9th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2017-053**
20-22 September 2017 - METU, Ankara TURKEY

ANALYSIS, DESIGN AND TEST OF A JET VANE BASED THRUST VECTOR CONTROL FOR TACTICAL MISSILES

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ABSTRACT

Extensive maneuverability on a tactical missile with the aspect of intercepting in a short range or acquiring targets in 360° space can be achieved in various methods. One way to do that is jet vane based thrust vector control (TVC).In this study, a performance analysis of TVC includes multiple jet vanes has been conducted by means of determining the optimum CFD approach, creating a suitable mechanical design and experimenting on test stand with capability of multi axis force measurement. This analysis comprises solely the lift generation performance of the design. A 3D steady-state RANS solver with k-ω *turbulence model proposes around 9% error compared to static firing. Additionally, realizable* k-ε *and Transition SST and Spalart-Allmaras turbulence models also included for comparison.*

INTRODUCTION

TVC is a way of missile orientation adjustment in 3-dimensional space that uses the generated nozzle flow which enables a considerable improvement on flying capabilities of the air vehicle. Various TVC methods have been in service for decades and in this study, the applications that are valid for missile systems are covered. Further information about the physics on thrust generation and TVC phenomenon, also their related area of utilizations can be found in reference section [Schaefermeyer, 2011] [Babu and Prasad, 2012] [Simmons, 2000]. Classification of TVC applications with respect to nozzle types is presented in Figure 1 and for this study the jet vane based TVC is considered.

TVC based on jet vanes is highly effective and easily adapted solution for an air defense missile as it aims to find and eliminate even low altitude and rapid inbound missiles. TVC is quite efficient way to maneuver at subsonic speed during initial launch sequence since the force generated by TVC provides enough moment around the center of gravity and this force is enough to make a vertical launched missile turn to horizontal direction. This phenomenon is another successful outcome for being free of positioning the missile launch vehicle to the direction of incoming target as this action contains substantial time penalties [Facciano et al., 2002]. Figure 2 shows an example of countermeasure missile deployment against targets and expresses the importance of response time. Regardless of the launch platform, the flight

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trajectory with absence of TVC demonstrates altitude gaining response to threat whilst a 3 axis TVC is a better solution for a low altitude cruise missile. Because of this fact, a 3 axis TVC based on jet vanes is examined for this study since almost all aspects of the system can be either computed or experimented and it can be easily manufactured, a clear indication of a quick rise on technological readiness level. It has to be stated that the descent on effectiveness of jet vanes when flight mach number increases and the complete ineffectiveness of them after engine burnout are the greatest disadvantage of jet vane based TVC configuration. [Riddle, 2007] Despite the disadvantage, packaging and cost of this configuration makes it a valuable solution for TVC.

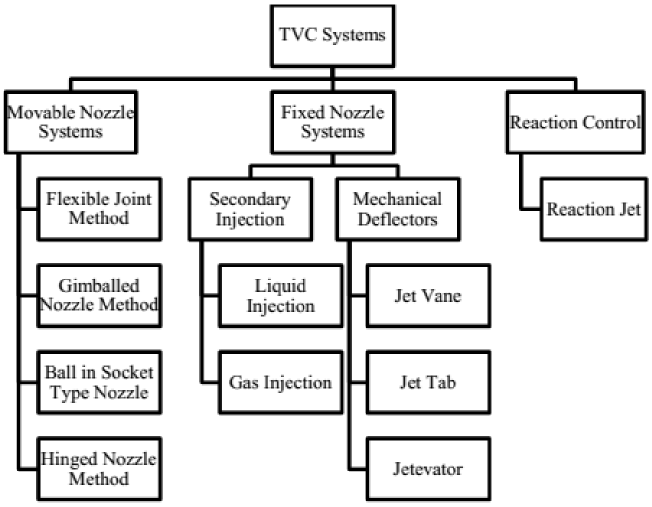


Figure 1: TVC applications with respect to nozzle types [Çelik, 2014]

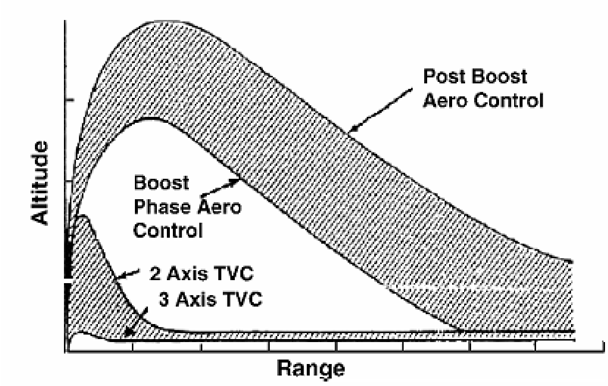


Figure 2: Vertical launch trajectories against low-altitude targets[Facciano et al., 2002]

Design and validation process of jet vane comprises 4 main stages: CFD analysis to explore the converging solution space, carrying out an applicable and producible mechanical design, a thermo-mechanical analysis to investigate the forces and heat applied onto prototype and a static firing to validate this prototype. In the scope of this study, a jet vane design effort has been performed by conducting CFD analysis with Reynolds averaged Navier-Stokes (RANS) solver with k-ω turbulence model to acquire the lift forces against various angle of attack (AoA). Additionally, three commonly used turbulence models; realizable k-ε and transition SST and Spalart-Allmaras will be run to find out which one is more suitable for examining the domain. The design effort continued to attain a viable test procedure with a multi axis for measurement test stand as prototype testing is prone to encounter error. In the end, computational and experimental results are compared to work on improvements of design process.

