

**CFD ANALYSIS OF SMALL CALIBER SPINNING
PROJECTILE WITH VARIETY BOATTAIL AND BASE
CONFIGURATIONS**

BY

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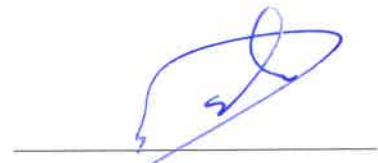


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[Dedication]

This thesis is dedicated to my family, friends, and professors who always were there and supported me throughout my education journey.

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|

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LIST OF ABBREVIATIONS AND NOMENCLATURE

NACA	National advisory committee for aeronautics	C_D	Drag coefficient
BRL	Ballistics research lab	C_{D_0}	Zero yaw drag coefficient
ARL	Army research lab	C_{D_b}	Base drag coefficient
CFD	Computational fluid dynamics	$C_{D_{\delta^2}}$	Yaw drag coefficient
CAD	Computer aided design	C_{L_α}	Nonlinear lift coefficient
RANS	Reynolds average Navier-Stokes	$C_{L_{\alpha_0}}$	Linear lift coefficient
URANS	Unsteady Reynolds average Navier-Stokes	$C_{L_{\alpha^2}}$	Cubic lift coefficient
LES	Large eddy simulation	$C_{N_{p\alpha}}$	Nonlinear magnus force coefficient
DES	Detached eddy simulation	$C_{N_{p\alpha_0}}$	Linear magnus force coefficient
DNS	Direct numerical simulation	$C_{N_{p\alpha^2}}$	Cubic magnus force coefficient
SST	Shear stress transport	C_{M_α}	Nonlinear overturning moment coefficient
WALE	Wall-adapting local eddy	$C_{M_{\alpha_0}}$	Linear overturning moment coefficient
6DoF	Six degree of freedom	$C_{M_{\alpha^2}}$	Cubic overturning moment coefficient
CP	Center of pressure	$C_{M_{p\alpha}}$	Nonlinear magnus moment coefficient
CG	Center of gravity	$C_{M_{p\alpha_0}}$	Linear magnus moment coefficient
BT	Boattail	$C_{M_{p\alpha^2}}$	Cubic magnus moment coefficient
AoA	Angle of attack	C_{l_p}	Spin Damping moment coefficient

M	Mach number	$\dot{m}_{inlet}$	Inlet mass flow rete
α_t	Total angle of attack	$\dot{m}_{outlet}$	Outlet mass flow rete
α	Angle of attack	V	Volume
β	Sideslip angle	t	Time
ρ	Air density	τ	Shear stress
v	Free stream velocity	μ	Kinematic viscosity
S	Reference area	Q	Heat
p	Spin rate	W	Work
p	Free stream pressure	f	Body force
D	Drag force	R	Gas constant
L	Lift force	c_v	Specific heat at constant volume
MAGF	Magnus force	k	Turbulent kinetic energy
OM	Overturning moment or pitching moment	ϵ	Dissipation rate
MAGM	Magnus moment	ω	Specific dissipation rate
SDM	Spin damping moment	e	Internal energy
P_B	Base pressure	T	Temperature
Re	Reynolds number	a	Sound velocity
R_T	Radius tangent ogive nose	SBC	Small base cavity
A_B	Projectile base area	LBC	Large base cavity
cal	Projectile caliber	y^+	Wall dimensionless distance

ABSTRACT

Full Name : [Hassan Khormi]
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Range extension got a great interest in the field of artillery and spinning projectiles. Reducing base drag is an effective way for rang extension, since it is the dominant component in transonic and supersonic Mach numbers. Boattailing is considered as one of the most implemented technique to reduce base drag. This work utilizes variety of passive drag reduction techniques over M33 12.95 mm projectile. Multiple design variations on projectile boattail and base are considered. This includes varying boattail angle, use of riblets, use of arced boattail, and introducing two different sizes of base cavity. Computations are conducted using computational fluid dynamics CFD using Ansys Fluent to solve RANS equations. Simulations are performed over Mach numbers from 0.6 to 2.5 and from 0° to 4° angle of attack. The aim of the simulations is to calculate most affecting aerodynamic forces and moments which include drag force, lift force, magnus force, magnus moment, overturning moment and spin damping moment. Then these coefficients are compared for all design variations. Results are validated by comparing with experimental and numerical results from the literature. Furthermore, a mesh independence study is done for verification and a value of y^+ was ensured to be less than 1. In addition, LES model was used over M33 and over riblets BT configurations at Mach 1.2. Moreover, to investigate projectile stability, coupled CFD and six degree of freedom simulation was conducted at various spin rates. It was found that every configuration has good performance at certain speed range with regard to zero yaw drag. Also, non-linearity in magnus moment was noticed for arc BT in which it is consistent with similar configuration in the literature. Moreover, In LES the estimation was found more accurate than URANS models, when comparing to experimental results.

ملخص الرسالة

الاسم الكامل: حسن محمد حسن خرمي

عنوان الرسالة: التحليل باستخدام ديناميكا الموائع الحسابية للمقذوفات الدوارة ذو العيار الصغير بأشكال مختلفة في ذيل المقذوف

التخصص: هندسة طيران وفضاء

تاريخ الدرجة العلمية: ٢٠٢٣/١٢ م |

يعتبر إطالة مدى وصول المقذوفات أحد أبرز اهتمامات الباحثين في مجال المقاذيف الدوارة وعلوم المدفعية. أحد أهم الأساليب الفعالة هي تقليل قوة السحب الناتجة من قاعدة المقذوف، حيث أنها تعتبر العنصر الغالب في فترة الطيران في السرعات الحول صوتية والفوق صوتية. ويلعب تشكيل ذيل المقذوف دوراً مهماً في تقليل قوة السحب، لاسيما الناتجة عن قاعدة وذيل المقذوف. في هذه الرسالة استخدمت عدة أساليب خاملة لإطالة مدى المقذوفات الدوارة وطبقت على المقذوف M33 ذو العيار ١٢,٩٥ مم. اختلفت التصميمات من حيث تغيير ذيل المقذوف، وتضمنت تغيير زاوية الذيل واستخدام المسننات والمنحنيات وحجمين مختلفين من التجويفات. أجريت الحسابات باستخدام ديناميكا الموائع الحسابية عن طريق حل معادلات نايفر ستوك في حالة المتوسط الزمني والمعروفة ب(RANS). أجريت المحاكاة على سرعات متعددة ابتداءً من رقم ماخ ٠,٦ وحتى ٢,٥ وزوايا هبوب بدرجات من صفر وحتى أربع درجات. تهدف المحاكاة إلى حساب قوى وعزوم ديناميكا الهواء على المقاذيف الدوارة وتتمثل في قوة السحب وقوة الرفع وقوة ماجنس وعزم الالتفاف وعزم ماجنس والعزم الموهن للدوران. بعد ذلك تمت مقارنة هذه القوى والعزوم لمختلف التصميمات. وقد تم التحقق من نتائج المحاكاة من خلال مقارنتها بالتجارب المخبرية والمحاكاة والتي أجريت في أبحاث ودراسات سابقة. وكذلك تمت بعض إجراءات التحقق في هذه الدراسة مثل تطبيق دراسة عدم اعتمادية الشبكة الحسابية. إضافة إلى ذلك استخدم نموذج اضطراب حركة الموائع لمحاكاة الدوامات الكبيرة والمعروف ب(LES) على التصميم ذو الذيل المسنن على سرعة ماخ ١,٢. وكذلك استخدمت طريقة الحسابات المدمجة بين ديناميكا الموائع الحسابية وال معادلات الحركة ذات الست درجات، وذلك لقياس تأثير ديناميكا الهواء على استقرارية المقذوف وقياس أثر الدوران. أظهرت نتائج الدراسة أن التصميمات المختلفة ساهمت في رفع أداء ديناميكا الهواء بنسب متفاوتة، تختلف باختلاف السرعة والتصميم. وأظهر نموذج اضطراب حركة الموائع لمحاكاة الدوامات الكبيرة دقة أعلى من نموذج نايفر ستوك في حالة المتوسط الزمني.

CHAPTER 1

INTRODUCTION

1.1 Background

Spinning projectiles, also known as Spin-Stabilized projectiles, is a class of ballistics that are stabilized dynamically and gyroscopically [1]. Ballistics is the science that deals with the motion of projectiles [2]. Unlike ballistic missiles that are fin stabilized, spinning projectiles are not statically stable. Types of projectiles that are categorized under spinning projectiles may include bullets and artillery shells.

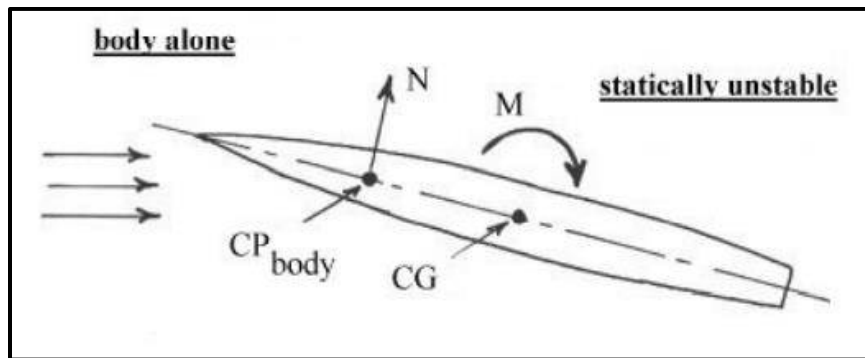


Figure 1. CP and CG locations on spin-stabilized projectile [1].

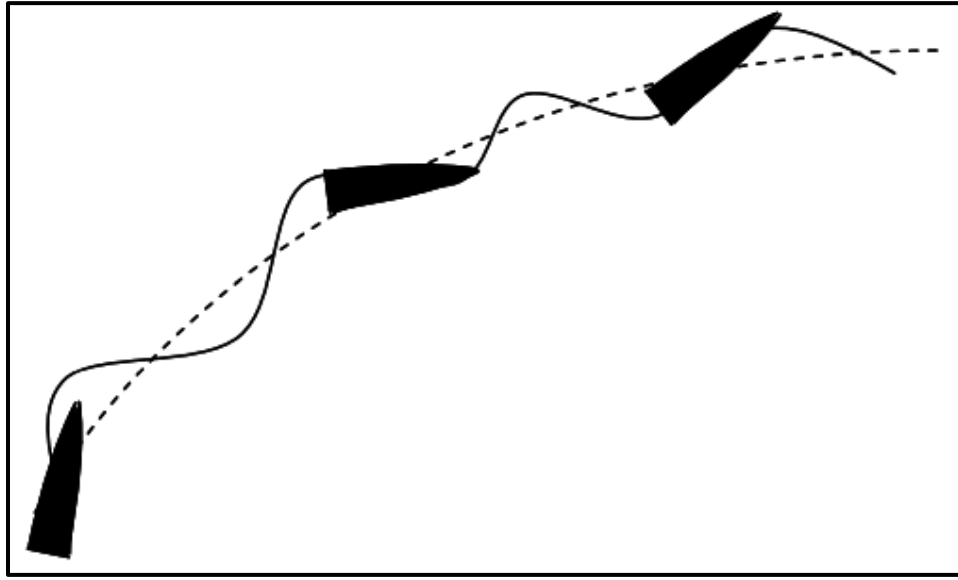


Figure 2. Projectile Trajectory and precession [1].

Ballistics are usually studied under three different phases [1, 2, 3]. First phase is interior ballistics, which concerns about the propulsion. Chemical reaction transfers kinetic energy to the projectile throughout the barrel and provides it with translational velocity and spin rate. Once projectile exits the barrel, it is studied under the phase of exterior ballistics where trajectory is considered. Projectile trajectory is affected by mass, geometry, spin rate, barrel exit velocity, and atmospheric conditions. The aim of studying projectile trajectory is to extend the range and maintain stability. Thus, the current work is an attempt to calculate the static aerodynamic coefficients that are associated with projectile range and stability for various boattail and base configurations. The third phase is the terminal ballistics. In this phase lethality, terminal velocity, and angle of impact are concerned.

Ballisticians began to improve accuracy of drag measurements since 1850 [2] . In 1917, M. Garnier published a table of projectile resistance function. Then, this table was modified by US army with extension to higher velocity in 1918 [4, 5]. Later, it was named as G1 drag function,

referring to G1 projectile reference model. More models were then proposed reaching to G8, that include other design configurations. In 1919, Fowler formulated reasonably complete aerodynamic force-moment system for spinning projectiles [2]. The resultant was an approximate analytical solution of a differential equation. By 1937, Courant and Hilbert showed a solution method of differential equation for the supersonic flow past planar and axisymmetric bodies [6]. During the second world war, exterior ballistics science experienced a great leap by the development of: a fully operational supersonic wind tunnel, free-flight spark photography ranges, and relatively high speed computer [2]. By 1980, computers had advanced to reach to a stage that permitted solving Navier-Stokes equations [7].

1.2 Aerodynamic forces and moments

NACA and BRL aeroballistics are common system in defining aerodynamic coefficients. BRL aeroballistics system will be adopted throughout the thesis [8]. In exterior ballistics, the term “yaw” indicates any angular motion of projectile symmetry axis relative to flight trajectory. On the other hand, in aircraft aerodynamics “yaw” or “sideslip” terms are used to describe the nose pointing to the left or right of the flight path, whereas “pitch” or “angle of attack” refer to the nose pointing above or below aircraft path. Expressly, yawing motion in aeroballistics describes any combined pitching and yawing motions. In addition, yaw angle is known as total angle of attack [9]. The definition of total angle of attack is given by [2, 9]:

$$\sin \alpha_t = \sqrt{(\sin \alpha \cos \beta)^2 + \sin^2 \beta} \quad 1.1$$

For ($\alpha_t < 15$ degrees), a good approximation for total angle of attack is:

$$\alpha_t \approx \sqrt{\alpha^2 + \beta^2} \quad 1.2$$

Where α and β are angle of attack and side slip angle, respectively.

