Lever mechanism were suggested.

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Nomenclature

h-	Annulus plate and nozzle axis offset
δ-	Gap (Clearance between TVC Component and Nozzle Exit
Re-	Nozzle Exit Radius
$\in$-	Expansion Ratio
$\propto$d-	Nozzle Divergence Angle
Ac-	Cross Sectional Area
γ-	Gap(clearance) Ratio between Nozzle Exit and annulus plate
σ-	Blockage Ratio
V_R-	Resultant Area Weighted Velocity
C-D	Convergent Divergent Nozzle