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Research Article

The effects of different wing configurations on missile aerodynamics

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ABSTRACT

In the present study, missile aerodynamic analysis is performed using different wing configurations at subsonic and transonic speeds. The wing is critical component in point of aerodynamic efficiency for a missile that speed is especially closer to transonic level because of flow separation. Flow on the wings may adversely effect tailfins of missile at high speed since it may cause vortex generation and flow disturbances. There are few studies that investigate the missile wing using different configurations at critical speeds when examined the previous studies. Therefore, in this study, three different wing configurations are investigated and aerodynamic performance is compared with each other at 0.7 and 0.9 Mach numbers and 5° angle of attack (AoA). In beginning of this study, missile model with only tailfins is selected from previous study that contains experimental data. Because the experimental data for the selected missile model are available at supersonic speeds, the aerodynamic analysis to verify the solutions is carried out at supersonic speeds. After wing is mounted to the selected missile, aerodynamic analysis is carried out using three different wing configurations that are Tapered Leading Edge, Tapered Trailing Edge, and Double Tapered wings. Lift to drag ratio (C_L/C_D) is calculated to compare wing configurations and it is concluded that Tapered Leading Edge wing configuration shows higher performance then other wing configurations. C_L/C_D values are 2.327, 2.306, 2.303 at 0.7 Mach number and 2.45, 2.429, 2.423 at 0.9 Mach number for Tapered Leading Edge, Tapered Trailing Edge, and Double Tapered, respectively. When the results are compared each other, C_L/C_D values at 0.9 Mach number is higher about % 5.28, %5.33 and %5.21 than the C_L/C_D values at 0.7 Mach number for missile with Tapered Leading Edge, Tapered Trailing Edge, and Double Tapered, respectively.

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INTRODUCTION

In the defense industry, missiles and rockets technologies are continuously developed by the engineers. Energy saving is an important issue for all industries and it can be possible to achieve by increasing the efficiency. Therefore, missile internal and external parts have been investigated and improved to increase efficiency or reduce cost etc. External parts of the missiles are especially crucial in

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terms of aerodynamic performance. Thus, design of missile canard, wing and tailfin are critical issue to determine lift to drag ratio which specifies the aerodynamic performance.

The analysis of a missile aerodynamic is crucial assignment to design external geometry. The aerodynamic analysis is costly and its require time. Therefore, some simulation and computation programs are used to perform aerodynamic analysis. In addition, wind tunnel test is implemented to predict flight performance accurately. In order to validate and verify, wind tunnel data and simulation or software package program results are compared. The lift, drag and moment coefficients are most important parameters to evaluate the performance of missile. The following paragraphs are mentioned about previous studies related with missile aerodynamics.

The study was proposed for missile aerodynamic prediction by Teo [1]. The aerodynamic data was obtained from wind tunnel test and the validation process was performed using missile DATCOM. It was concluded that the skin friction and axial force coefficients values were good agreement with experimental data. Similar study was also presented by Sooy and Schmidt [2]. In this study, Missile DATCOM (97) and Aeroprediction 98 (AP98) were used to predict aerodynamic coefficients. The paper was proposed to observe missile DATCOM accuracy at high angles of attacks by Abney and McDaniel [3]. The results of study were showed that the longitudinal center of pressure location and normal force value were good agreements with experimental data at high angle of attacks and subsonic speeds. Lesieutre et al. [4] improved code to predict the missile aerodynamic coefficients. The code was tested at NASA Langley Research Center and it was observed that the improved code gave reasonable results when compared experimental data. The prediction of aerodynamic coefficients was performed for a standard spinning projectile using Navier-Stokes flow solver at subsonic and supersonic speeds by Silton [5]. Smith [6] performed solution of projectile aerodynamics using two Euler solutions at supersonic speed. Finite Volume Method (FVM) and Method of Characteristic (MoC) were used. It was concluded that the FVM showed the shock waves and vortices that occurs the nose while vortices and expansion region was not observed for solution MoC. The CFD analysis related with missile aerodynamics was performed by Khanolkar et al. [7]. The results of this study were compared with experimental data and it was concluded that CFD simulation and real cases were reasonably good agreements.

The experimental study was carried out for observation canard shape effects on aerodynamic performance by Guy et al. [8]. The study was performed at 0.5 Mach number and the efficiency evaluated according to pitching moments. The prediction of adverse rolling moment was performed to control missile canard by McDaniel et al. [9]. The code that predicts aerodynamic coefficients was used to decide rolling moment effects at subsonic and supersonic speeds. Li et al. [10] carried out wind tunnel test, the CFD simulation and MATLAB/Simulink to solve aerodynamics of the tailfin projectile. Karman-Tsien rule was utilized to convert air compressibility into 0.6 Mach data. Honkanen et al. [11] performed wind tunnel test for a missile with split-canard to observe aerodynamic characteristic and CFD simulation was then carried out to compare the results at different AoA and subsonic flow. The non-standard AGARD-B missile model was tested in the wind tunnel by Vidanović et al. [12]. In this study, validation process was firstly carried out using CFD simulation and experimental data results for AGARD-B missile model with generic nose configuration. The solution was then performed for the non-generic nose and comparison was observed that the nose shape geometry effects on aerodynamics of selected missile model were very small while the change of pitching moment coefficient was noticeable. The other study was presented to reduce aerodynamic drag using Reynolds averaged Navier-Stokes (RANS) and Euler equations by Ageev and Pavlenko [13]. It was concluded that aerodynamic drag coefficients were reduced about 20% by improving the front part of Sears-Haack body. Yin et al. [14] studied to estimate spin deformation of missile and its aerodynamic characteristics using the unsteady Reynolds-averaged Navier Stokes equations (URANS). Li et al. [15] proposed variable sweep wing missile by simulation aerodynamic analysis and showed whether the variable sweep wing missile was convenient or not for different flight conditions. The similar study using concept of variable sweep wing missile was also presented to observe aerodynamic performance for supersonic flow by Yi et al. [16].