EXPERIMENTAL ANALYSIS OF TVC

Mechanical Design Phase

Computational design process of a jet vane based TVC is conducted by optimizing the geometry for certain requirements where the mechanical design process is constructed upon it. The optimized geometry is aimed to be the least weighted one that meets the lift and drag forces to be matched certain values at predetermined angle of attack. At mechanical design phase, the aerodynamic surface output from this CFD analysis has to become solid considering all mechanical interfaces, heat load from the missile nozzle and required forces in order to generate pitch and yaw moments.

CFD analysis provided the basic dimensions of the aerodynamic surface and its position backwards of the nozzle. The primary outputs of the design shows a symmetric diamond and trapezoid shape which is already expected as minimum drag generating one. A general view of aerodynamic surface is given on Figure 3.

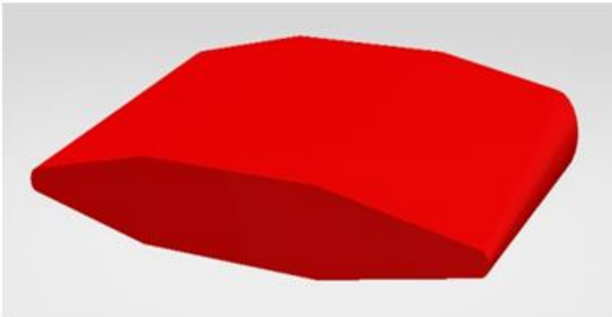


Figure 3: Aerodynamic geometry of jet vanes

Jet vane based TVC is positioned at the rear of missile therefore, the major issue is the heat generated by the propellant. It is obvious that a material which is able to sustain its mechanical strength and has satisfactorily little amount of ablation against heat is required. For this matter, an alloy of a refractory metal has been selected via material characterization tests. This alloy is not enough to protect compounds behind it since there are delicate electronics and mechanisms. A refractory material formed as base for aerodynamic geometry and a phenolic based insulation which has great conductive heat transfer moderation characteristic has to be applied to design. Pressure and heat loads are considered to appoint the number of fasteners however; the main issue is heat infiltration through the radial direction. An example of TVC includes multiple jet vanes, insulation and connection element to the shroud of the missile has been presented in Figure 4 [Murty M. S. R. C. &Chakraborty D., 2015].

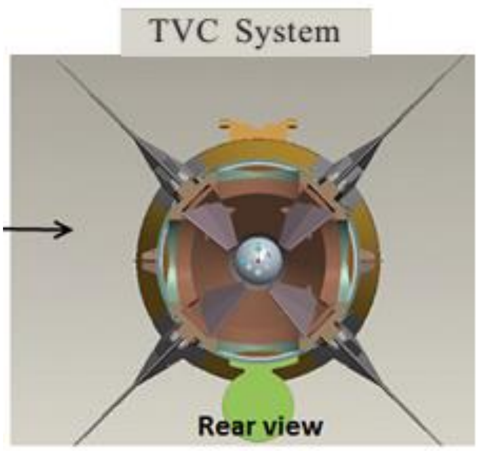
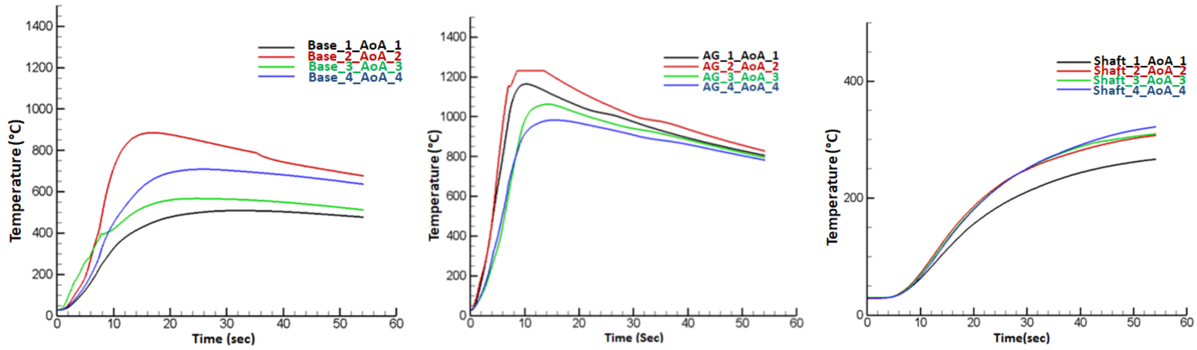


Figure 4: Jet vane based TVC from the rear[Murty M. S. R. C. &Chakraborty D., 2015]

Selected materials and connection types are assembled to form a solid base of design in order to validate it on preliminary test runs. It is obvious that most likely failure mode will be caused by the heat transfer from the exhaust to the assembly therefore; temperature gathering from multiple locations is conducted on these tests. In Figure 5, three component of the assembly is dedicated to this task in order to find out temperature distribution along individuals and between them. It is expected that the temperature gathering will provide more accurate values than the CFD results due to surface ablation where heat transfer mechanisms significantly deters which is found in a study with a refractory material [Rainville et. al., 2004].



(a) **(b)** **(c)**

Figure 5: (a) Temperature distribution for four TVC on base
(b) Temperature distribution for four TVC on aerodynamic geometry
(c)Temperature distribution for four TVC on shaft

The stated tests are conducted several times for the performance on different AoA however; the refractory material that is used for aerodynamic geometry has shown poor confidence with base's material. This material difference creates an unequal thermal expansion on joint between these two and TVCs on different location in consecutive test runs have been break off from the joint. Even though, the thermo-mechanical analysis is improved via collected data, the result falls far behind what the test result presents. Most likely reason is neither the surface ablation of the vanes nor thermal interactions of components can be modeled because of the physical difficulties on the phenomenon. The studies on that field shows extensive works, therefore it is determined as impractical to apply on design [Yu et. al., 2004] [Harrisson et. al., 2003] [Nunn, 1988] [Dulke, 1987] The result of thermo-mechanical analysis that given in Figure 6 shows the joint between these two component transfers the load directly onto bolts and leads to a bolt failure; on the other hand this case did not happen in reality.