1.2.1 Drag force

Direction of drag force opposes projectile forward velocity. It consists of skin friction, wave drag and base drag, which is related to this research. It is caused by low air pressure pocket that is caused by air turbulence. Drag has major effect on projectile trajectory. Studies show that spinning projectiles can travel almost twice the range in a zero drag environment, at certain muzzle velocity and firing angle, as depicted by Figure 3. Furthermore, drag force has substantial effects on impact angle and velocity [1].

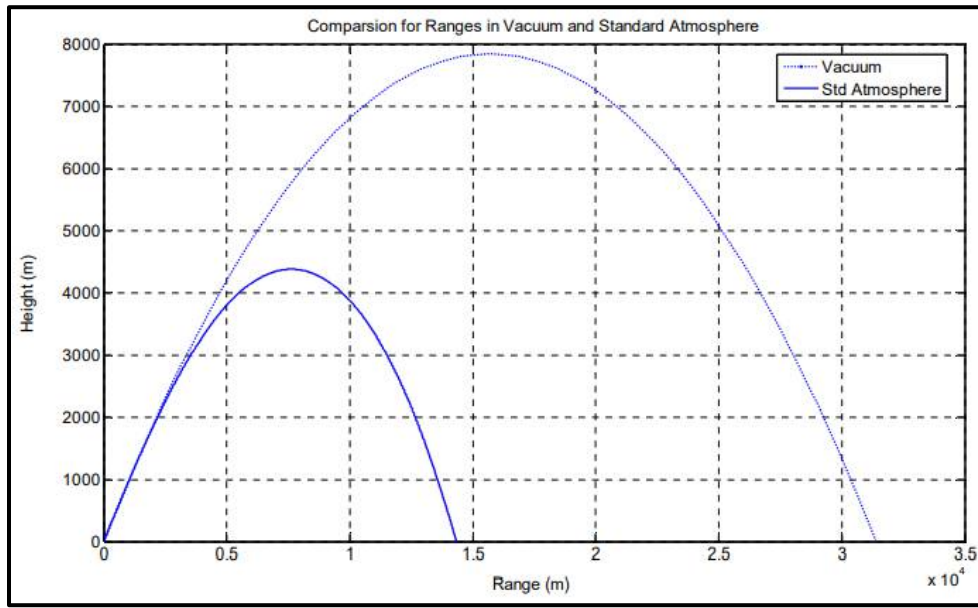


Figure 3. Range comparison between Vacuum and atmospheric firings [1].

Drag force is given by:

$$D = \frac{1}{2} \rho v^2 S C_D \quad 1.3$$

The reference area S is defined by:

$$S = \frac{\pi d^2}{4}$$

Where d is the reference diameter which is usually taken as the diameter of the cylindrical section.

C_D is the total drag coefficient which composes of zero-yaw drag coefficient and yaw drag coefficient. Both components vary with Mach number.

$$C_D = C_{D_0} + C_{D_{\delta^2}} \delta^2 \quad 1.4$$

Where $\delta = \sin \alpha_t$

1.2.2 Lift force

Lift force is the force perpendicular to the trajectory, and it can be calculated as:

$$L = \frac{1}{2} \rho v^2 S C_{L_\alpha} \sin \alpha_t \quad 1.5$$

Where C_{L_α} is given by $C_{L_\alpha} = C_{L_{\alpha_0}} + C_{L_{\alpha_2}} \delta^2 \quad 1.6$

1.2.3 Magnus force

As projectile spins with small angle of attack, a weak asymmetry of the boundary layer is induced which causes unequal pressure around projectile body. Hence, magnus force is produced [10, 11]. Its direction depends on the directions of angle of attack and spin. Figure 4 and Figure 5 show magnus effect and its distribution on a spin-stabilized projectile.

However, it is given by:

$$MAGF = \frac{1}{2} \rho v^2 S \left(\frac{pd}{v} \right) C_{N_{p\alpha}} \sin \alpha_t \quad 1.7$$

Where magnus force coefficient is given by:

$$C_{N_{p\alpha}} = C_{N_{p\alpha_0}} + C_{N_{p\alpha_2}} \delta^2 \quad 1.8$$

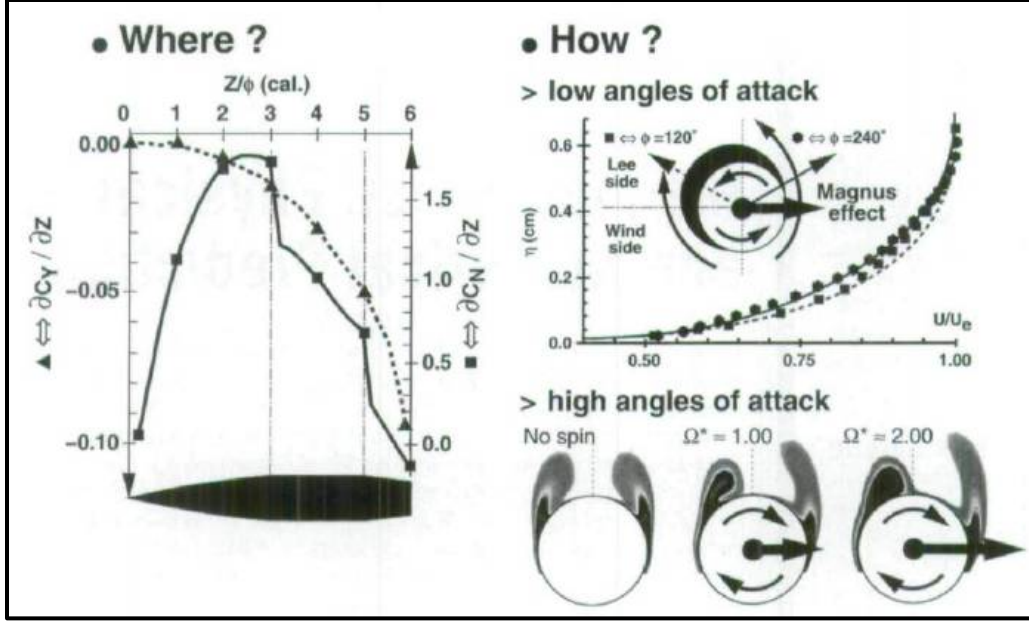


Figure 4. Physical aspects of magnus effects on spin-stabilized projectile [10].

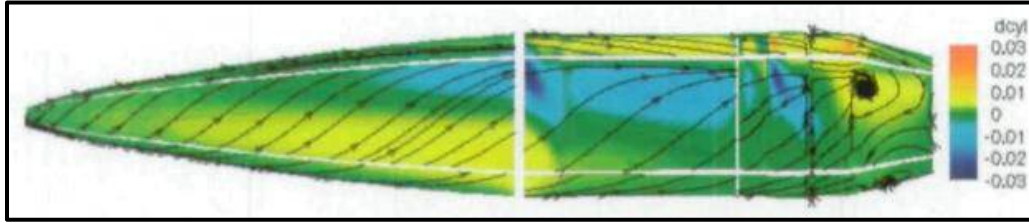


Figure 5. Magnus force coefficient over spin-stabilized projectile [10].

1.2.4 Overturning moment

Overturning moment is associated with lift force and it is also known as pitching moment. It is given by [2, 3, 9]:

$$OM = \frac{1}{2} \rho v^2 S d C_{M_\alpha} \sin \alpha_t \quad 1.9$$

Where

$$C_{M_\alpha} = C_{M_{\alpha_0}} + C_{M_{\alpha_2}} \delta^2 \quad 1.10$$

1.2.5 Magnus moment

Magnus moment depends on the distribution of magnus force, flight Mach number and yaw angle. Usually, the acting magnus force can be neglected. However, magnus moment should be

considered, because high magnus moment can cause dynamic instability [2, 12]. Magnus moment is given by

$$MAGM = \frac{1}{2} \rho v^2 S d \left(\frac{pd}{V} \right) C_{M_{p\alpha}} \sin \alpha_t \quad 1.11$$

Where

$$C_{M_{p\alpha}} = C_{M_{p\alpha_0}} + C_{M_{p\alpha_2}} \delta^2 \quad 1.12$$

It is important to mention that the center of pressure of lift force is different from the center of pressure of magnus force.

1.2.6 Spin damping moment

Spin damping moment is the moment that acts to reduce the spinning and its direction always opposes projectile spinning direction. As a standard a factor of $\left(\frac{pd}{V} \right)$ is maintained to calculate damping coefficient and to account for difference in velocity. Thus, it is calculated by

$$SDM = \frac{1}{2} \rho v^2 S d \left(\frac{pd}{V} \right) C_{l_p} \quad 1.13$$

1.3 Thesis objective

The purpose of the present work is to utilize a variety of passive drag reduction techniques over an existing projectile. Computations will be carried out using computational fluid dynamics CFD using Ansys Fluent to solve RANS equations. The following points will be considered during this study:

- The projectile of study will be nominated such that there is sufficient baseline information in terms of detailed geometry and aerodynamic coefficients. This information is necessary for validation purposes.
- All design variation will concentrate on projectile boattail and base.

- All design modifications are derived from the literature to achieve results that are built upon previous works.
- It will be considered that all design modifications are not studied before in the literature.

The aim of design changes is to minimize projectile drag. Thus, results of drag and other steady aerodynamic coefficients will be compared. In addition, Large Eddy Simulation LES will be carried out over one configuration as well as the original configuration, at one speed. Aerodynamic coefficients will be determined, which include drag force, lift force, magnus force, magnus moment, spin damping moment and overturning moment. Then these coefficients will be compared for each design variation. Furthermore, coupled CFD and 6DoF will be carried out to investigate projectile gyroscopic stability. This will be achieved by using dynamic mesh with multiple simulation at different spin speed. Lastly, a comparison will be made between SST $k-\omega$ and LES results.

The organization of the thesis will be as follows:

Chapter 1 introduces the topic of spinning projectiles with brief history of aerodynamic analysis. Then aerodynamic forces and moments acting on spinning projectiles are described.

Chapter 2 presents a literature review of different aerodynamic methods and tools that are used to estimate aerodynamic forces and moments of projectiles. In addition, range extension techniques were reviewed extensively. They are categorized into passive and active methods.

In Chapter 3, theses methodology is explained. It starts with describing the governing equation and turbulence model transport equation. Then design modifications were illustrated. For each design, the computational model and meshing method is shown. Lastly, it discusses the pre-processing setups and simulations environments.

Chapter 4 concerns about solution validation and verification. For validation, results are compared to literature. In verification, solution setups and methodologies is verified and it is shown that they lead to converged and sufficiently resolved solutions.

Chapter 5 discusses thesis results and findings. That includes presenting and discussing the calculated aerodynamic coefficients and flow properties. Furthermore, results comparison between different designs and turbulence model is performed.

Finally, Chapter 6 summarizes the thesis conclusions and suggests future works.]

CHAPTER 2

LITERATURE REVIEW

2.1 Computational fluid dynamics on spinning projectiles

Before the evolvement of computers and numerical solution techniques, aerodynamic coefficients and flow field of spinning projectiles were predicted by experiments, such as supersonic wind tunnel test and free-flight spark photography ranges. In addition, flight test was one of the main methods used to predict flight and trajectory characteristics of spinning projectiles. For fast and low cost coefficients prediction, semi-empirical codes were developed to estimate aerodynamic coefficients and flight trajectories. Examples of these code include Missile DATCOM [13], PRODAS [14], and Aeroprediction code [15]. However, Computational fluid dynamic CFD tools have facilitated aerodynamic simulations of complex geometry with higher accuracy than semi-empirical codes and lower cost than wind tunnel and flight experiments.

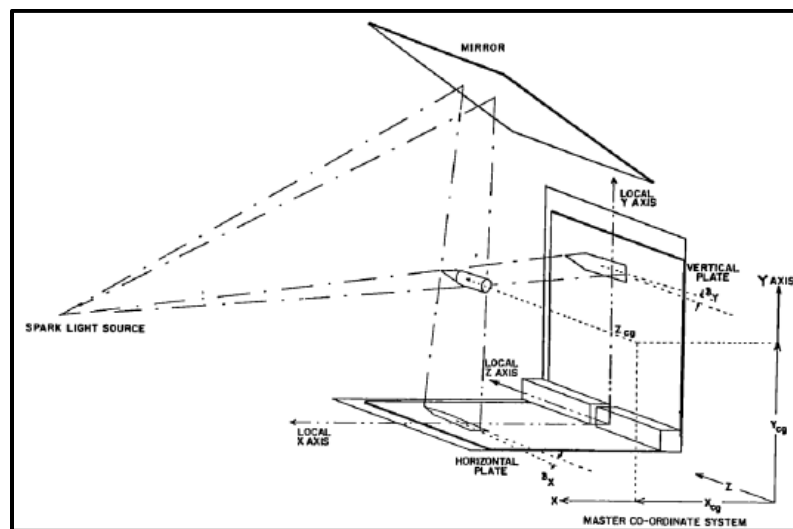


Figure 6. Spark rang test setup and coordinate system [2].

In 2002, S. Siltan [16] conducted CFD simulations using Navier-Stokes solver for 12.95 mm caliber projectile, where $k-\epsilon$ turbulence model was applied. The simulation predicted the aerodynamic coefficients over Mach number 0.7 to 2.7 and for 0° and 2° angles of attack. Then, numerical results are compared with experiments and Aeroprediction code. Results show a good agreement between Numerical and experimental approaches as elucidated in Figure 7. Beside the aerodynamic coefficients, this study investigated the flow field from subsonic to supersonic regimes, in which flow characteristic is understood. However, spin damping and pitch damping moments were not obtained, due to solution approaches.