Vidanović et al. [17] proposed related with Multidisciplinary design optimization (MDO) for external missile configuration. Drag and lift coefficients were predicted at supersonic flow and different AoA. CFD solution and experimental study were performed for N1G test model and AGARD-B model. Another aerodynamic analysis and optimization study was proposed by Ryan [18] for morphing guided unpowered projectiles. It was showed that the optimized model ensured more range when compared with baseline model. In addition, Vidanović et al. [19] performed shape optimization of missile fin and investigated aerodynamically heated structure. The purpose of this study was to show differences aerodynamic analysis with thermal effect and without thermal effect. Şumnu and Güzelbey [20] presented a study to find optimum geometry of missile wing by using Multi-Objective Genetic Algorithm. The results were observed that aerodynamic performance of optimum shape of missile was higher than base model. The optimization of control surface size of a long range projectile was performed by using multi-objective Particle Swarm Optimization Algorithm to increase aerodynamic performance at subsonic and supersonic flow regime by Vasile et al. [21].

In this study, we would like to investigate different wing configurations, which have not been commonly studied in the literature, to observe how to affect the aerodynamic performance at subsonic and transonic speeds for selected missile. Therefore, three different wing configurations are

Figure 1. Dimensions of selected missile model (all dimensions mm) [17].

formed and aerodynamic analysis results are compared to decide which one is convenient and show superior aerodynamic performance. In addition, the aerodynamic solution is performed at supersonic speed to decide whether the wing is efficient or not for high speed.

MATERIAL AND METHOD

Missile Geometry and Mesh Generation

In this section, missile model and mounted wing geometry are described. The selected missile model dimensions and mounted wing geometry are given in Figure 1 and Figure 2, respectively. The dimensions of wing for three configurations are given in Table 1. In this study, solid model of missile geometry is drawn using ANSYS (17.2 version) in Designmodeler. Cylindrical computational fluid domain is also generated around the missile body to analyze the flow field. The radius of cylinder computational domain is seven times of the missile body length. In addition, the length of the domain is ten missile body lengths. Figure 3 shows the computational fluid domain for the missile.

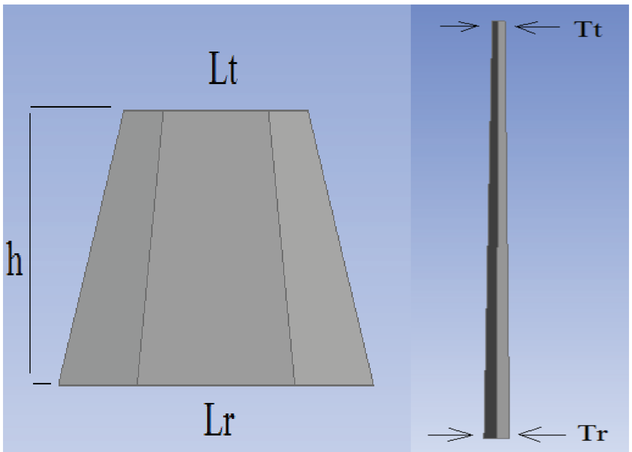

Figure 2. Geometry of wing

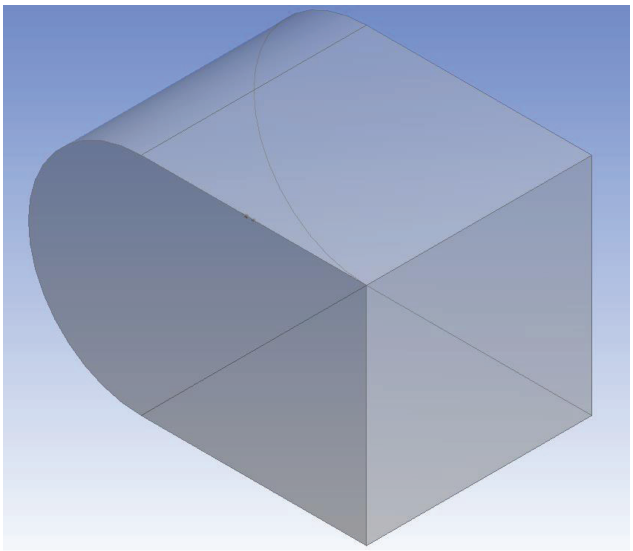

Figure 3. Computational fluid domain

Table 1. Dimensions of Wing Configurations

Parameters (mm)	Tapered Leading Edge	Tapered Trailing Edge	Double Tapered Edge
h (height of wing)	70	70	70
Lr (Root length of wing)	120	120	120
Lt (Tip length of wing)	90	90	70
Tt (Tip thickness)	1,5	1,5	1,5
Tr (Root thickness)	3	3	3

Missile wing model is formed three different types and mounted to selected missile body. Tapered Leading edge wings, Tapered Trailing edge wings and Double Tapered wings are presented in Figure 4, Figure 5 and Figure 6, respectively.