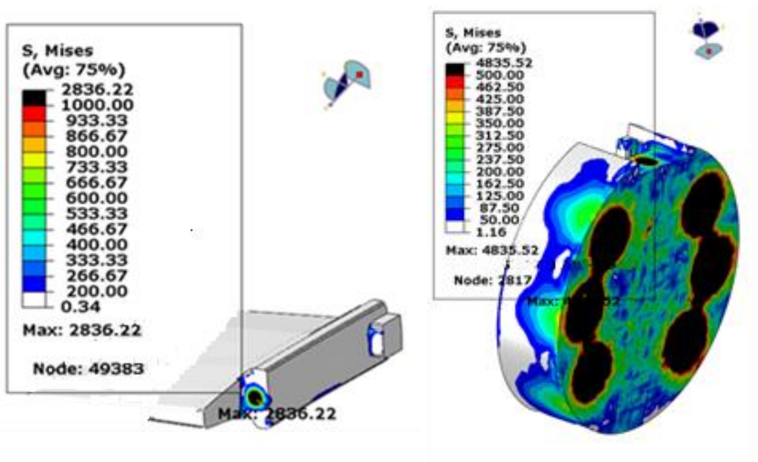


Figure 6: Preliminary thermo-mechanical analysis on jet vane and its base

To prevent failure during the service time of TVC, the joint between aerodynamic geometry and base has to be removed. In order to be in the safe side, the material for a joint component is selected as base's material since the mechanical strength of it is significantly higher in greater temperature. Additionally, the temperature increment on aerodynamic geometry originated by nozzle exhaust is approximately 400°C higher than the base even the measurement points on these components are 4 millimeters apart. Thus, the material reselection should also help to reduce the maximum temperature on TVC.

As a result of this action, preliminary CFD and thermo-mechanical analysis are conducted again and re-designed geometry with stated refractory material presents greater safety factor comparing to previous design approach as it can be seen on Figure 7. It is determined that the preliminary design phase is satisfactory to continue with multi-axis test stand to acquire lift force generation performance of TVC.

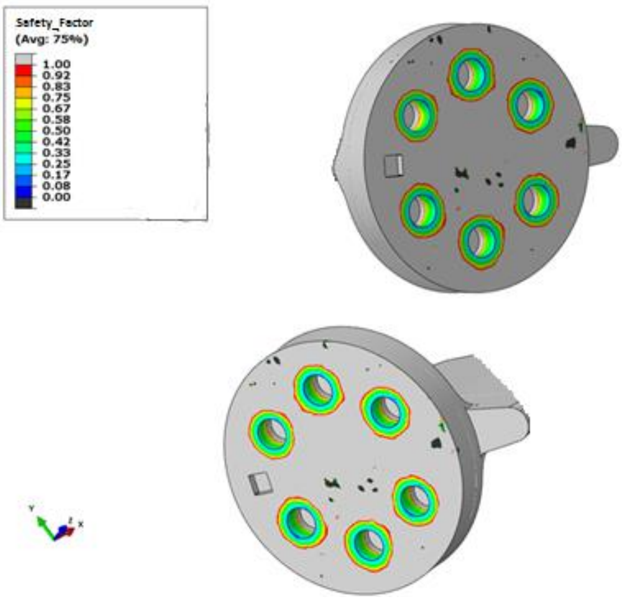


Figure 7: Conclusive thermo-mechanical analysis on jet vane

Multi-axis Force Measuring Test Stand Phase

A multiple jet vane TVC design requires multi axis force measuring test stand which means thrust and both side forces can be detected simultaneously. Success criterion of the jet vanes is determined by the proportional representation of generated forces to missile thrust and proper positioning of measuring instruments is absolutely essential.

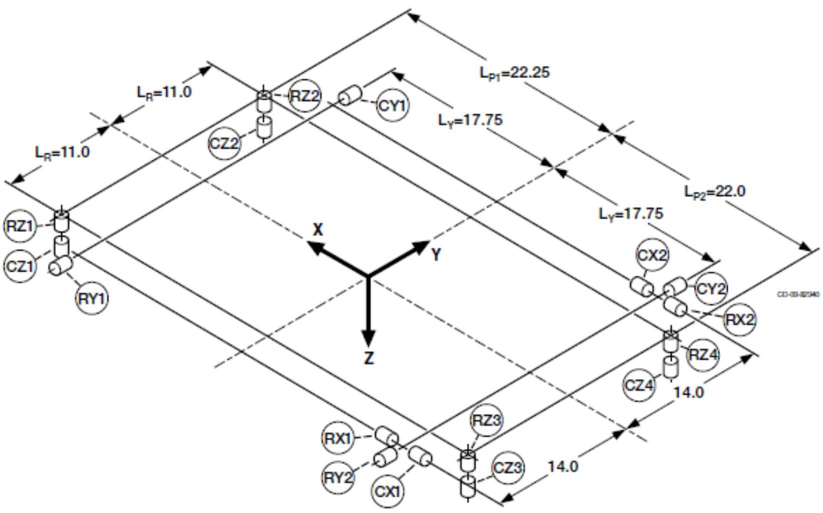


Figure 8: Multi-axis force measurement test stand schematic of NASA [Wong K. C., 2003]