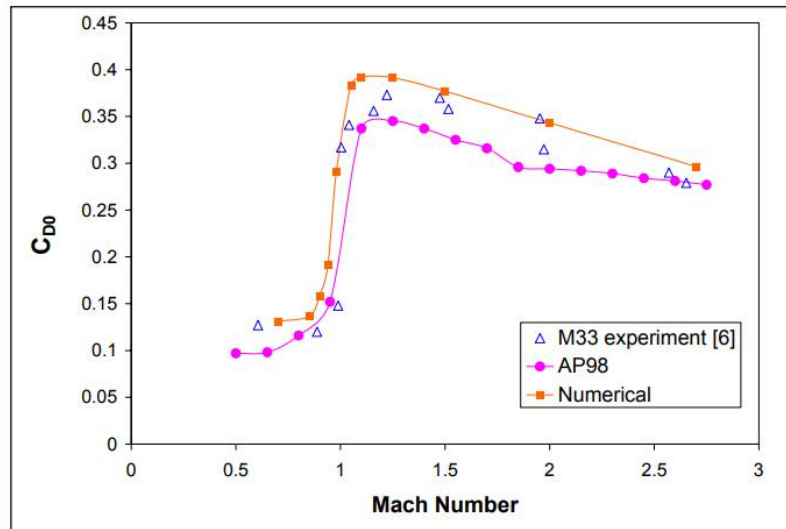


Figure 7. Comparison between experimental, numerical, and semi-empirical results of zero-yaw drag coefficient [16].

In 2005, a numerical prediction of flight trajectory and aerodynamic characteristics was performed by J. Sahu for a finned projectile [17]. In this work, Free flight aerodynamics and trajectory are computed simultaneously using coupled CFD rigid body dynamic method, where time accurate Navier-Stokes computation is employed. Generally, good agreement was found between flight test, and computed trajectory and projectile attitude.

Additionally, computations of nonlinear and damping coefficients are concerned. Reference [18] discussed different aerodynamic models and approaches to obtain magnus moment and spin damping moment for a spin stabilized projectile. Investigations were performed from 0.4 to 4.5 Mach number on a 25-mm projectile. RANS calculation and time accurate detached-eddy simulation were used, and results were compared to experimental data. It was found that RANS calculation was able to estimate static aerodynamic coefficients and center of pressure within 10% accuracy compared to experimental data except for magnus moment, which was not accurately predicted at subsonic and transonic speeds. Thus, time-accurate numerical simulation is necessary for the calculation of magnus moment at the denoted speeds. For roll damping moments, both time-accurate and steady state simulation obtained them within 15% of the experimental data.

An attempt was made in [10] to numerically predict magnus effect of fin-stabilized and spin-stabilized projectiles. URANS Spalart-Allmaras model was found adequate to predict magnus effect of finned projectile in supersonic regime. For spinning projectiles, RANS methods give satisfactory results in the supersonic regime, while RANS/LES hybrid approaches well describe magnus effect in subsonic and supersonic flow conditions.

RANS and RANS/LES simulations are also used for flow at high angle of attack. DeSpirito studied different approaches for predicting the aerodynamic coefficients of 155 mm projectile at high angle of attack [19]. Coefficients were well predicted by RANS methods at 20° angle of attack or less, except for magnus coefficients for $AoA < 5^\circ$. For $AoA > 20^\circ$, time accurate RANS or LES were found necessary for accurate computations.

Reference [20] concerned about the flow of the base region. Due to the complex physics of the flow caused by rapid expansion, compressible effect in the shear layer, and strong adverse pressure gradient it is difficult to characterize the flow using steady approaches. However, modification was made on Spalart-Allmaras turbulence model to investigate the base flow at supersonic regime. Generally, these modifications achieved good agreement with the experimental results.

Recently, numerical analysis was performed to calculate aerodynamic coefficients of a 120 mm projectile [21]. Coefficients of zero yaw drag, yaw drag, lift, magnus force, overturning moment and roll damping moment were predicted. SST $k-\omega$ model was selected over Spalart-Allmaras because of its better agreement with the experimental results. Mach numbers from 0.14 to 1.2 were considered, at 0 and 2.5 angles of attack. CFD results were then compared with results from the semiempirical code PRODAS in which good agreement was shown over most of Mach number range.

2.2 Range extension and drag reduction techniques

Range extension got a great interest in the field of artillery and spinning projectiles. Various methods have been discussed in the literature. These methods can be classified as passive or active. Most of the techniques concentrate on increasing base pressure, since it is responsible for about 50% of the total drag [22]. Active methods include the use of controllable fins and canards, base bleed, and rocket assistance. In the contrary, passive method include optimization of boattail shape, optimization of nose and ogive, the use of riblets, base cavity, and steps ahead of the base.

2.2.1 Active range extension techniques

Attempts were made by W. Calarese in 1979 to reduce after body drag using hot gas injection and boat tailing [23]. The experiments were conducted on GAU-8 projectile at Mach 3. Different gas temperatures and boattail angles were investigated. Experimental results show total reduction in drag of 30% to 40% using slight gas injection. For boat tailing, 15% drag reduction was achieved. In addition, the effectiveness of helium injection over the air was indicated.

Gas ejection was incorporated by [24] for $M = 2$ projectile velocity. 1 and 0.5 caliber boattail lengths at 3°, 6° and 9° boattail angles were tested. It was concluded that boattail angle is not sensitive to ejection rate. Another study [25], conducted an experiment to reduce base drag by combining boattail and base blowing at $M = 3$. The minimum drag was found at around 6° boattail angle with base blowing.

The first key in advancing range extension techniques was accomplished in 1995, using controlled canards [26]. The additional canards use inertial sensor data to command the optimum deflection for maximizing lift. This method achieved a maximum range of 41 km. Though, there were adverse effects of increasing flight time and decreasing terminal velocity. Hence, decreased lethality.

US army emerged the use of rocket-assisted projectile [27]. The range of the standard 155mm projectile was extended from 14 miles to 18 miles. However, technical advances are being made to 155mm projectile to achieve a range between 44 and 62 miles. In 2018, “extreme range” artillery project was developed by Nammo company. Ramjet propulsion was incorporated to artillery shell to achieve long-range precision fire. More than 100 km adversarial range was reached.

2.2.2 Passive range extension techniques

Multiple studies have concerned about increasing range by optimizing the shape of projectile nose and ogive or boattail and base. Investigation and experiments conducted on missiles and projectile shows that there is an interrelationship between base pressure and boundary layer [28]. In addition, it is noted that base pressure is affected by free stream Mach number, Reynolds number, and temperature distribution in the boundary layer which is resembled by Prandtl number. Furthermore, large variation of base pressure is shown when varying tail tapering angle. Figure 8 and Figure 9 explain the relationships of Mach number and Reynolds number with base pressure.

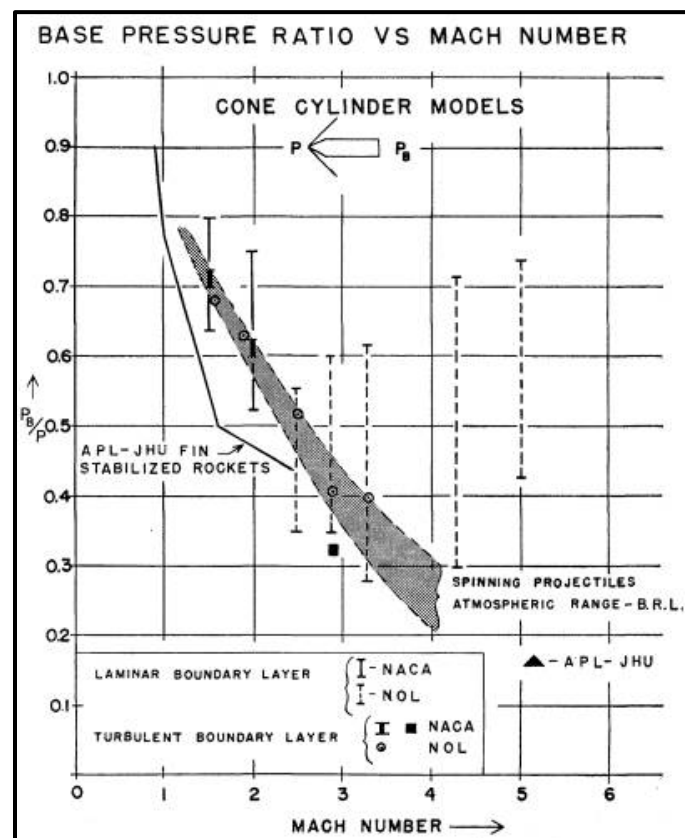


Figure 8. Base pressure versus M number [28].

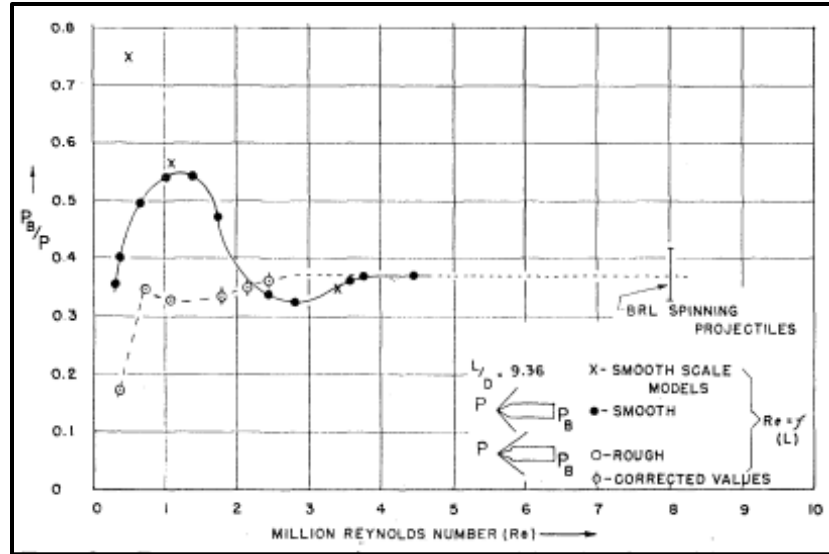


Figure 9. Base pressure versus Re number [28].

Warsop has reviewed some control methods of turbulent flow [29]. Passive and active methods were addressed for flow separation control and skin friction drag reduction. The use of riblets is considered as passive turbulent flow control. studies about riblets began since 1970. Investigations show that Mach number and Reynolds number have little influence on riblets effectiveness. Under adverse pressure gradient, up to 13% percent drag reduction is shown by experiments. However, the performance of riblet is governed by its shape and flow misalignments. Optimization of riblets with yaw angle effect was discussed in reference [30]. Different geometry and tip angle were tested. It was found that trapezoidal grooved riblets with 45° tip angle are less affected by yaw angle, compared to other geometry.

The effect of nose shape was concerned with regard to drag reduction. Generally, the longer the nose, the lower the drag as presented by figure 10 [2] . Additionally, drag is also affected by the radius of the nose ogive. This effect is depicted by Figure 11, where R_T is the radius of a tangent ogive nose whose length is the same as actual nose.

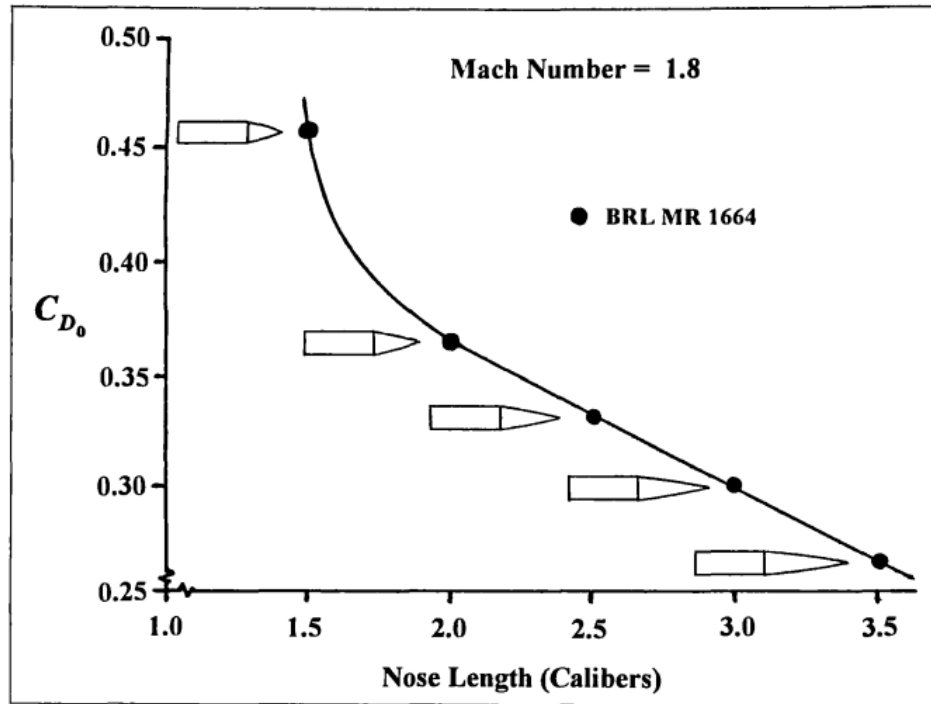


Figure 10. Effect of nose length on zero-yaw drag [2].