Mesh generation is crucial issue to obtain accurate results. Therefore, hybrid mesh construction is formed around missile body and computational fluid domain. Mesh generation is carried out using ANSYS (17.2 version) Mesh. In order to capture flow field sufficiently around missile body, wings and tailfins, hexahedral mesh is formed. Tetrahedral mesh construction is also formed for the remaining part of computational domain. The selection of this mesh type was proven in previous study of Şumnu et al. [22] by comparing experimental values. It was showed that CFD solution results were quite closer to experimental results. Therefore, the mesh type selection is convenient to find reasonable results. Mesh generation for whole missile body and around the missile wing are showed in Figure 7 and Figure 8, respectively. After the mesh generation processes, mesh independency studies performed to find sufficient mesh element number. This is important issue in terms of solution time and obtaining accurate results. Therefore, the analysis is carried out between 550000 and 4 million mesh elements. The efficient mesh element number is then found as 2836796. Mesh independency chart is presented in Figure 9.

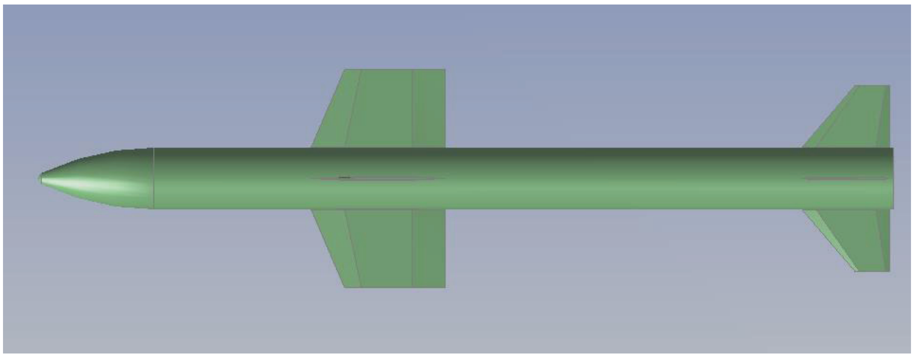

Figure 4. Tapered leading edge wings

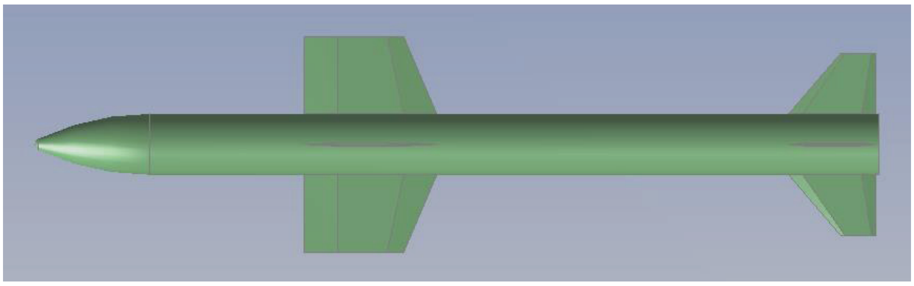

Figure 5. Tapered trailing edge wings

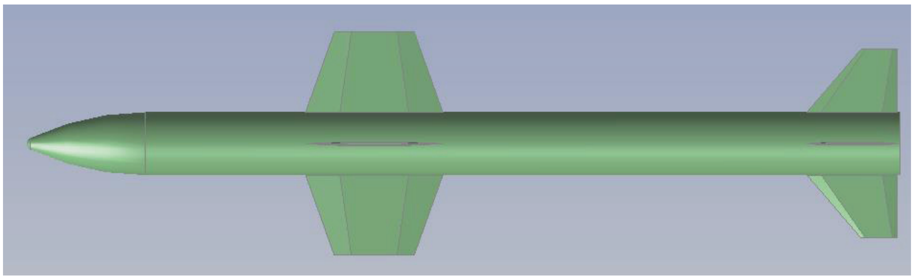

Figure 6. Double tapered wings

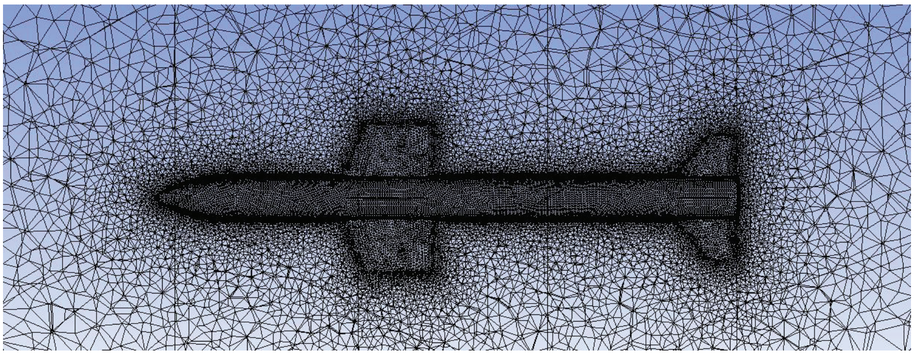

Figure 7. Mesh generations for missile body

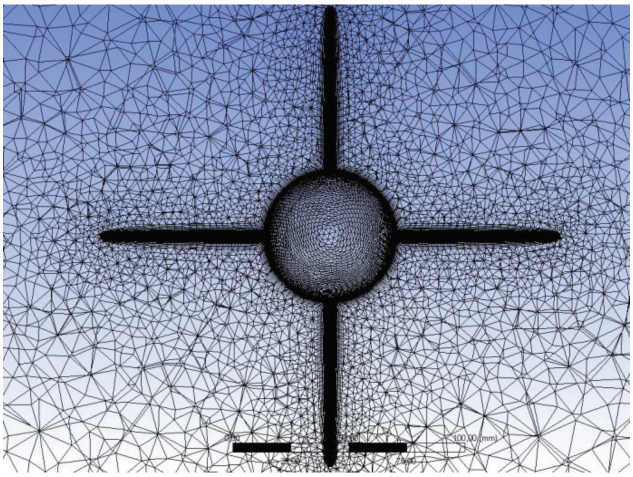

Figure 8. Mesh generations around the missile wing

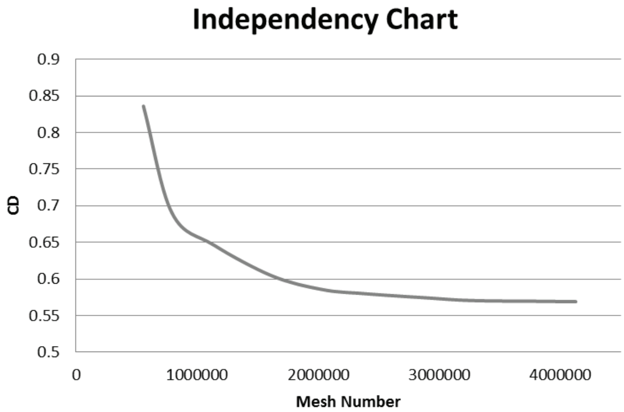

Figure 9. Mesh independency chart

CFD Analysis

The CFD analysis of missile geometry is performed using ANSYS (17.2 version) Fluent software which uses finite volume method. Reynolds average Navier-Stokes equations (RANS) are utilized to solve problem. In this study, implicit, steady and density-based solver is used to solve the flow field. Turbulence model is selected as SST-k-ω including both k-w and k-e turbulence models since this turbulence model is appropriate to simulate flow of air that occurs around missile body, wings and tailfins and gives quite accurate results. This model simulates the complex flow in the inner and outer regions of boundary layer by using k-w model and standard k-e model [23]. SST k-w turbulence model gives accurate results near the wall and in case of circulation and separation because of use both k-w and standard k-e models. The study of Vidanović et al. [12] that is related with missile aerodynamics was showed that use of SST k-w model gives accurate results.