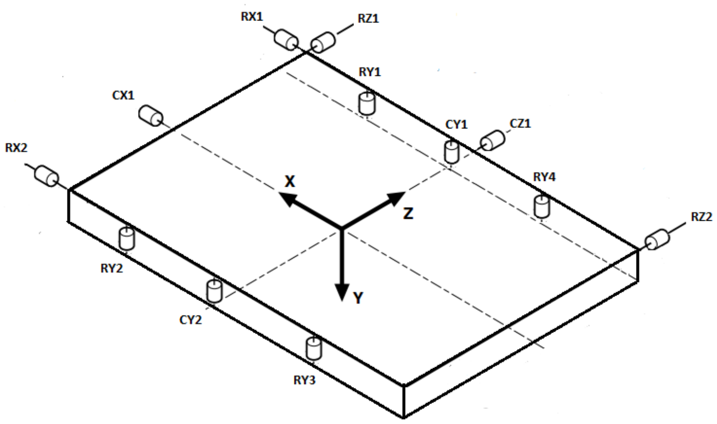


Figure 9: Multi-axis force measurement test stand schematic of this study

Figure 8presents a 6 DoF force measuring test stand if the need is finding all forces and moments, additionally Figure 9 presents this study's test stand which can accommodate applied forces only. While the engine is coupled by four jet vane based TVCs, a test stand that should be placed onto the platform and that should measure forces on all axis has to be designed. The platform can be used for other engine's captive firing purposes and the test stand should be compact to dislocate it easily. Therefore, the test stand has two mechanical components that one will serve as a base for it and the other is the moveable part which is suspended on top of the base by load cells. This allows the component to be freely in action either on one hypothetical surface with all axes or on all axes with pitch, yaw and roll moment. These types of approach can be defined as 3 DoF and 6 DoF for a test stand respectively. 6 DoF test stands which can be simplified to become a 3 DoF stands are presented in Reference Section by means of its design aspects and calibration methodology for further information [Wong K. C., 2003] [Miloš et. al., 2015] [Ankeney and Woods, 1963]. In this study, the applicable features of them are considered.

It can be seen in Figure 8(b) that the test stand has calibration load cells to ensure the proper accuracy before every test cycle. Load cells on each axis are positioned to single surface to avoid misjudging the tension-compression state of them. Calibration load cells are the ideal force generators in order to calculate a calibration matrix and proportional error of measuring load cells. The calibration matrix is a mathematical representation of the interaction between known forces and measuring load cells [Wong K. C., 2003]. This representation is defined as the inverse matrix of the slopes which they are found by examination of all axes to each axis. For example in Eq. (1); c_{11},c_{12} andc_{13} describe the effect of known force in x direction on measuring load cells in x, y and z direction respectively. Similar analogy can be made for the rest of axes. This calibration matrix is then used to correct the measured forces on the actual test in order to have pure down-axis forces which will provide the thrust and lift. The calibration matrix also gives the inside knowledge on how much measuring error the test stand contains.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} R_{x_1} + R_{x_2} \\ R_{y_1} + R_{y_2} + R_{y_3} + R_{y_5} \\ R_{z_1} + R_{z_2} \end{bmatrix} \tag{1}$$

Validation of a test stand is required to have the knowledge about the inaccuracy of readings as the objective reading should be well above the error margin so that the measurement can be meaningful. Nonetheless, the validation process can be conducted by various approaches where there is not any standard; commonly, analysis on hysteresis, non-linearity and repeatability is enough to determine the accuracy. [The Institute of Measurement and Control, 2013] Hysteresis, non-linearity and repeatability is aimed to be calculated as literature suggested, additionally a single inaccuracy value for test stand has to be settled. For this matter, RSS methodology is adopted as mentioned error parameters are not correlated. Thus Eq. 2 is used to get the result with considering all axes and both compression and tension states (total number of 5 states).

$$RSS_{test\ stand} = \sqrt{(Hysteresis)^2 + (Non-linearity)^2 + (Repeatability)^2} \quad (2)$$

As a missile engine testing includes explosive materials, the calibration procedures can not be conducted with the actual testing subject. Therefore couple differences in measurement will be occurred and have to be corrected. The three important aspects are the test stand-base static firings thrust difference which will contribute to the side forces, misalignment of test subject with test stand which will generate undesired side force and misalignment of thrust vector due to imperfect production of nozzle contour. These error sources are taken into account with 3-dimensional force vector discretization.

The data acquisition and signal processing are another important phases of testing; even the test stand calibrated, validated and corrected properly, the acquisition and post-processing can be definitive parameters to examine readings accurately. Therefore a portable DAQ component with high resolution, high sampling rate and high sensitivity rate is used which is IMC Chronos CRFX-400 and it is compatible with the load cells that are used on test stand.

The noise canceling is required due to test engine behavior on the test stand where there is considerable vibrations affecting load cells. The DAQ component's sampling frequency and rate is identical to load cell output which ensures the signal has one peak frequency to be found by FFT in amplitude spectrum. FFT is known as a solid approach to noisy signal by transforming the data to frequency domain which enables to examine it properly [McAmis, 1991] [Brimhall et. al., 2008].The filter design has considerable effort in data reduction process since captive firing contains important data such as ablation of insulation material creates sudden pressure increment or a multiple stage engine has a transition sequence which generates pressure increment due to deliberate stage separation. As a result of this, an accurate filtering has desired upmost, therefore a 4th order Runge-Kutta Method for a second order filtering has been chosen. The reason behind this logic is the amount of collected data that has to be filtered. Higher order Runge-Kutta methodology is found to be effective in forward-backward filtering in 3-dimensional space or enormous data set. [Murray and Storkey, 2011]

Experimental Readings in Static Firing

The results in experimental approach on jet vane based TVC design is presented here starting with calibration process and collected data set of side forces on static firing. The calibration matrix is presented below and the significant aspect is its close proximity to an identity matrix since it is a clear identification of freedom between axes.

$$[M_c] = \begin{bmatrix} 1{,}00598 & -0{,}00194 & -0{,}00638 \\ -0{,}00253 & 1{,}00207 & 0{,}00280 \\ -0{,}00523 & -0{,}00022 & 1{,}00204 \end{bmatrix}$$

To investigate how well the calibration procedure change the raw data into calibrated data and the proximity of calibration load cell force and calibrated data, Figure 10 and Figure 11 is plotted. Here, the calibration procedure made the test stand output to measured force error 0.15% on average and competitively similar between actual force applied and the calibrated data.