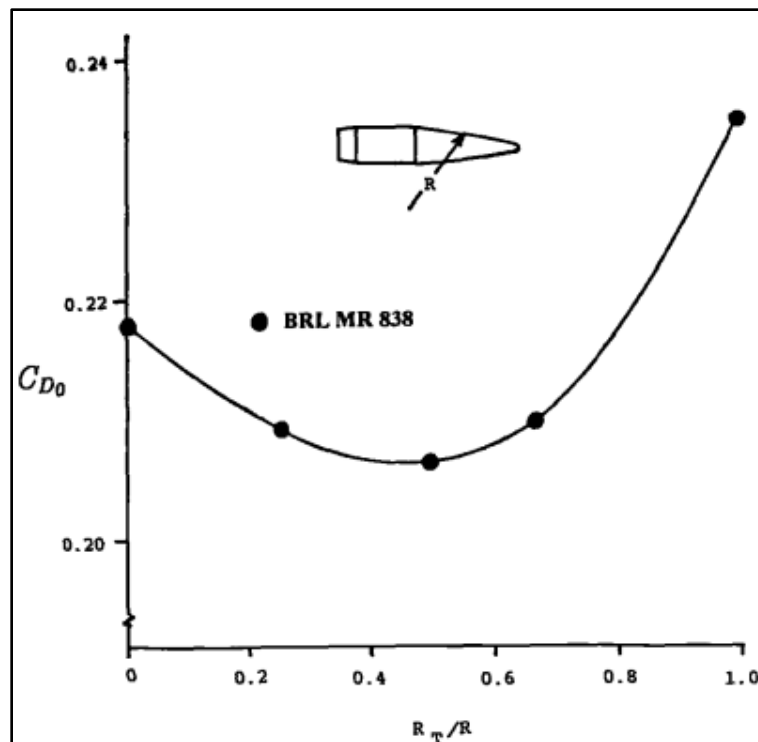


Figure 11. Effect of ogival nose radius on zero-yaw drag at $M = 2.44$ [2].

Other passive techniques to reduce pressure drag include modification of boattail and base configuration. Since this work will study various aft-body shapes, a sperate section will be devoted to review works accomplished with respect to projectiles boattail and base.

2.2.3 Boattail and base modifications

Reducing base drag is an effective way for rang extension, since it is the main component in transonic and supersonic Mach numbers [31]. Boat-tailing is considered as one of the mostly used technique to reduce base drag, which is governed by base area and base pressure [32]. Generally, it is desirable to minimize projectile base area and maximize base pressure. Having longer and steeper baottail angle reduces base area. Though, steep angle may lead to flow separation due to high flow turning angle. Hence, boattail should be optimized to minimize base area where flow is kept attached. 7° boat-tail angle is indicated as the optimized angle for the lowest pressure drag in transonic speeds [2, 20, 23, 32, 33].

Also, lower drag is exhibited as boattail length increases [2, 32]. However, the practical boattail length is found between 0.5 and 1 caliber. At longer boattails, spinning projectile stability is adversely affected, due to the increment in magnus moment [2]. Effect of boattail parameter on drag is elucidated in figures 12, 13 and 14.

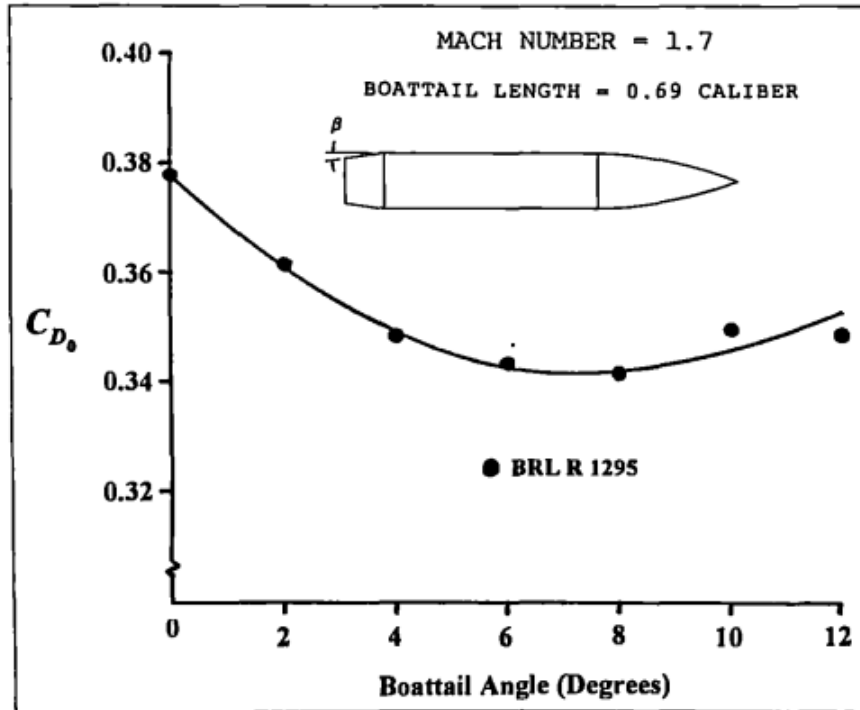


Figure 12. Change of zero yaw drag coefficient with respect to boattail angle [2].

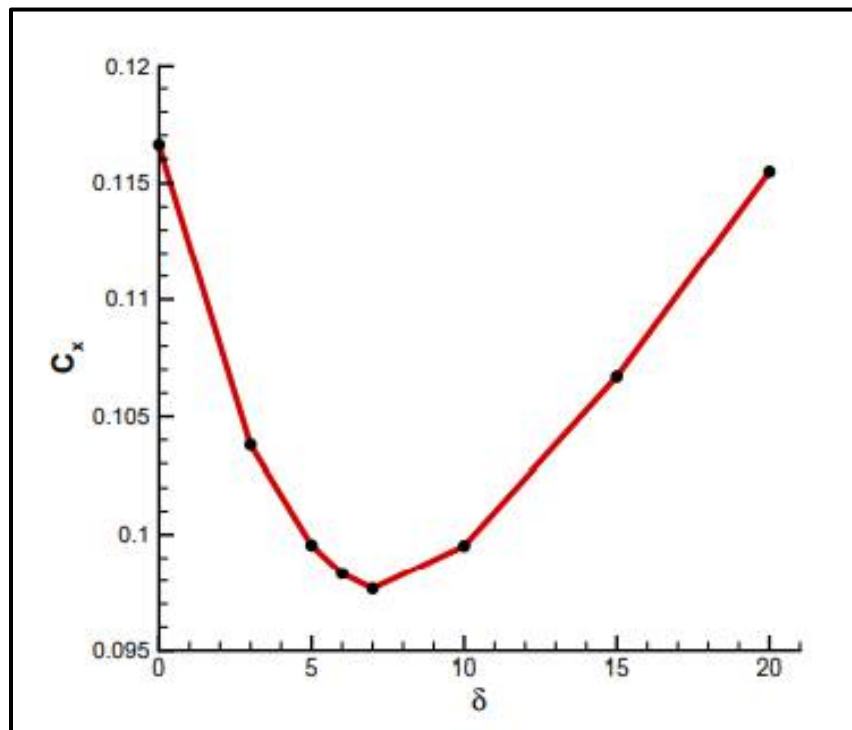


Figure 13. Change of axial force coefficient with respect to boattail angle [20].

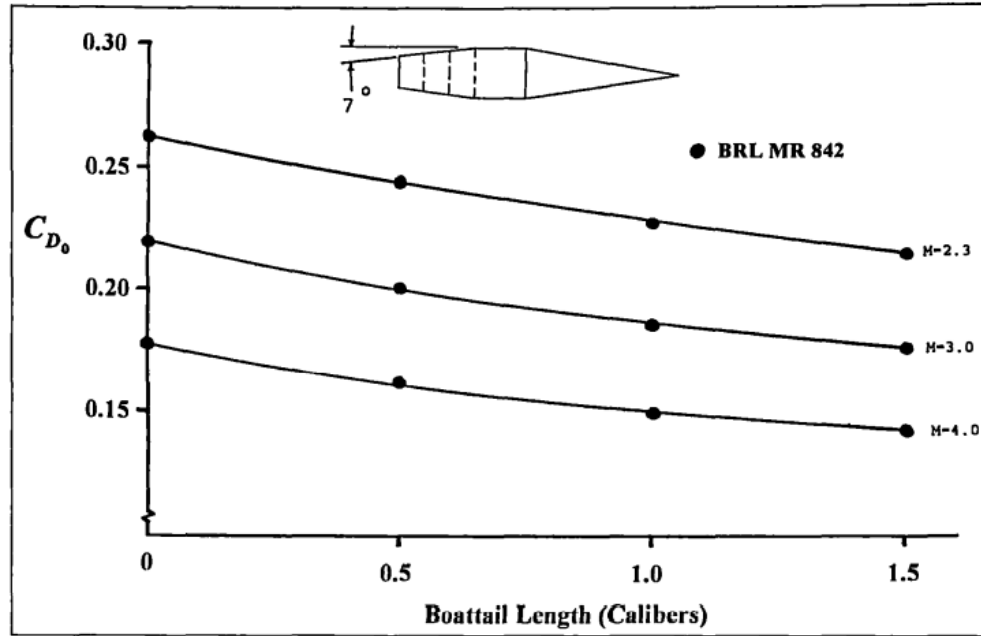


Figure 14. Change of zero yaw drag coefficient with respect to boattail length [2].

In 1979, effects of varying boattail and nose radius on a 5.56 mm caliber projectile was studied by M. Pino [34]. The aim of the study was to enhance projectile performance without causing any modification in manufacturing processes of either the bullet or muzzle rifling. Thus, changing on ogive or spin rate is not considered. In addition, elimination of certain design parameter was analyzed to facilitate the manufacturing process. Tests were performed by a supersonic wind tunnel and in an aeroballistics range facility. It was concluded that elimination of bullet boattail degrades the performance in terms of flight time and firing accuracy. Whereas no change on performance was captured by modifying nose radius.

Viswanath and Patil analyzed the characteristics of the zero yaw drag for projectiles with square base profile, shown in Figure 15 [35]. Results were compared to counterpart projectiles that have circular arc and conical boattail, where base areas are equal. Experimental results shows that square base offered a base drag reduction at transonic speed compared to other configuration,

although the total drag is higher than circular arc boattail at Mach 2. High drag on square base was due to low pressure on the base region caused by vortical flows.

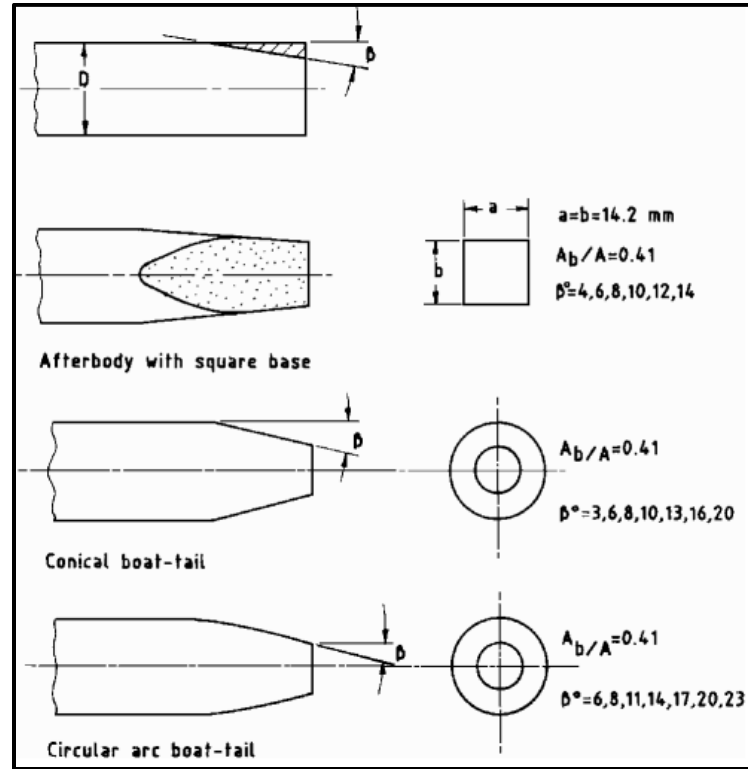


Figure 15. Geometry of square and axisymmetric afterbody models [35].

Later in 1999, Viswanath studied various afterbody configurations for drag reduction at transonic and supersonic speeds [22]. Configurations involve multi-step, conical and circular arc boattails, which are presented by Figure 16 and Figure 17. Highly optimized multi-step model provides total drag reduction as much as 50%. However, the lowest drag was exhibited in the circular arc configuration. Also, flow visualization and features were discussed for the multi-step configuration.

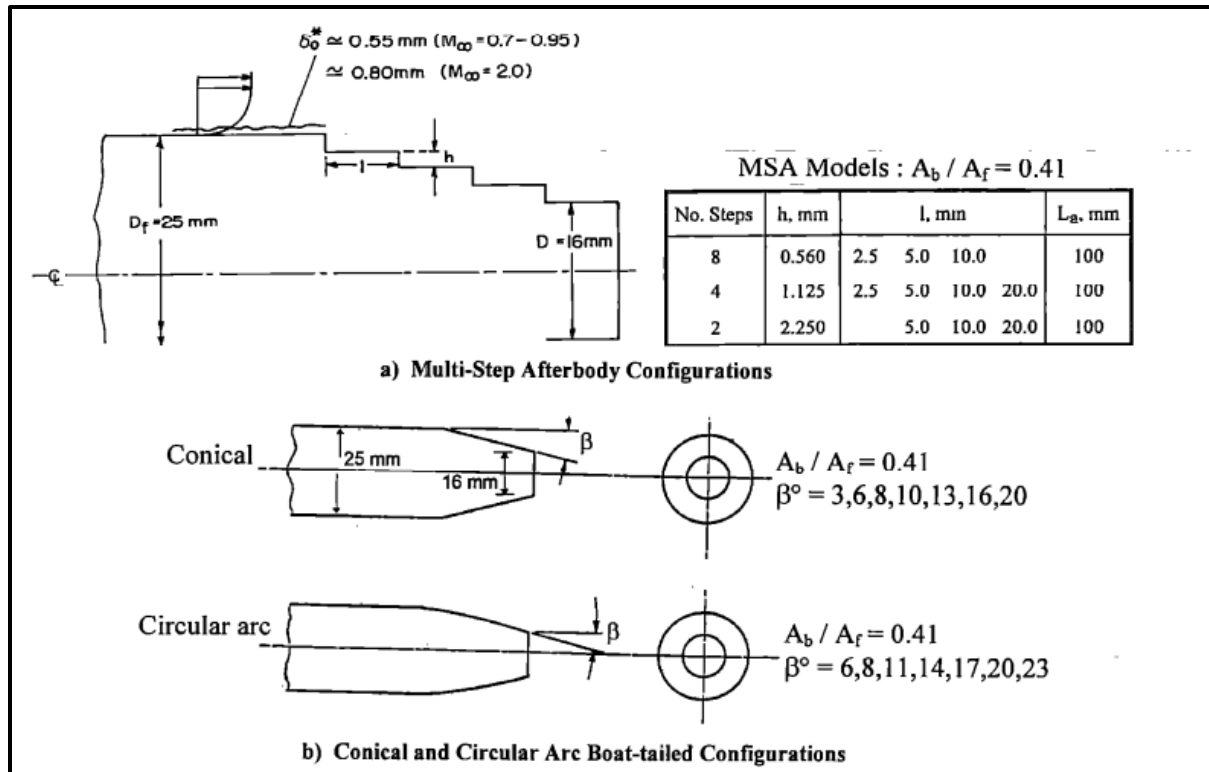


Figure 16. Geometric details of boattail configurations [22].