In addition, CFD solution was performed to validate and compare whether the selected turbulence model gives acceptable results or not. Therefore, experimental results reported the study of Vidanović et al. [17] is compared with CFD results [22] and it was observed that the selected turbulence model gives reasonable results with the experimental study.

For the solution method, Green-Gauss cell based that is discretization model is used since it gives reasonable results for second order finite volume method. The convergence of solution is decided by investigating two criteria. These are flow residuals and the change of aerodynamic coefficient during the solutions. The computation run is finished when the flow residuals are 10^{-5} and the change of aerodynamic coefficients value is less than 1% during 100 iterations.

The governing equations of continuity, momentum and energy are given following equations [24].

$$\frac{\partial}{\partial t}\vec{U} + \frac{\partial}{\partial x}\vec{F} + \frac{\partial}{\partial y}\vec{G} + \frac{\partial}{\partial y}\vec{H} = 0 \tag{1}$$

$$\vec{U} = \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{Bmatrix} \tag{2}$$

$$\vec{F} = \begin{Bmatrix} \rho u \\ \rho u^2 + p - \tau_{xx} \\ \rho v u - \tau_{xy} \\ \rho w u - \tau_{xz} \\ \rho u E + p u - q_x - u\tau_{xx} - v\tau_{xy} - w\tau_{xz} \end{Bmatrix} \tag{3}$$

$$\vec{G} = \begin{Bmatrix} \rho v \\ \rho u v - \tau_{yx} \\ \rho v^2 + p - \tau_{yy} \\ \rho w v - \tau_{yz} \\ \rho v E + p v - q_y - u\tau_{yx} - v\tau_{yy} - w\tau_{yz} \end{Bmatrix} \tag{4}$$

$$\vec{H} = \begin{Bmatrix} \rho w \\ \rho u w - \tau_{zx} \\ \rho v w - \tau_{zy} \\ \rho w^2 + p - \tau_{zz} \\ \rho w E + p w - q_z - u\tau_{zx} - v\tau_{zy} - w\tau_{zz} \end{Bmatrix} \tag{5}$$

The flux terms are $\bar{F}$, $\bar{G}$ and $\bar{H}$. $\bar{U}$ is the solution vector due to the fact that the elements in $\bar{U}$ (ρ, ρu, ρv, ρw, ρE) are dependent variables. Heat flux vector is q. Density, total energy and pressure are symbolized r, E and p, respectively.

RESULTS AND DISCUSSION

The supersonic missiles have generally only tailfins since wing and canard cause flow separation, vortex in high flow speed. Therefore, wing and canard may be decrease the aerodynamic performance for supersonic missile. However, in subsonic speed, missile wing provides advantages due to fact that it can increase lift and provide stability. Thus, wing can be mounted to subsonic missiles and increase the lift to drag ratio.