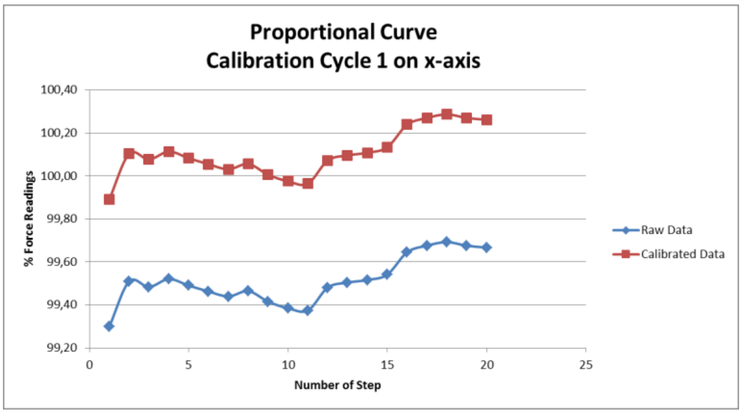


Figure 10: Comparison of raw and calibrated data on x-axis calibration

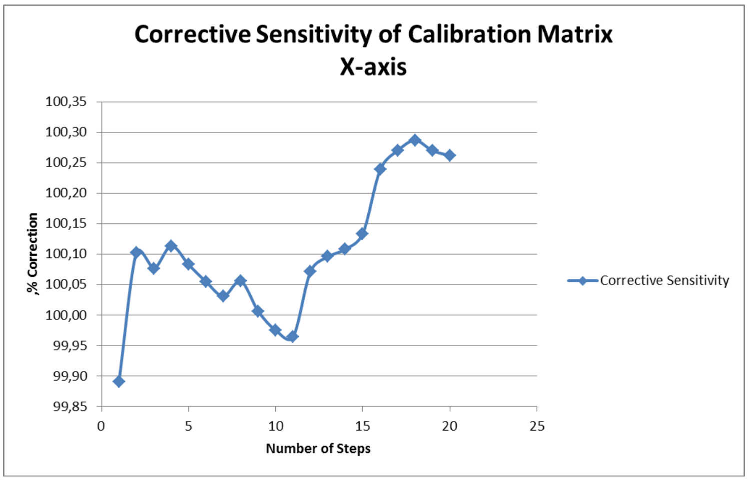


Figure 11: Corrective sensitivity on x-axis with comparison of actual and calibrated data

The validation of test stand is conducted by stated approach and the inaccuracy level is determined as 0.5%. The calculated parameters are presented in Table 1, here the significant values are found in non-linearity and repeatability which is deduced as the test stand holds great inertia that generates proportionally increased reaction force on load cells.

Table 1: Inaccuracy parameters and total inaccuracy level of test stand in proportional state

State	Hysteresis (%)	Non-linearity (%)	Repeatability (%)	RSS at States (%)	Total Inaccuracy (%)
X-axis	0,01958	0,13140	0,13140	0,18686	0,38059
Y-axis in compression	0,07849	0,09564	0,05863	0,13692	
Y-axis in tension	0,04226	0,02391	0,11408	0,12398	
Z-axis in compression	0,01985	0,26404	0,03831	0,26754	
Z-axis in tension	0,05428	0,01670	0,03185	0,06511	

Corrective factor on each axis is computed as these values are necessary to get the relation between the test engine and test stand. In Table 2, As it is stated earlier, the first column represent the ultimate difference created by test stand under test engine firing alone condition, the second column represent the centerline misalignment of test engine with the aspect of moment and force deviation and the third column represents the thrust misalignment of test engine that caused by the imperfection of nozzle manufacturing. The total amount of correction factor on x-axis is negligible since the value is under 5 N and it has not been shown in Table 2. The values for y and z-axis have been used to reduce the error amount in test scenario of TVC as an error filtering methodology.

Table 2: Corrective factors for forces on y and z axes in amount of error

Corrective Factor	**Test Stand (N)**	**Centerline Misalignment (N)**	**Thrust Misalignment (N)**	**Total**
Y-axis at max	13,32027	25,35519	19,88094	38,42437
Y-axis at min	12,72836	24,24935	19,01386	37,89557
Z-axis at max	21,98956	24,97548	48,14915	74,60249
Z-axis at min	20,16577	24,70125	46,04919	74,05210

By determined Runge-Kutta technique, the raw data that collected by DAQ instrument is filtered with the least valuable data loss as both can be seen in Figure 12. The data is gathered on y-axis which also measures the gravitational change by the burnout fuel; thus the reading does not end with zero lift force as it should be. This data is intentionally chosen to indicate how much measurement noise has been introduced in captive firing and the validity of the noise removal application as the consumed fuel weight is precisely known by the manufacturing quality assurance procedures. The axis labels and quantities are hidden due to privacy considerations. Figure 13 is separately given in order to show the match quality of stated jet vane deflection scenario and it presents that despite the level positions of the jet vanes are found as descending if the repositioning of them takes less than 0.1 seconds; the valuable lift output requires more than this duration for a tactical missiles, therefore the difference is neglected.