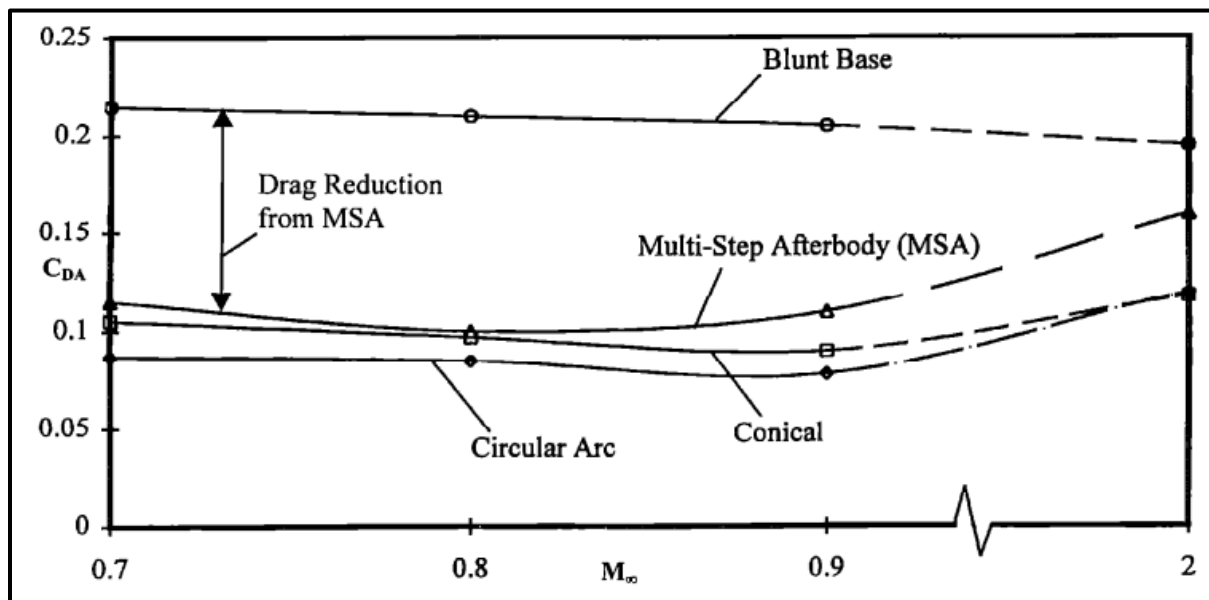


Figure 17. Total drag characteristics for different boattail configurations [22].

In 2008, S. Siltan and S. Dinavahi considered different boattail configurations and their contribution to base drag on a 12.95 mm caliber projectile [32]. The computation was conducted numerically, over 0.6 - 2.7 Mach number. Large base drag was observed in the transonic speeds. However, negative base drag was noticed in the subsonic speed. To verify that this phenomenon is not numerical, various meshes, turbulence models and flow solvers were tested. Then, multiple boattail configurations were investigated for base drag reduction. In addition to the baseline configuration, 8 boattail configurations were studied, as shown by Figure 18. It was noticed that the longer the boattail, the lower is the total drag which is clear from Figure 19. Also, effects of boattail angle on drag were observed and depicted in figure 20. Drag increment and reduction is associated with the length of wake region behind the projectile. Observations reveal that the longer the wake the lower is the base pressure, Hence the larger is total drag. Lastly, the authors indicated the importance of investigating the effects on the other aerodynamic coefficients.

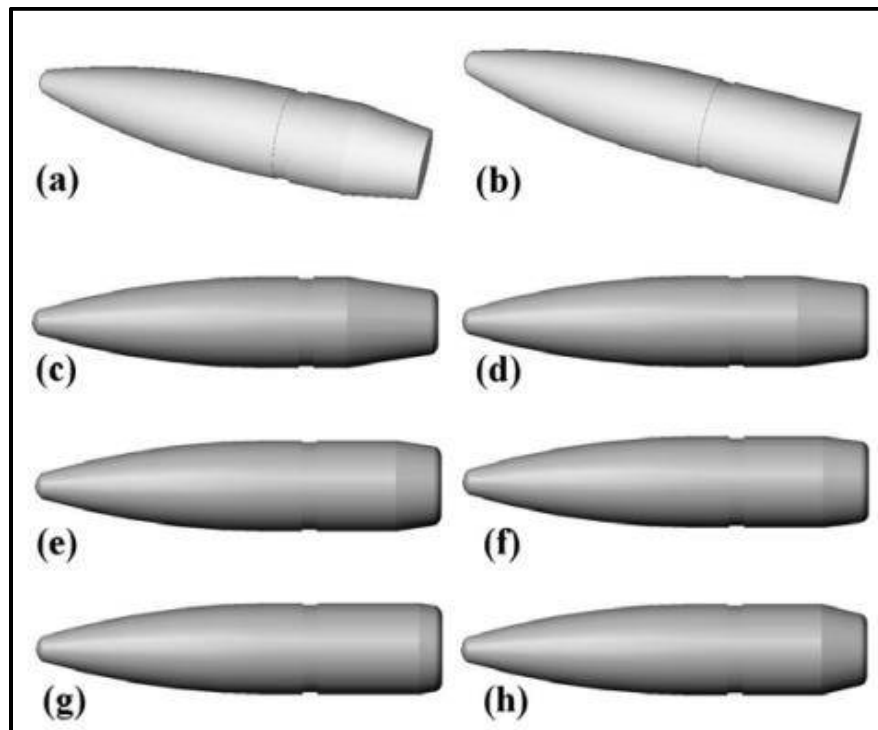


Figure 18. Considered boattail configurations [32].

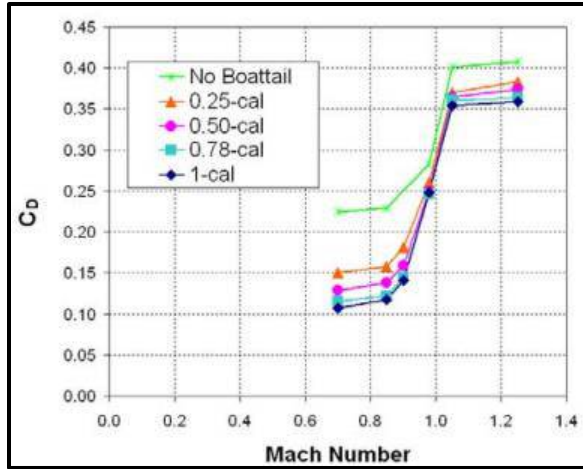


Figure 19. Effects of boat-tail length on drag coefficient [32].

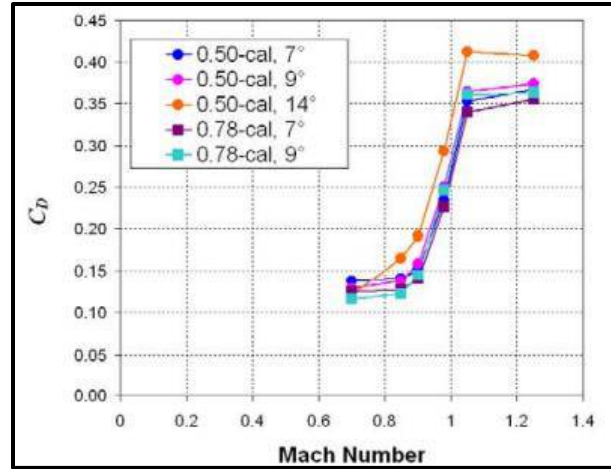


Figure 20. Effects of boat-tail angle on drag coefficient [32].

The effect of base shape on aerodynamic coefficients was studied over Mach number from 0.7 to 2.5 [12]. steady and dynamic coefficient were computed using CFD. Investigated base shapes include square base, boattailed, chamfered base, filleted base and hemispherical base. These are shown in Figure 21. Significant effects were found on the drag, magnus moment and pitch damping moment. Finite volume method was used to solve time dependent RANS equations. The lowest exerted drag was found on boattailed and hemispherical base configurations. Though, high magnus moment was observed which lead to dynamic instability, especially for the hemispherical configurations. However, acceptable dynamic stability can be attained at high flying Mach number regimes.

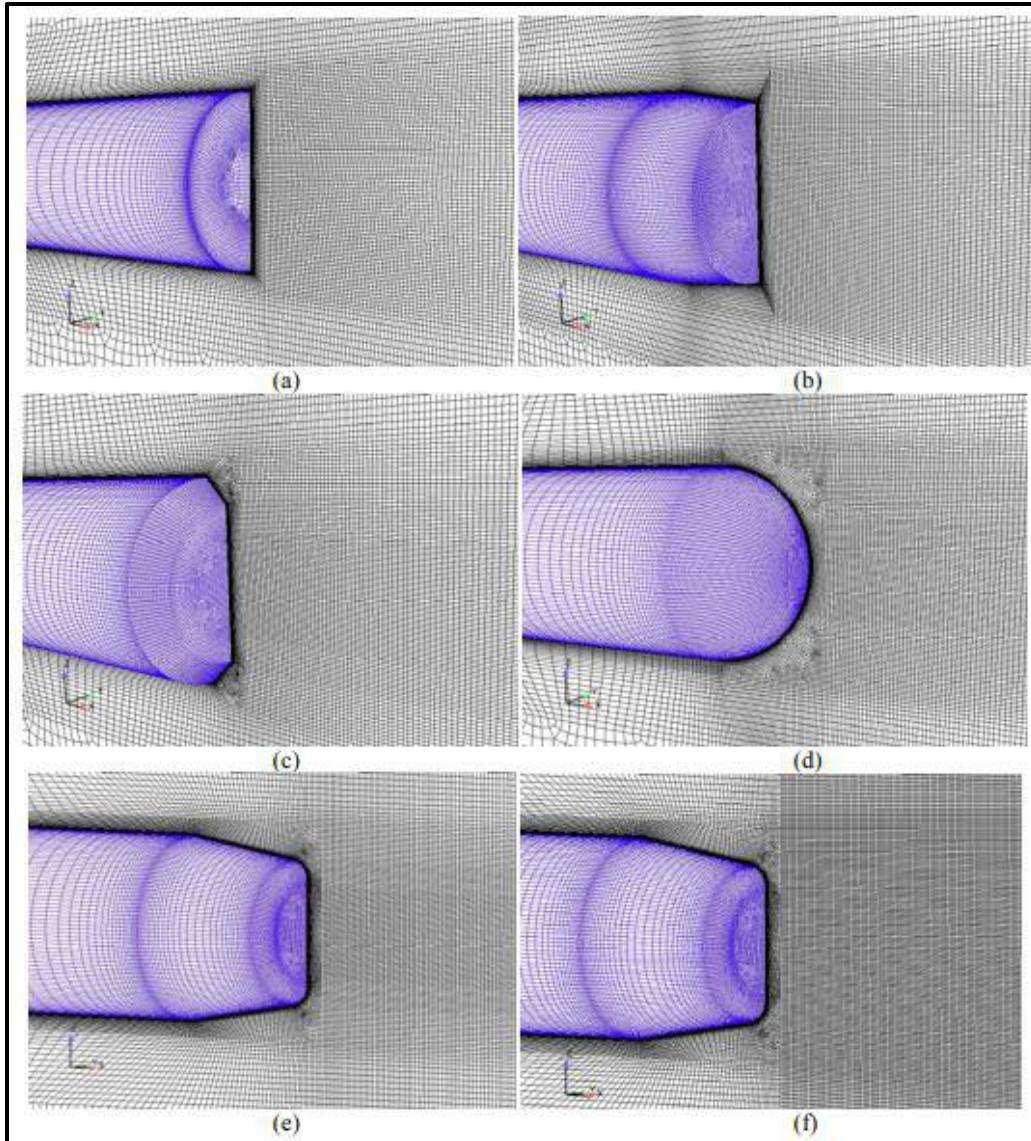


Figure 21. Considered base shapes and mesh [12].

Later, Aerodynamic coefficients were determined for different boattail angles and fillet radius of a small caliber ammunition [33]. The purpose of the study is to determine the effects of the different parameters on the yaw limit cycle, isolating the effect of the nonlinear magnus moment. The tested parameters are 6° , 7.5° , and 9° boattail angles and 0.0254 mm, 0.508 mm, and 1.016 mm base radius. The test was conducted experimentally using spark photography facility of army research laboratory ARL. Minimal effect of base radius was shown on drag coefficient as appears

in Figure 22. However, distinctive effects in magnus moment were noticed between the sharp and filleted base. For boattail angle, 5% difference was found in drag coefficient between 6°, 7.5°, and 9° angles, with the lowest in 6°.