In this study, selected missile model has only tailfin configuration and the experimental study was implemented at different supersonic speeds and angles of attack [17]. The CFD solution of selected missile model was performed to observe whether the solution method was correct or not by comparing with experimental data [22]. Different wing configurations are then mounted to missile and these are investigated and compared each other's in terms of aerodynamic performance at subsonic (0.7 Mach number) and closer to transonic (0.9 Mach number) speeds. Lift to drag ratio (C_L/C_D), which is the most important to determine the aerodynamic performance, is calculated for each wing configuration and Mach number at 5° AoA. The result of solution shows that Tapered Leading edge wing configuration indicated better performance when compared with other wing configurations. Since lower pressure area occurs on leading edge and pressure differences between front and back of the Tapered Leading edge wing, while drag coefficient reduced, lift coefficient increased. Generally, tapered wing provides advantages in point of aerodynamic performance because tip length of wing is reduce and induced drag decreases by reducing the size of wingtip vortices. Aerodynamic coefficient values (C_L, C_D) and lift to drag ratio are presented for each wing configuration and Mach number in Table 2.

Pressure contours are presented to show effect of the wing configurations at 0.7 and 0.9 Mach numbers between the Figures 10 and 15. In addition, pressure contour is presented in Figure 16 to observe missile with wing configuration how to effect at supersonic speed for 1.4 Ma. When the pressure contour figures are examined, it can be concluded that the high pressure area occurring at leading edge for Tapered Leading Edge wing configuration is lower than the other wing profiles. However, this pressure differences value is small, so, lift to drag ratio values are closer each other as seen in Table 2. These three wing configurations can be used to increase performance at subsonic speeds. However, when Figure 16 is observed, the shock waves can be easily seen. The lower pressure area occurs back of the wing which may cause higher drag forces. Thus, the missile with wing configuration may not efficient in terms of aerodynamic performance at high speed. In addition, the shock wave that occurs on wing, may adversely affect the missile tailfins due to flow separation and vortex. This is also proven by the study of Singh [25] that presented aerodynamic missile analysis at subsonic and supersonic flow regime by comparing aerodynamic drag coefficient. It was concluded that subsonic flow condition was more stable than supersonic flow for missile with wing and tailfins configuration.

Table 2. C_L and C_D values for different wing configurations.

Mach Number	Wing Configurations	CL	CD	CL/CD
0.7	Tapered Leading Edge	1.3366	0.5742	2.327
	Tapered Trailing Edge	1.3189	0.5718	2.306
	Double Tapered	1.2974	0.5633	2.303
0.9	Tapered Leading Edge	1.4203	0.5796	2.45
	Tapered Trailing Edge	1.4011	0.5768	2.429
	Double Tapered	1.378	0.5686	2.423