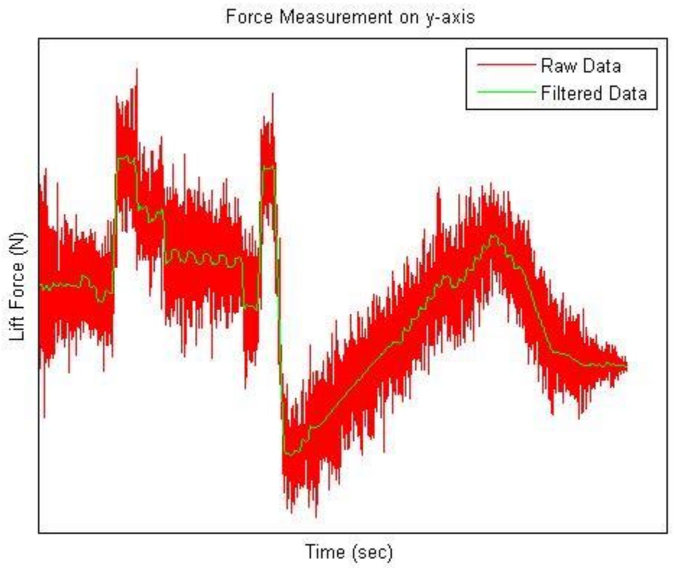


Figure 12: Noise filtering with 4th order Runge-Kutta Method

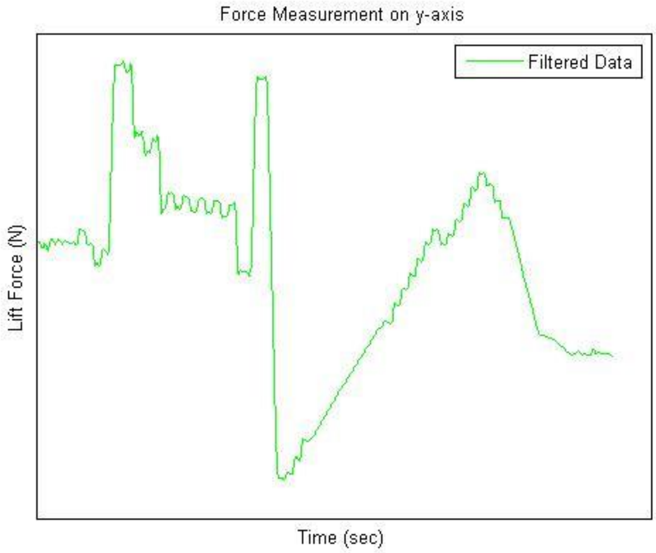


Figure 13: Filtered data of y-axis

As the filtering data is given here to demonstrate the capability of filtering methodology, the test scenario also has to be presented here. The test scenario of 4 jet vane based TVC coupled with engine is presented in Figure 14. TVC is positioned in (+) formation at rear section which enables direct lift force measurements by related axes. As an example, the pitch maneuver is generated by horizontal jet vanes which will be measured by gravitational y-axis. The half of the total value will present the single vane lift force output. As it can be seen clearly, the scenario investigates numerous AoA which is essential to get a performance analysis. There are three important findings will be acquired with the test as the effect of ablation on lift generation, response time of the vanes which is the actual lift force generation after command and of course the lift forces versus AoA.

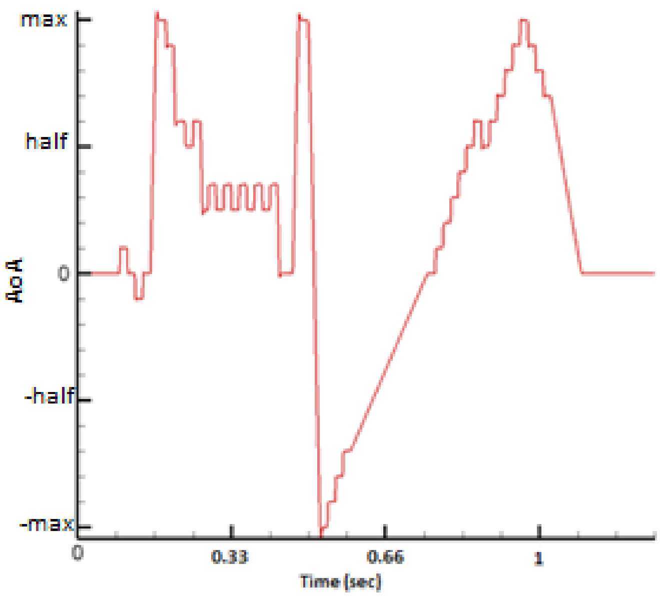


Figure 14: Test scenario of the study

According to test procedure that has been stated in this chapter has been conducted and lift force on y and z axes has been found as in Figure 15. Ideally, these two axes have to present identical outputs and trend shall be matched with predetermined test scenario. As it is also stated that the error amount on axes are below 100 N due to applied calibration and corrective procedures therefore readings are valid to deduce.

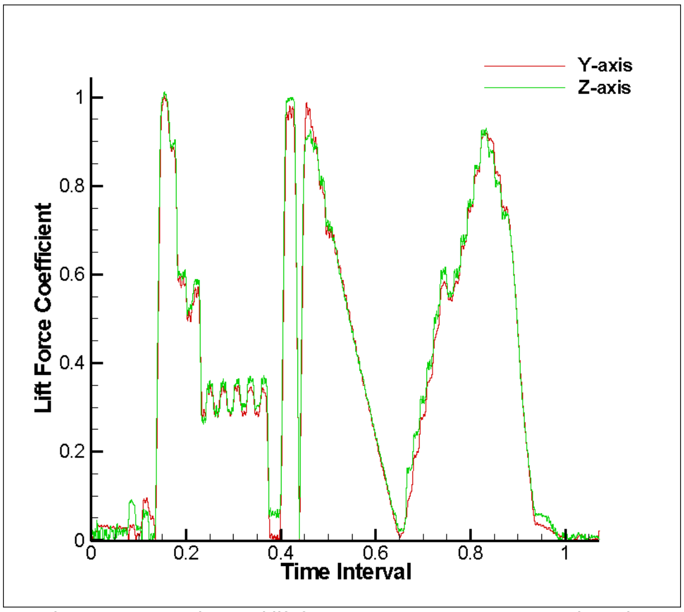


Figure 15: Experimental lift force measurements on y and z axis

Figure 14 shows both y and z axis thrust proportioned lift forces as a coefficient since the amount of percentage is hidden due to privacy concerns. Additionally, the negative angles are reversed to compare the generated lift force with the rest. Overall, the trust stand provided coherent readings on both axes, though there are minor differences.