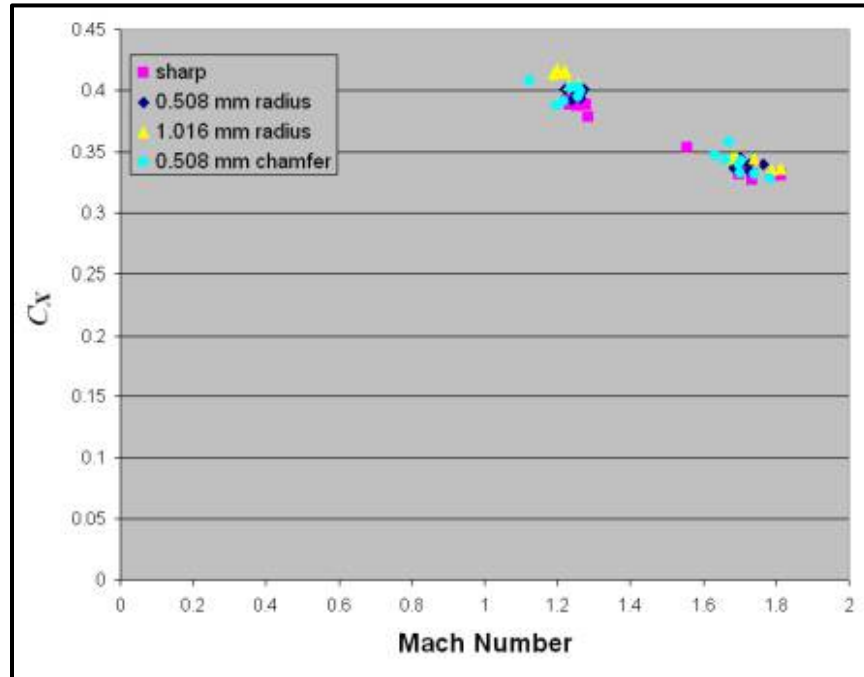


Figure 22. Axial force coefficient versus Mach number for various boat-tail radius [33].

Experimental and computation analysis is conducted on a projectile with slot cavities [31]. The purpose of the cavity is to reduce the drag by suction and blowing effect. Tests were carried out over supersonic speeds at Mach numbers 1.36, 1.65, and 1.83. width of the slots were 0.5 mm and 2.0 mm. because suction and blowing effect are small in supersonic regime compared to subsonic and transonic, small base drag reduction was found for the 0.5 mm slot. For 2.0 mm slot, increase in drag coefficient was reported. Figures 23 and 24 shows projectile geometry and drag force comparison for the three configurations, respectively.

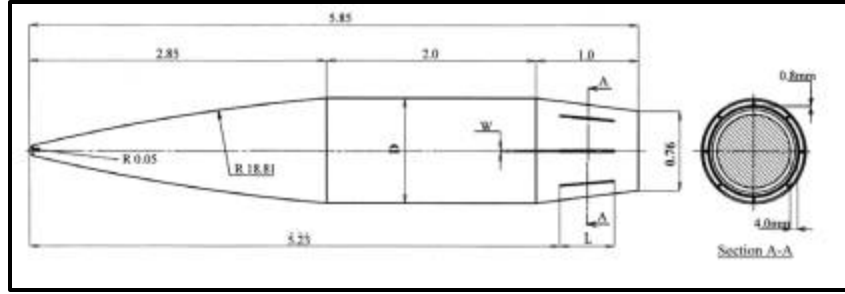


Figure 23. Slotted projectile geometry [31].

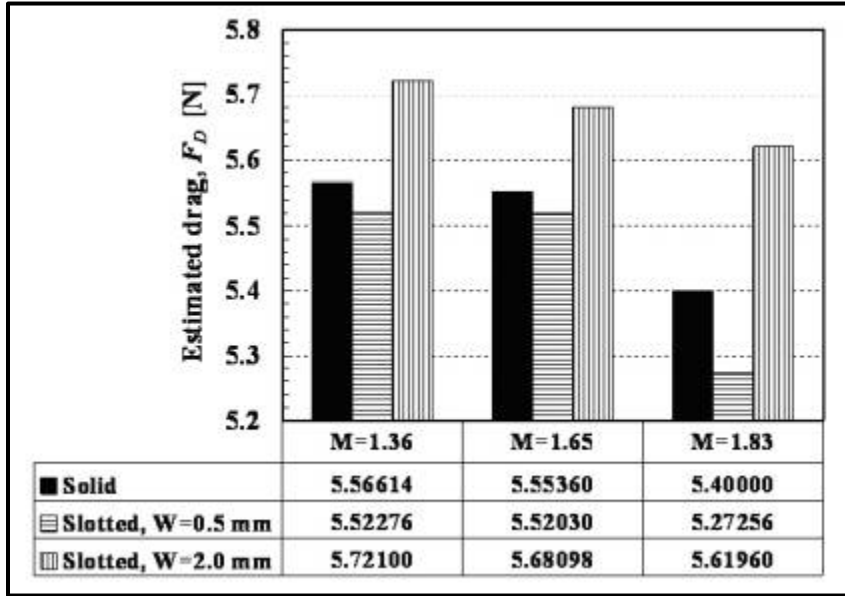


Figure 24. Drag force comparison [31].

Variation in Aft end configuration on finned projectile was studied to investigate their effect on stability range and maneuverability [36]. Figure 25 shows the considered baseline configurations. The number of mesh element varied between 12 million and 18 million depending on the configuration. Computations conducted using realizable k- ϵ , cubic k- ϵ , k- ϵ -R and shear stress transport SST turbulence models. Simulations were performed on 0.5, 0.65, and 0.8 Mach numbers. Promising Results are shown for (b) configuration in Figure 25, in terms of maneuverability.

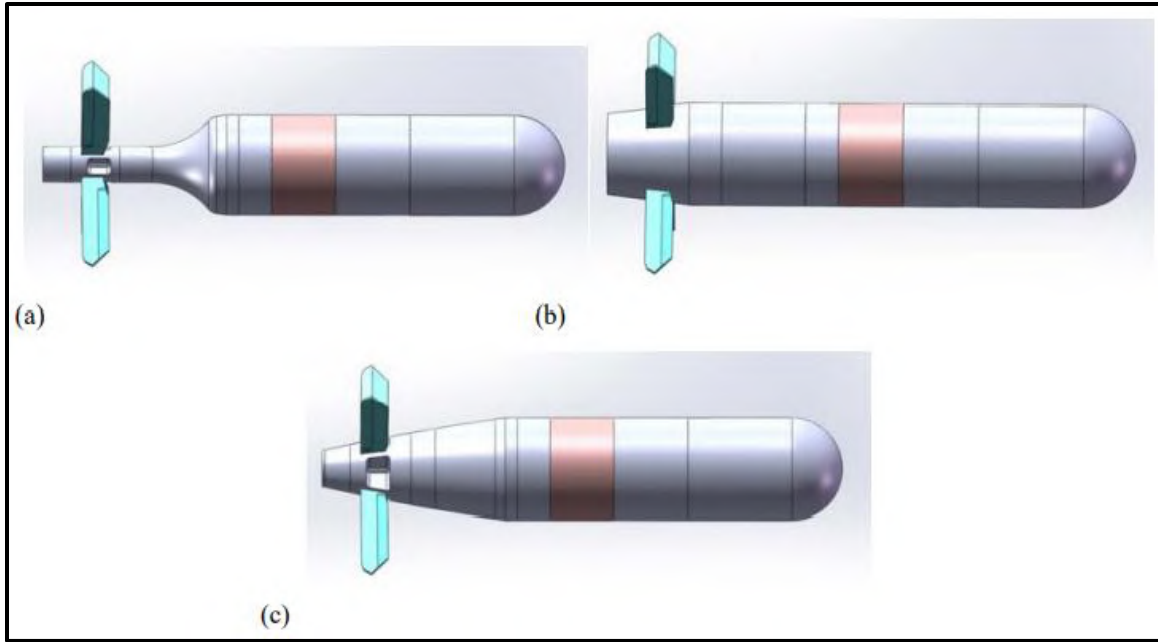


Figure 25. Three considered baseline configurations [36].

In 2010, Mutwakil Mohammed has studied different techniques for drag reduction on a 155mm projectile [37]. Ansys Fluent was the main CFD software utilized in the simulations. MC DRAG, Missile DATCOM and wind tunnel were used for Validation. During the study, boattailing, base cavity and base bleed were applied. Then, a combination of two methods and all three methods were implemented which led to a significant drag reduction.

Recently, more boattail design variations were studied [38]. The objective of the work is to find an optimized boattail design for base drag reduction. The baseline geometry is the M549 155 mm projectile model. Computations were carried out on 3 dimensional geometrical models using $k-\omega$ SST turbulence model, for its good behavior in solving boundary layer and separated flow problems. Design variations include the use of riblets on the boattail and base, as well as introducing rear cavity with 15.5 mm and 23.25 mm thicknesses, as presented in Figure 26. However, the lowest drag was found at the 15.5 mm thickness cavity.

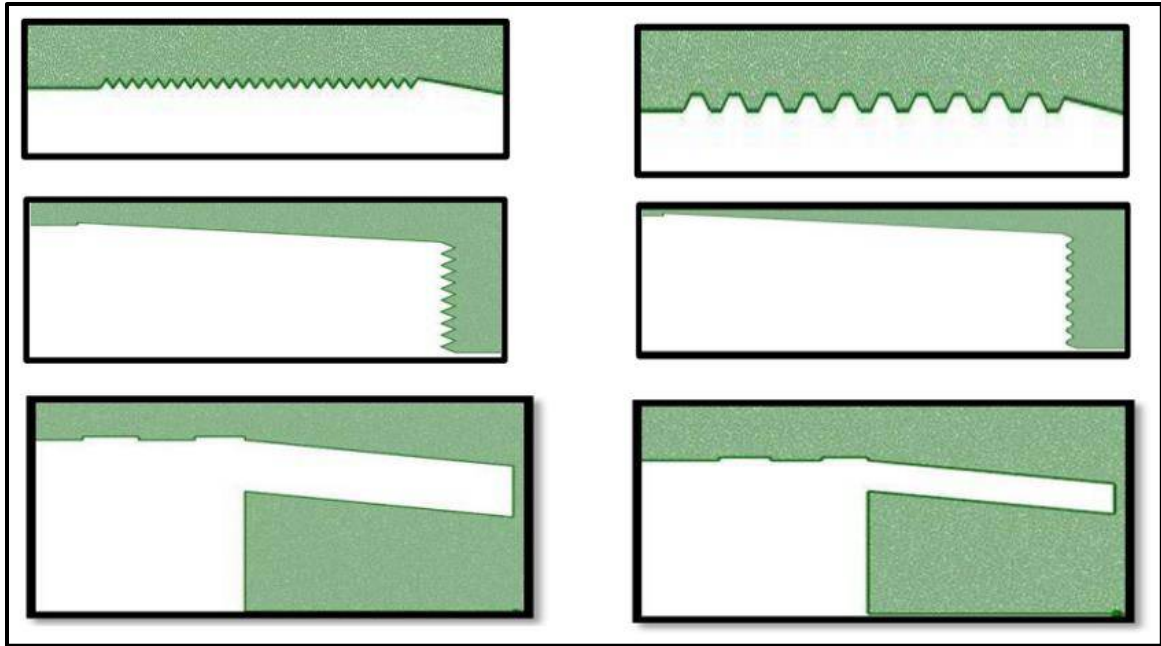


Figure 26. Tested design configurations [38].

CHAPTER 3

METHODOLOGY

Simulation and analysis in the thesis were done in several steps. At first the projectile that will be modified on boattail and base is nominated. Then, a variety of designs were applied according to the literature. After that, ANSYS mesh and Fluent were used for pre-processing and problem setups. For the solver, Steady state density based RANS, large eddy simulation LES and coupled URANS - six degrees of freedom 6DoF were implemented. This chapter will explain these processes and setups in details. Also, mathematical modeling which includes governing equations, turbulence models and solvers will be elucidated.

3.1 Mathematical modeling

3.1.1 Governing equations

In this thesis Ansys Fluent was used to conduct all CFD calculations, in which Navier-Stokes equations are discretized and solved in their three dimensional integral forms. Basically, conservation of mass and momentum is implemented. Because of flow high speed, compressibility was accounted. Hence, energy equation and ideal gas equation were solved. In addition, Sutherland's law is included to account for the effect of heat on air viscosity, which enhances model credibility.

1. Conservation of mass (Continuity equation) [39].

Continuity equation was solved by Fluent on its integral form which is given by:

$$\frac{\partial}{\partial t} \iiint \rho dV + \iint \rho \mathbf{V} \cdot d\mathbf{S} = 0 \quad 3.1$$

Here, V is the control volume and S is the surface area.