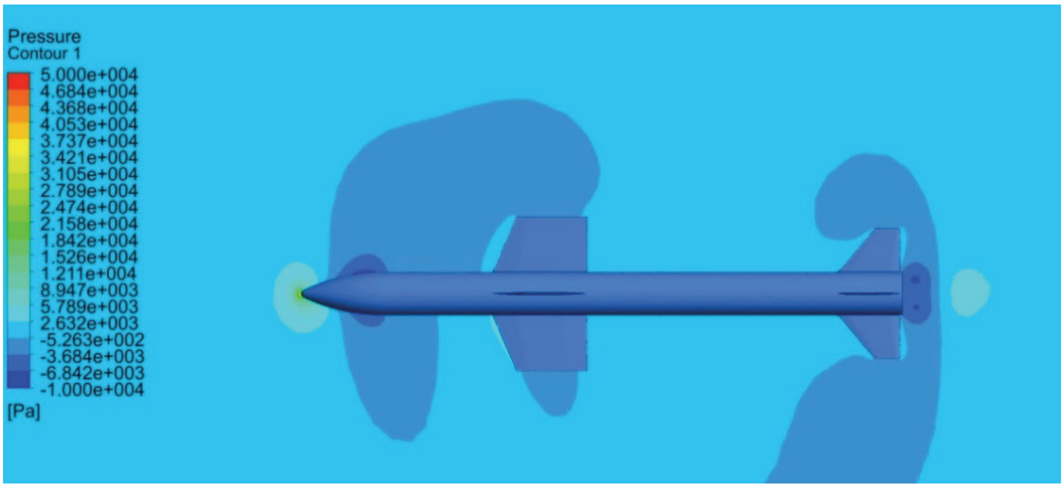

Figure 10. Pressure contour for tapered leading edge wing at 0.7 Mach Number

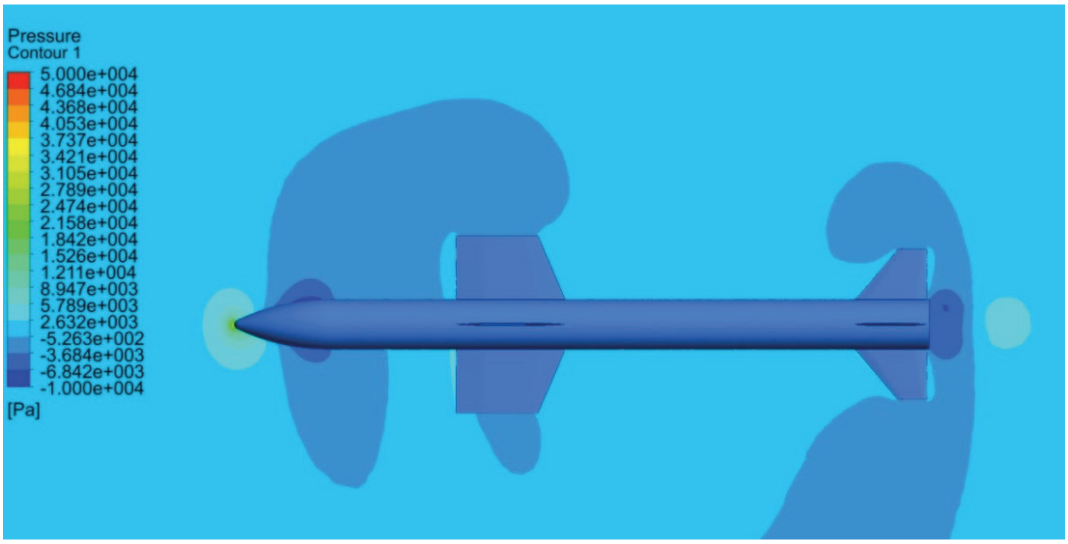

Figure 11. Pressure contour for tapered trailing edge wing at 0.7 Mach number

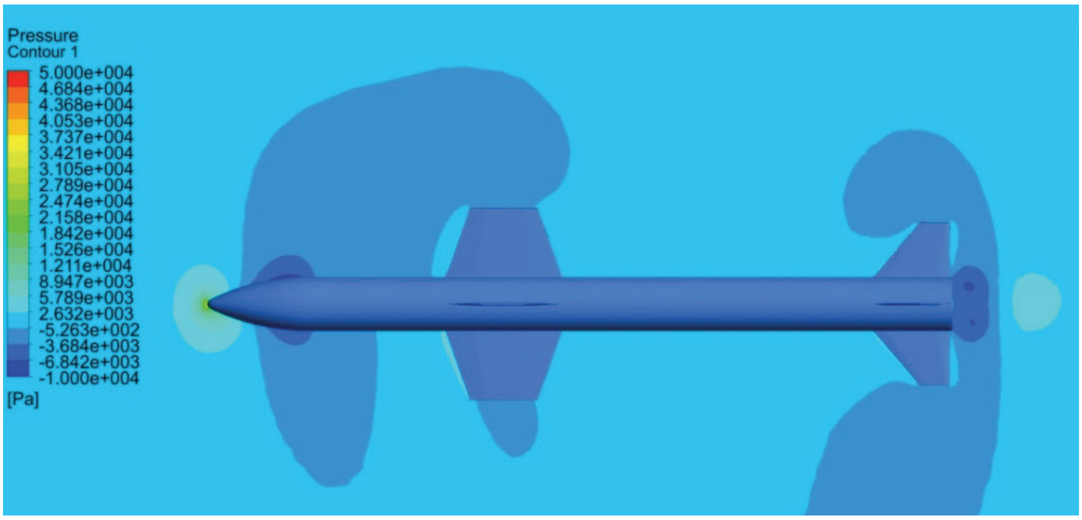

Figure 12. Pressure contour for double tapered wing at 0.7 Mach number

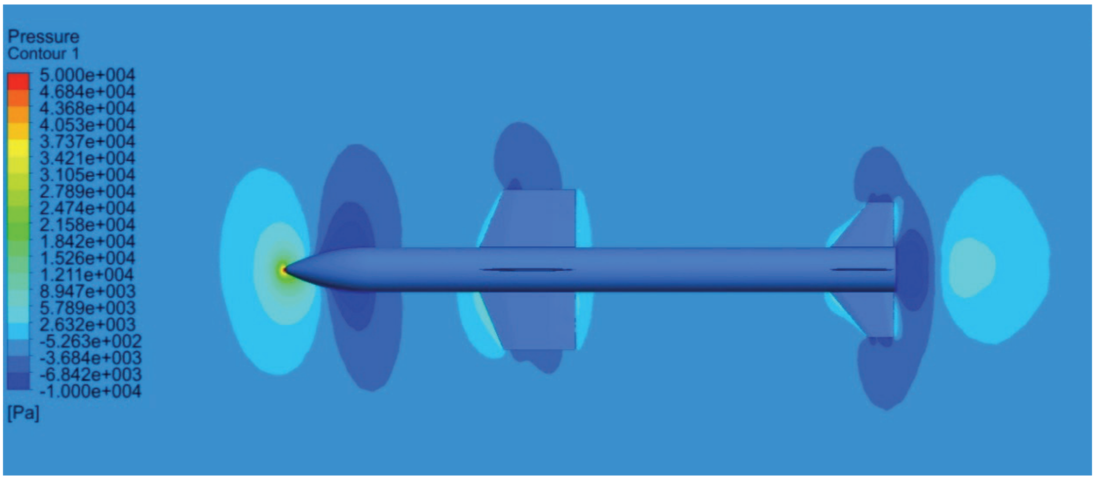

Figure 13. Pressure contour for tapered leading edge wing at 0.9 Mach number

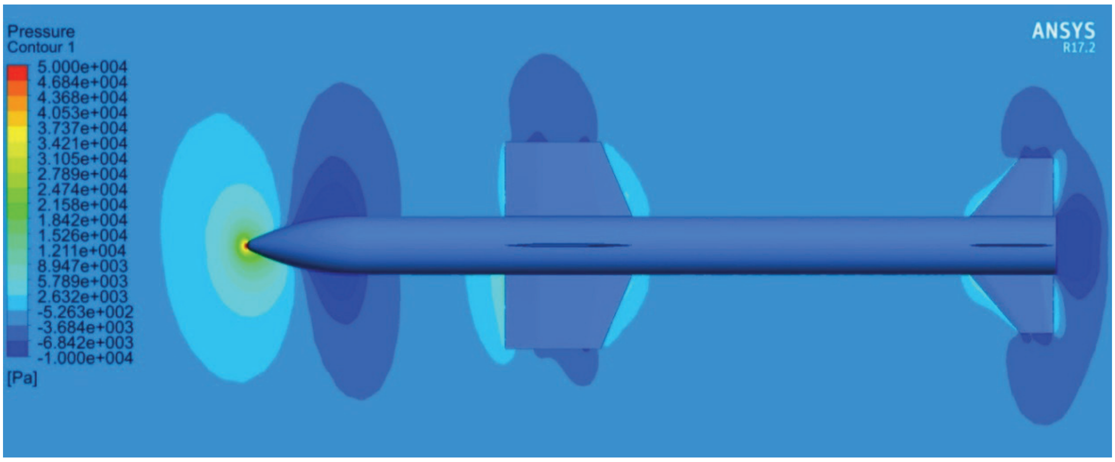

Figure 14. Pressure contour for tapered trailing edge wing at 0.9 Mach number

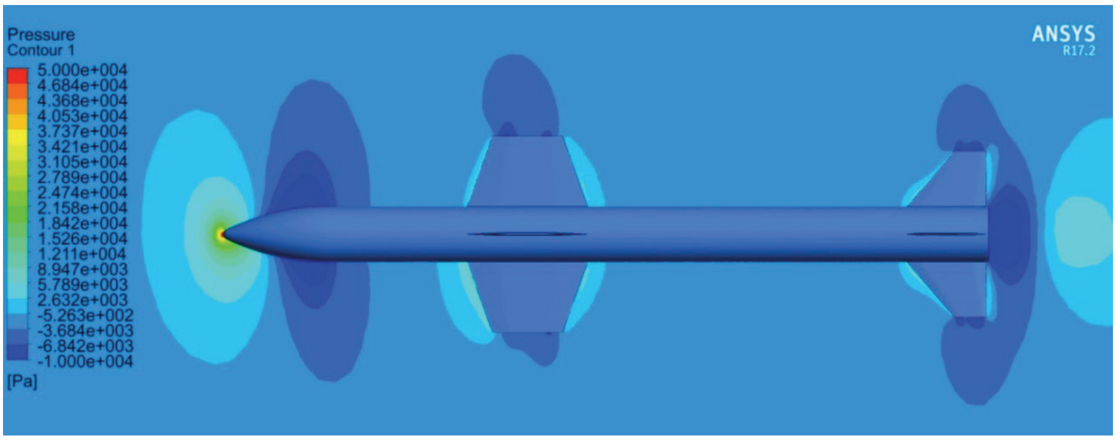

Figure 15. Pressure contour for double Tapered wing at 0.9 Mach number.

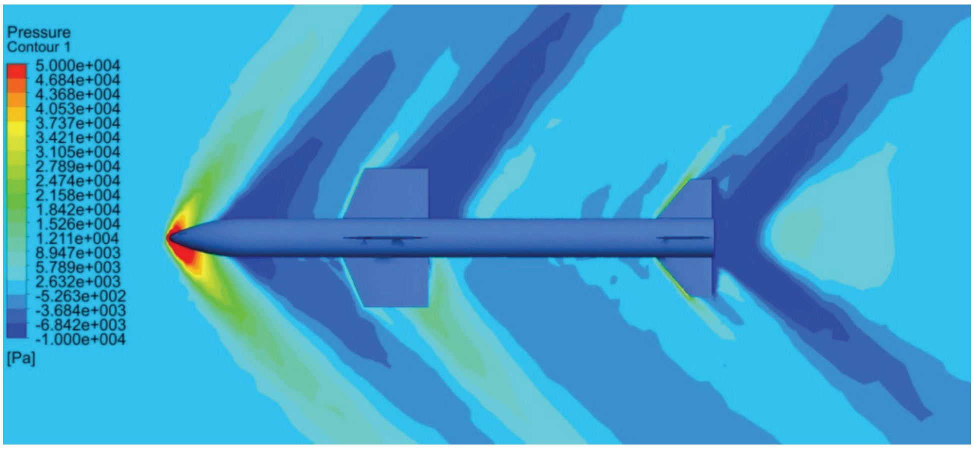

Figure 16. Pressure contour for tapered leading edge wing at 1.4 Mach number

Velocity streamline figures are presented in Figure 17 to 19 for 0.7, 0.9 and 1.4 Mach numbers, respectively. In order to show flow field occurring missile wing, the section of velocity streamline is taken from wing profile. When the Figures 17 and 18 are examined, it can be inferred that vortex occurs on missile wing but, it has very small area at 0.7 and 0.9 Mach numbers. However, when examined the Figure 19, the vortex formation and flow disorder are observed on the root of wing and missile body. This is the reason why drag coefficient increases at supersonic flow region. Moreover, the flow separation occurs due to vortices and this may be originated from pressure reduction on the rear region of wing. Hence, it can be stated that missile with wing configuration may reduce aerodynamic performance at supersonic speeds since adverse pressure gradient occurs rear region of wing and tailfin.