Around time interval of 0.1, there are inconsistency with lift forces which is caused by the inaccuracy of the load cells for too low measurement demand. As it can be seen in calibration corrective sensitivity, the maximum error amount is generated by the test stand is here at the lowest measures. Additionally, the intended lift force is quite lower too. As an example, the maximum lift force is over 10 times larger and it is the minimum calibration level for the test stand. Clearly, the methodology presented in this chapter misses the lower levels of lift force and misjudging the amount of error leading to considerable percentage of difference between axes. Therefore, it is concluded as there is a minimum lift generation measurement limit.

Over time interval 0.2, the surface ablation provides losses on lift forces as the maximum variation can be seen on maximum angle lift force between 0.85 and 0.5 time interval. The operational time interval jet vane based TVC is lower than 0.85, by the time the aerodynamic wings placed outer surface of the missile is in effect. The valuable information is how much lift force loss is occurred due to this effect and it is around 10%

Considerable difference between y and z axis can be seen around 0.5 time interval which can be explained by the implementation of fuel consumption rate assumption. On that particular time burn rate of the fuel can be different from the ideal case; even the generated lift forces are equal between both axes, error on summation of the fuel consumption onto y-axis will cause such an effect.

To add up, the multi-axis test stand trials provides valuable inside knowledge on lift forces for various AoA, therefore it is found to be comparable with a CFD effort aiming to have solid method to analyze geometries without conducting test.

3-D FLOW ANALYSIS OVER JET VANE

Conditions of 3-D flow analysis have to be carefully chosen to get the accurate solutions. Boundaries of the mesh grid includes engine, nozzle, TVC and far field which is specified for the mounting interfaces and beyond. Both engine interior and jet vane assigned with no slip wall boundary condition. Pressure inlet and pressure outlet boundary conditions have been utilized. Pressure profile of the inlet has been acquired via chemical solver NASA CEA while outlet pressure value has been obtained using standard atmosphere conditions. [McBride & Gordon, 1996]Boundary layermesh uses 5 layers near wall with the growth ratio of 1.1 and first layer thickness of 1 mm to keep y+ in the range of 1 to 5. All the wetted surfaces have inflation layer to properly calculate flow inside boundary layer for turbulence models that does not use wall function. 3 different grid is generated with mostly tetrahedral elements whose numbers are ranging from 0.7 million to 3 million. Figure16 shows the generated mesh (1.4 million elements)with looking through the nozzle in section view. Interfaces on the shroud are hidden for a better view.

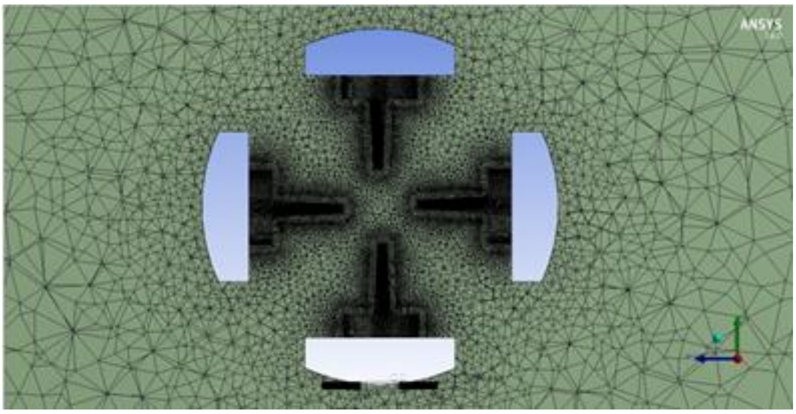


Figure 16: Generated mesh grid for multi-vane TVC

3D steady-state RANS calculation has been found suitable and performed at different angles of attack with different turbulence models such as Spalart-Allmaras, realizable k-e, standard k-w and transition SST with varying grid quality and starting with the lowest quality mesh. Standard wall function has been employed for Spalart-Allmaras and realizable k-e models. Results have been summarized in Table 3 below.

Table 3: Turbulence model performance on low quality mesh

Low Quality Mesh (0.7m)		
	Angle of Attack	**Error (%)**
K-Epsilon	x	4,71
	2x	5,54
	4x	19,52
K-Omega	x	2,62
	2x	6,60
	4x	18,92
Transition-SST	x	2,59
	2x	6,84
	4x	18,63
Spalart-Allmaras	x	3,52
	2x	6,28
	4x	18,90

As can be seen from the summarized results, largest error has been obtained at the maximal angle of attack value as expected. Next step is generating better quality solution grid with 1.4 million elements to evaluate grid dependency, however this time only the highest angle of attack value is utilized for all turbulence models in order to save time and resources. Results of medium quality mesh are shown in Table 4.

Table 4: Turbulence model performance on mid quality mesh

Mid Quality Mesh (1.4m)		
	Angle of Attack	**Error (%)**
K-Epsilon	4x	11,34
K-Omega	4x	10,84
Transition-SST	4x	10,61
Spalart-Allmaras	4x	11,95

Transition-SST model obtained the most accurate result however, it differs from result of k-omega by only %0,2. Knowing, transition-SST is a 4 equation and k-w is a 2 equation model, it is obvious that transition-SST converges slower than the k-w model. The accuracy difference is thought to be affordable compared to shortened 2 hours convergence time. Thus k-omega has model has been selected as the turbulence model for remaining iterations.

A better quality mesh is created again for the mesh dependency study however, this time only k-w turbulence model has been used at the maximal angle of attack which resulted in %2 improvement in terms of accuracy while analysis time is increased by 85 hours which is a result of memory shortage. For this reason medium quality mesh (1.4m) has been evaluated as satisfactory.