The above equation is a conservation form of the continuity equation, which is derived on the basis of a fixed finite control volume in space. It tells that the net mass flow out of control volume through surface S equals the time rate of decrease of mass inside the control volume V . Also, it can be written in differential form as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad 3.2$$

2. Conservation of momentum (Navier-Stokes equations) [39, 40].

The integral form of the momentum equation was solved in the three dimensions evolving viscosity and compressibility. It is written in the cartesian coordinate as:

$$\frac{\partial}{\partial t} \iiint \rho \mathbf{V} dV + \iint (\rho \mathbf{V} \cdot d\mathbf{S}) \mathbf{V} = - \iint p d\mathbf{S} + \iiint \rho \mathbf{f} dV + \iint \nabla \cdot \boldsymbol{\tau} dV \quad 3.3$$

Here, $\mathbf{f}$ is body forces divided by unit mass. The equation is derived from newton's second law,

$\mathbf{F} = \frac{d}{dt}(m\mathbf{v})$, applied on a control volume that is fixed on space. Momentum equations can be

represented in differential form and are known as Navier-Stokes equations. For three dimensional

flow it can be written in conservative form in x , y , and z as:

$$\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = & -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\lambda \nabla \cdot \mathbf{V} + 2\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \\ & \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + \rho f_x \end{aligned} \quad 3.4$$

$$\begin{aligned} \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = & -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \frac{\partial}{\partial y} \left(\lambda \nabla \cdot \mathbf{V} + 2\mu \frac{\partial v}{\partial y} \right) + \\ & \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right] + \rho f_y \end{aligned} \quad 3.5$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left(\lambda \nabla \cdot \mathbf{V} + 2\mu \frac{\partial w}{\partial z} \right) + \rho f_z \quad 3.6$$

The above three equation represent the complete form of Navier-Stokes equations, in which unsteady, viscous, compressible and three-dimensional flow is described. Appeared forces on fluid element composes of pressure force, viscous force, including shear and normal stresses, and body forces such as gravity and electromagnetic forces.

3. Conservation of energy (Energy equation) [39, 40].

The integral conservation form of energy equation is given by:

$$\frac{d}{dt} \iiint \rho e dV + \dot{Q}_{viscous} - \oint p \mathbf{V} \cdot d\mathbf{S} + \iiint \rho (\mathbf{f} \cdot \mathbf{V}) dV + \dot{W}_{viscous} = \frac{\partial}{\partial t} \iiint \rho \left(e + \frac{V^2}{2} \right) dV + \oint \rho \left(e + \frac{V^2}{2} \right) \mathbf{V} \cdot d\mathbf{S} \quad 3.7$$

Here, $\dot{Q}_{viscous}$ and $\dot{W}_{viscous}$ denotes heat and work caused by flow viscosity.

Energy equation states that rate of change of energy inside fluid element equal to the net heat flux into element plus the rate of work done on element due to body and surface forces. Essentially, it is derived from the first law of thermodynamic, which state the change of internal energy of fluid element equal to the change of heat added and work done on that fluid element, or mathematically: $dq + dw = de$

The complete energy equation can also be written on differential form as

$$\frac{\partial(\rho e)}{\partial t} + \nabla \cdot (\rho e \mathbf{V}) = \rho + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) - p \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + \lambda \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)^2 + \mu \left[2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + 2 \left(\frac{\partial w}{\partial z} \right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 \right] \quad 3.8$$

4. Ideal gas equation.

Since the simulated flow is compressible, which means that the density varies spatially and timely, perfect gas equation is utilized to calculate the change in flow density throughout the domain. It relates density to flow pressure and temperature by

$$p = \rho RT \quad 3.9$$

In Ansys fluent, different form of perfect gas equation is used which is written as

$$\rho = \frac{p_{op} + p}{\frac{R}{M_w} T} \quad 3.10$$

Where p_{op} is the operating pressure and M_w is molecular weight.

5. Equation of estate

Above are four equations, though they involve five unknown variables. They are V , T , ρ , e , and p . Therefore, additional equation is required to complete the system, in which it will be a thermodynamic state relation for e that is applicable for calorically perfect gas.

$$e = c_v T \quad 3.11$$

6. Sutherland law.

To enhance the credibility of the simulation, the variation of air viscosity with temperature is considered by the Sutherland law. It is given by

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0} \right)^{3/2} \frac{T_0 + 110}{T + 110} \quad 3.12$$

Here, μ_0 and T_0 are viscosity and temperature at a selected reference condition, respectively. In this thesis the reference condition is the standard sea level.

3.1.2 Turbulence modeling

Shear stress transport SST $k-\omega$ is the main turbulence model used for the different design configurations. According to literature, SST $k-\omega$ model performs well in capturing and modelling flow separation. Therefore, it was chosen for the analysis and simulation of base drag. Furthermore, LES is then implemented for limited cases, namely on original configuration and riblets boattail at Mach 1.2. The principle of LES is that the majority of turbulence eddies are resolved whereas small eddies, which is smaller than mesh cell, are modelled. It is an accurate model for capturing turbulence and estimating based drag, though it is very expensive, due to the high requirement of computational resources and time. Therefore, it is not considered feasible for most industrial applications. This explains why LES is used for limited cases in this thesis.

3.1.2.1 SST $k-\omega$

Essentially, SST $k-\omega$ is a Reynold Averaged Navier-Stokes model, known as RANS. In RANS models Navier-Stokes equations are first averaged over time with respect to flow properties. This means that every property in the equation is replaced by mean flow value over time plus a perturbation term. This results in what is known as Reynold stresses. However, $k-\omega$ model is categorized under Boussinesq family, in which Reynold stresses are related to mean velocity gradients. Unlike Reynold stress transport models, Boussinesq approach assumes turbulent viscosity μ_t as isentropic scalar quantity. Although this assumption is not true, it reduces computational cost and time by reducing the number of model equations and it is applicable to a variety of flow types. Here, turbulent viscosity is calculated by solving turbulent kinetic energy (k) and specific dissipation rate (ω).

The transport equations of SST k- ω are similar to the standard k- ω model transport equations. Nevertheless, in SST the model changes gradually from standard k- ω at the inner region of boundary layer or what is known as viscous sublayer, to k- ϵ in the outer region of boundary layer. That is done according to the performance of both models in the designated regions.

The transport equations of the k- ω model are written as [41]

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k + G_b \quad 3.13$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega + G_{\omega b} \quad 3.14$$

Here:

- G_k represents the generation of turbulence kinetic energy due to mean velocity gradient.
- G_ω represents the generation of the specific dissipation rate.
- Γ_k and Γ_ω are the effective diffusivity of k and ω respectively.
- Y_k and Y_ω are the dissipation of k and ω , respectively.
- S_k and S_ω are user-defined source terms.
- G_b and $G_{\omega b}$ account for buoyancy term.

In modelling turbulent viscosity, a limiter is introduced to avoid overprediction of the eddy-viscosity. It is estimated by:

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max \left[\frac{1}{\alpha^*}, \frac{SF_2}{a_1 \omega} \right]} \quad 3.15$$

Here, S is the strain rate magnitude, while α^* and F_2 are given by

$$\alpha^* = \alpha_\infty^* \left(\frac{\alpha_0^* + Re_t/R_k}{1 + Re_t/R_k} \right) \quad 3.16$$

$$Re_t = \frac{\rho k}{\mu \omega}, \quad R_k = 6, \quad \alpha_0^* = \frac{\beta_i}{3}, \quad \beta_i = 0.072$$

$$F_2 = \tan h(\phi_2^2) \quad 3.17$$

$$\phi_2 = \max \left[2 \frac{\sqrt{k}}{0.09 \omega y}, \frac{500 \mu}{\rho y^2 \omega} \right]$$

where y defines the distance to the next surface.

It can be noticed that equations above evolve many constants. The values of these constants are presented in the table below.

Table 1. SST k- ω model constant [41].

Constant	Value	Constant	Value
$\sigma_{k,1}$	1.176	α_∞^*	1.0
$\sigma_{k,2}$	1.0	α_∞	0.52
$\sigma_{\omega,1}$	2.0	α_0	1/9
$\sigma_{\omega,2}$	1.168	β_∞^*	0.09
a_1	0.31	R_β	8.0
$\beta_{i,1}$	0.075	R_k	6.0
$\beta_{i,2}$	0.0828	R_ω	2.95
ζ^*	1.5	M_{t0}	0.25

3.1.2.2 Large eddy simulation LES

As the name indicates, Large Eddy Simulation or what is known as LES is dependent on solving highly turbulent regions. It can be stated that turbulent flows are characterized by turbulent eddies. In RANS models, these eddies are modeled by what is referred to as eddy viscosity models or Reynolds stress models. On the other hand, Direct Numerical Simulation resolves all turbulent flow characteristics. Therefore, LES falls in the category between RANS and DNS. As mentioned earlier, LES resolve large eddies which dominates the turbulent flow. The term large eddies refer to the kinetic energy of each eddy. For low energy eddies, sub-grids models are implemented to capture it. The advantages of LES are that [41]:

- Passive scalars such as mass, momentum, and energy are mostly transported by large eddies.
- Large eddies are more dependent on geometry and boundary condition, while small eddies are not. Hence, they are universal and tend to be isentropic.
- There is a high chance of finding a universal model for small eddies.

Although LES is more expensive than RANS, it gives more accurate numerical results. However, DNS is much more expensive and it requires much more computational resources. Therefore, in this thesis it was decided to run only two LES cases to capture more of flow characteristics.

Figure 27 shows turbulent kinetic energy density versus eddies wave number. The area under the curve represents the kinetic energy that resamples the size of an eddy and can be calculated through turbulence model transport equations, while wave number indicate the diameter which is defined by

$$WN = \frac{2\pi}{d} \quad 3.18$$

Where WN is the wave number and d is the eddy diameter.

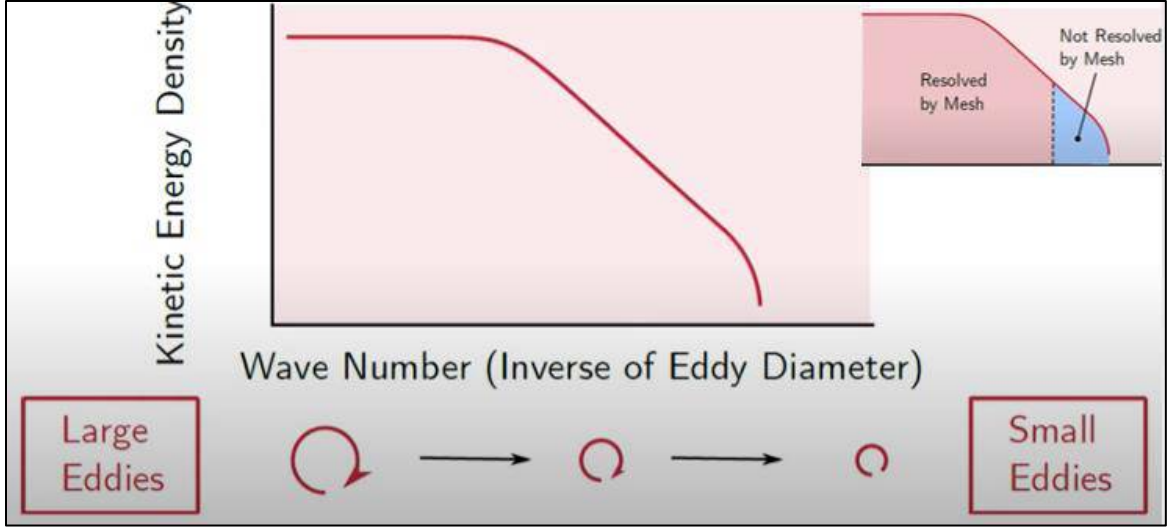


Figure 27. Distribution of turbulent kinetic energy on flow.

Strictly speaking, mesh resolution plays an important role in defining the amount of resolved eddies kinetic energy. Eddies that are smaller than a mesh cell are modelled by subgrid models. Hence, mesh cells should be sized according to the desired percentage of turbulent kinetic energy to be resolved. This is done by calculating what is known as integral length scale. It is a representative length of eddies at a certain location. It can be calculated through CFD post-processing by:

$$l_0 = \frac{k^{3/2}}{\epsilon} \quad 3.19$$

Where l_0 is the integral length scale, k is turbulent kinetic energy and ϵ is turbulent dissipation rate.

Then the percentage of eddies resolved across the domain is defined by how many cells is located within the integral length scale. It can be written as a factor f .

$$f = \frac{l_0}{\Delta} \quad 3.20$$

Where $\Delta = \sqrt[3]{Cell Volume}$

Table 2 shows the value of f that corresponds to percentage of resolved eddies.

Table 2. Percentage of resolved eddies corresponding to length scale to mesh factor [41].

% of resolved k	f
10	0.33
50	1.25
80	4.8
90	12.5

For sub-grid modelling, there are four models that can be used in Ansys Fluent. They are Smagorinsky-Lilly model, dynamic Smagorinsky-Lilly model, Wall-Adapting Local Eddy-Viscosity model WALE, and dynamic kinetic energy subgrid-scale model. Subgrid modelling starts with filtering operation of the Navier-Stokes equations. Then Boussinesq hypothesis is employed to model subgrid-scale turbulent viscosity. In this thesis, WALE model was implemented to compromise between accuracy and simplicity. Furthermore, WALE model has an advantage when dealing with laminar shear flow in which it returns zero value of turbulent viscosity. However, this is not the case in the Smagorinsky-Lilly model. Turbulent viscosity in WALE is computed using [41]:

$$\mu_t = \rho L_s^2 \frac{(S_{ij}^d S_{ij}^d)^{3/2}}{(\overline{S_{ij} S_{ij}})^{5/2} + (S_{ij}^d S_{ij}^d)^{5/4}} \quad 3.21$$

Where L_s and S_{ij}^d are defined as

$$L_s = \min (\kappa d, C_W V^{1/3}) \quad 3.22$$

$$S_{ij}^d = \frac{1}{2} (\overline{g_{ij}}^2 + \overline{g_{ji}}^2) - \frac{1}{3} \delta_{ij} \overline{g_{kk}}^2 \quad 3.23$$

$$\overline{g_{ij}} = \frac{\partial \overline{u_i}}{\partial X_j}$$

The values model constants κ and C_w are 0.41 and 0.325 respectively. d in the above model equation is the distance to the nearest wall.