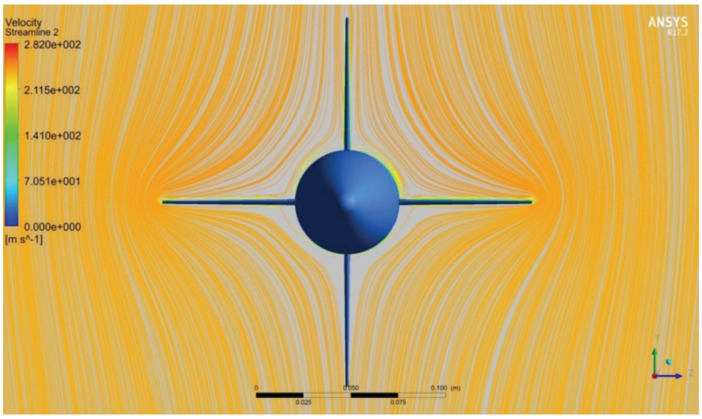

Figure 17. Velocity streamline for tapered leading edge wing at 0.7 Mach number

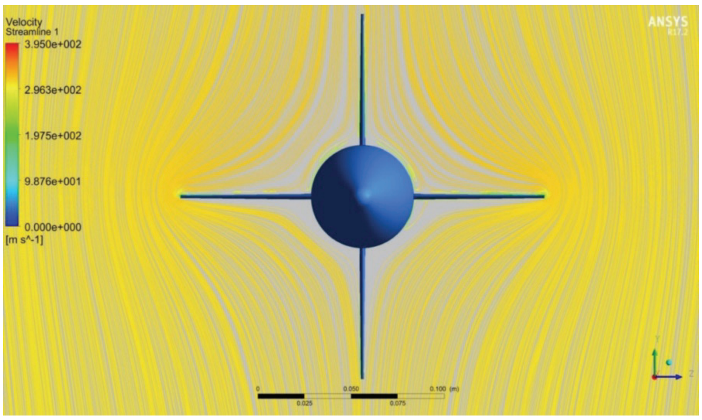

Figure 18. Velocity streamline for tapered leading edge wing at 0.9 Mach number

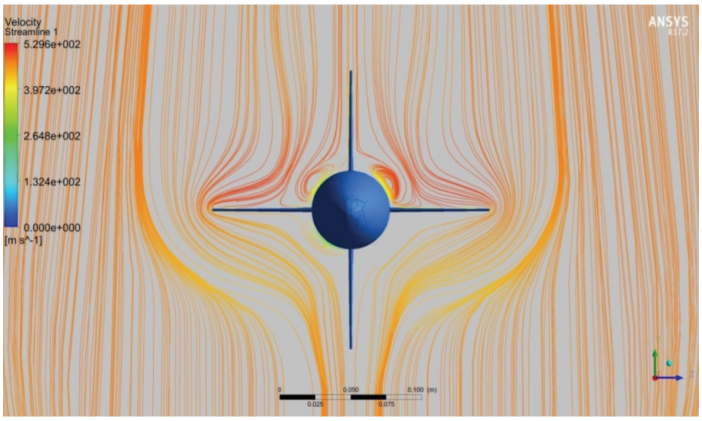

Figure 19. Velocity streamline for tapered leading edge wing at 1.4 Mach number.

CONCLUSION

In this study, different missile wing configurations were investigated to observe how to affect missile aerodynamics at subsonic (0.7 Mach number) and closer to transonic (0.9 Mach number) speeds and 5° AoA. For this aim, a missile model without wing configuration was selected from previous study which contains experimental data. The CFD solution was performed to verify and validate whether the solution method was correct or not [22]. The results of solution were good agreement with experimental results. After method was validated, the three different wing configurations were formed to mount the selected missile model and aerodynamic analysis was performed for each mounted wing configurations. The pressure contours and velocity streamline of CFD solutions were also given to show flow separation and vortices that occurs on mounted wing. Lift to drag ratio was calculated to observe which wing configuration indicated better performance. C_L/C_D values are 2.327, 2.306, 2.303 at 0.7 Mach number and 2.45, 2.429, 2.423 at 0.9 Mach number for Tapered Leading Edge, Tapered Trailing Edge, and Double Tapered, respectively. When the results are compared each other, C_L/C_D values at 0.9 Mach number is higher about % 5.28, %5.33 and %5.21 than the C_L/C_D values at 0.7 Mach number for missile with Tapered Leading Edge, Tapered Trailing Edge, and Double Tapered, respectively. It was concluded that the Tapered Leading Edge wing showed higher performance when compared the other wing configurations. In addition, supersonic flow was investigated for missile with wing configuration. When the pressure contour and velocity streamline was examined, the vortex formation and flow disorder are observed on the root of wing and missile body. This is the reason why drag coefficient increases at supersonic flow region. Moreover, the flow separation occurs due to vortices and this may be originated from pressure reduction on the rear region of wing. It was concluded that the wing configuration might not convenient at high speeds due to the vortex formation and arising adverse pressure gradient. In further work, aerodynamic shape optimization can be applied to find convenient geometry using design parameters of wing and reasonable results in point of aerodynamic performance for supersonic speeds. In this way, the negative effect of missile wing may be eliminated for high flow regime.

NOMENCLATURE

C_L	Aerodynamic lift coefficient
C_D	Aerodynamic drag coefficient
E	Total energy
$\bar{F}$	Flux term
$\bar{G}$	Flux term
$\bar{H}$	Flux term
k	Turbulent kinetic energy
Ma	Mach number
$RANS$	Reynolds average Navier Stokes
P	Pressure N/m^2
SST	Shear stress transport
e	Turbulent dissipation rate
t	Time
$\bar{U}$	Solution vector
u	Velocity in x direction, m/sec.
v	Velocity in y direction, m/sec.
w	Velocity in z direction, m/sec.
w	Specific turbulent dissipation rate

Greek symbols

r	Density of air. kg/m^3
t	Viscous stress
q	Heat flux

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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