Highly compressible, supersonic flow expected in the nozzle therefore density based solver has been chosen along with the implicit approach to increase stability of the calculations. All of the transport equations solved and density interpolation performed with first order upwind scheme also for stability reasons. AUSM flux function is used since it offers high levels of robustness and accuracy.

Velocity Distribution and pathlines of the flow have been given in Figure 17 and 18. TVC effects on velocity distribution can be seen in the crossplane view which has been taken from 10 centimeters and 40 centimeters downstream of the vanes.

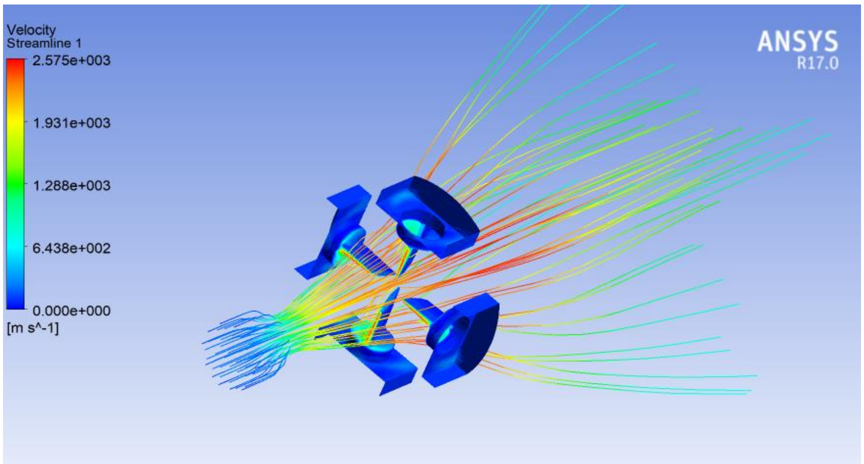
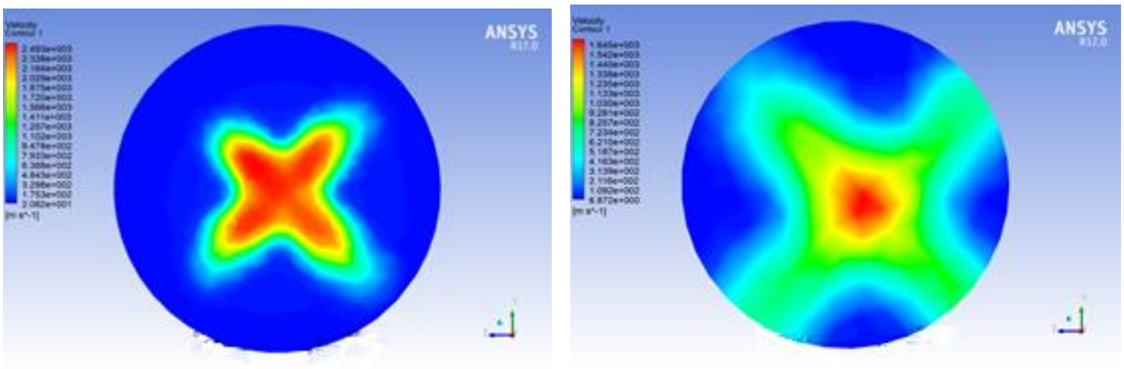


Figure 17: Streamlines on flow field



(a) **(b)**

Figure 18: Velocity distribution at 10 cm downstream (a) and 40 cm downstream (b)

CONCLUSION

A novel jet vane based TVC design including mechanical design phase, computational analysis phase and testing phase has been conducted to acquire the best possible option for turbulence model and mesh quality for such task. For a conclusive review of the findings on this matter, Figure 19 is plotted. The test measurement and k-omega turbulence model with 1.4M mesh elements CFD result show approximately 10% amount of error at maximum AoA with desirable amount of computational cost. To investigate the entire scenario with specified CFD approach, steady state analysis for each AoA on scenario is applied. At an interval around 0.3, 0.5 and 0.85 provides the most significant variance on comparison as 11%, 7% and 10% error which has an average close to 9%. That amount of error is considered as acceptable start point of a design.

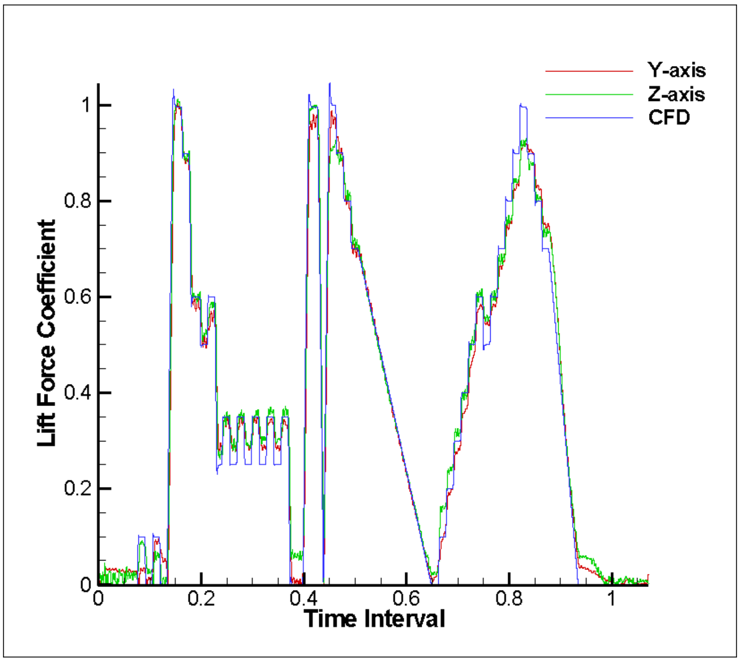


Figure 19: Lift force coefficient for test measurements and CFD result

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