3.1.3 Pressure based and density based solvers

In CFD there are two types of solvers, which are pressure based solver and density based solver. Essentially, each solver was developed to solve a certain range of flow speed. Pressure based is usually used for low speeds where incompressible flow assumption is valid, $M < 0.3$. In contrast, density based solver was developed to solve high speed compressible flows, $M > 0.3$. Later, both solvers are reformulated to be used beyond their original operative range. However, it should be used with caution when used outside their intended flows.

In both approaches, velocity field are obtained from momentum equations. In density based approach, flow density is obtained from continuity equation, whereas pressure is obtained from the state equation. On the other hand, pressure based approach solve pressure field by the pressure correction equation that is resulted from manipulations of momentum and continuity equations.

The main difference between the solvers is the equation coupling. Density based solver solves continuity, momentum, energy equation simultaneously before moving to other equations such as state equation and turbulent transport equations. However, there are two solution schemes to be used in pressure based solver. They are coupled and segregated schemes. In segregated scheme algorithms, the solver starts with solving for velocity by the momentum equation, then it moves to pressure correction equation. After that, it solves the remaining governing equations and turbulent transport equations. Though, coupled algorithms differ in coupling momentum and pressure correction equations, in which they are solved simultaneously. Figure 28 explains the method of each solver.

It should be noted that more equations coupling results in more computation time, but it is essential in solving high speed flows. What is done in equations coupling is that the nonlinear system of governing equations is solved iteratively before moving on to other equations. Thus, more coupling allows to solve more complex problem and requires more time. The table below illustrates the speed range for each solver type, which is an Ansys recommendation.

Throughout this thesis, density based solver is utilized for in RANS Calculation since flow speed ranges from 0.6 to 2.5 Mach number. In LES and six degrees of freedom calculation Coupled pressure based solver was used since flow speed is below 2 Mach number

Table 3. Flow speed and corresponding recommended solver.

Flow Mach number	$M \leq 0.3$	$0.3 \leq M \leq 2.0$	$2.0 \leq M$
Recommended solver	Segregated pressure based	Coupled pressure based	Density based

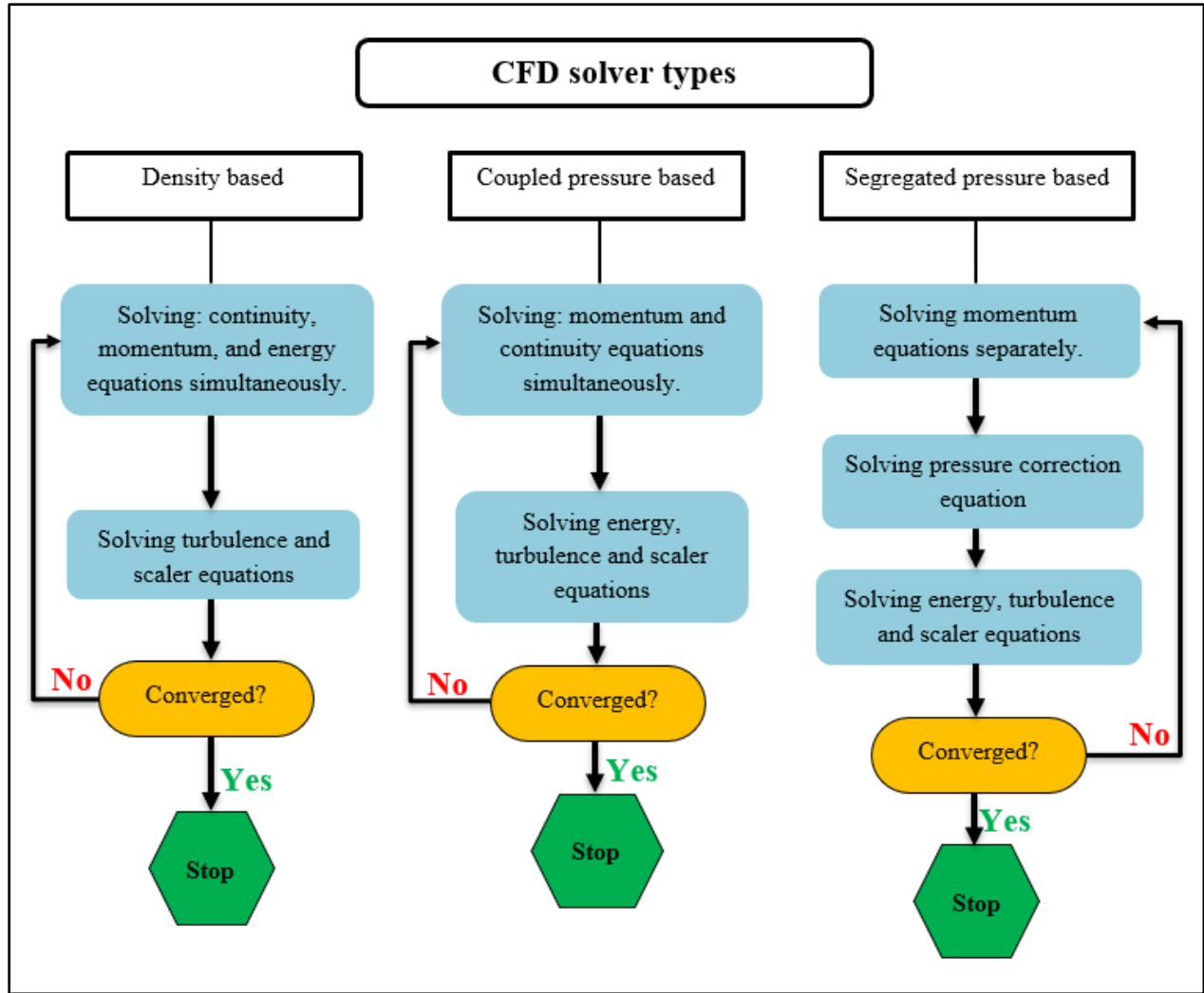


Figure 28. Solution Algorithms process of pressure based and density based solvers.

3.2 Baseline projectile geometry and design modifications

M33 is the selected projectile for this study. It is a 12.95mm-cal projectile. Geometry, mass properties and aerodynamic characteristics was obtained from [2, 16, 42]. The reason for nominating M33 bullet is that there is sufficient information about it in the literature, in terms of mass properties and wind tunnel test data that is utilized in validation. Table 4 shows mass properties of M33.

Table 4. M33 mass properties [42].

Property	Value	Unit
Diameter	12.95	mm
Length	57.757	mm
Mass	42	g
CG location from nose	34.706	mm
Reference area	0.0001317	m ²
Longitudinal moment of inertia I _{xx}	7.85×10^{-8}	Kg. m ²
Lateral moment of inertia I _{yy}	7.45×10^{-7}	Kg. m ²
Lateral moment of inertia I _{zz}	7.45×10^{-7}	Kg. m ²

Furthermore, boattail configurations of M33 were studied at different lengths and angles [32], where 7° boattail angle was found optimum for drag reduction in the transonic flow regimes. Consequently, boattail modifications will be studied in the following sequence:

1. Aerodynamic analysis will be conducted over the original design of M33 and results will be validated with the experimental values. Detailed dimension of the projectile is appeared in Figure 29. This configuration is denoted later by M33 or M33 9° BT.
2. A 7° boattail angle will be introduced, since it was found optimum at transonic speed and it is a good reference to be compared to other configurations. This configuration is presented in Figure 30. This configuration is denoted later by 7° BT.

3. Boattail angle will be increased to 10° , as shown in Figure 31. As a result, base area will decrease. On the other hand, this may lead to earlier separation due to adverse pressure gradient. This configuration is denoted later by 10° BT.
4. Riblets will be added to the 10° Boattail, as shown in Figure 32. The depth of the riblets is 0.015 of caliber size. The aim is to increase flow turbulence and delay the separation. Though, there may be undesired effects on total drag. This configuration is denoted later by riblets BT.
5. Base area will be kept as the 10° BT configuration and conical boattail will be replaced with arc configuration as in Figure 33. Here, the boattail angle changes gradually which may help in flow attachment. This configuration is denoted later by arc BT.
6. Cavity of 2 mm depth is introduced on projectile base, keeping original boattail parameters, which is presented in Figure 34. This creates a sort of vacuum at the base to decrease the effect of adverse pressure gradient. This configuration is denoted later by SBC which stands for small base cavity.
7. A larger cavity of depth 4 mm is introduced, as in Figure 35. Results of this configuration can be compared to the preceding configuration to investigate the effect of cavity size. This configuration is denoted later by LBC which stands for large base cavity.

In LES modeling, original configuration was studied in addition to 10° riblets, because of high turbulence introduced at boattail. On the contrary, 6DoF modeling is done on the original configuration after simplifying the geometry by removing the middle groove, to facilitate the creation of dynamic mesh.

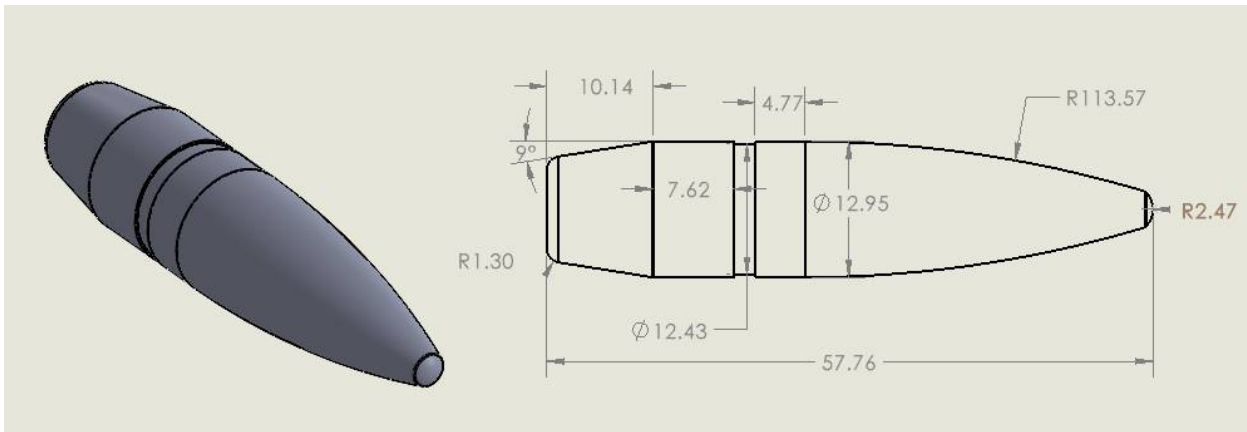


Figure 29. Original M33 Geometry (mm).

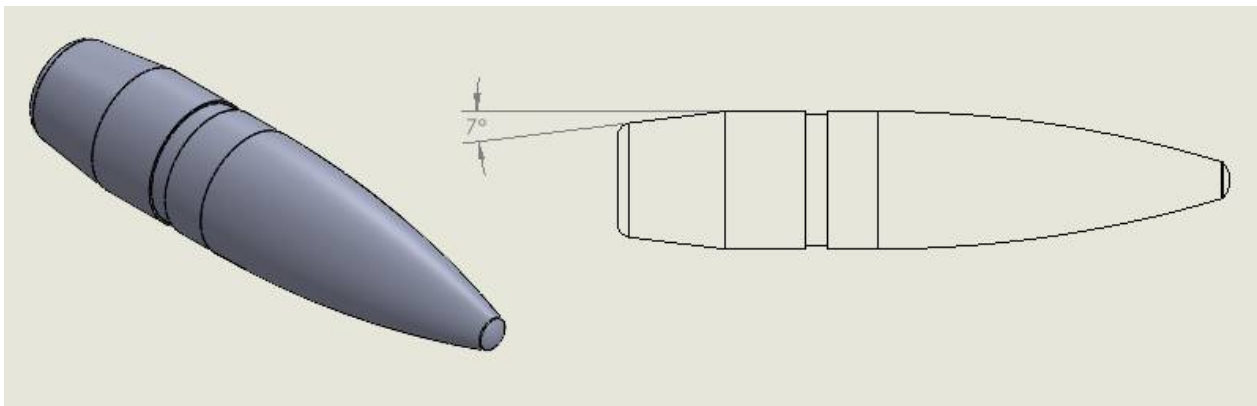


Figure 30. 7° Boattail (mm).

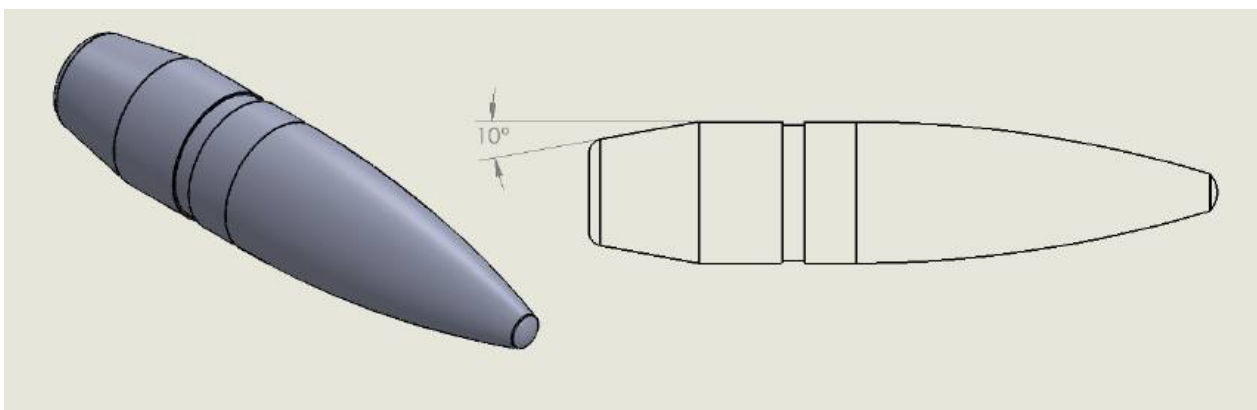


Figure 31. 10° Boattail (mm).

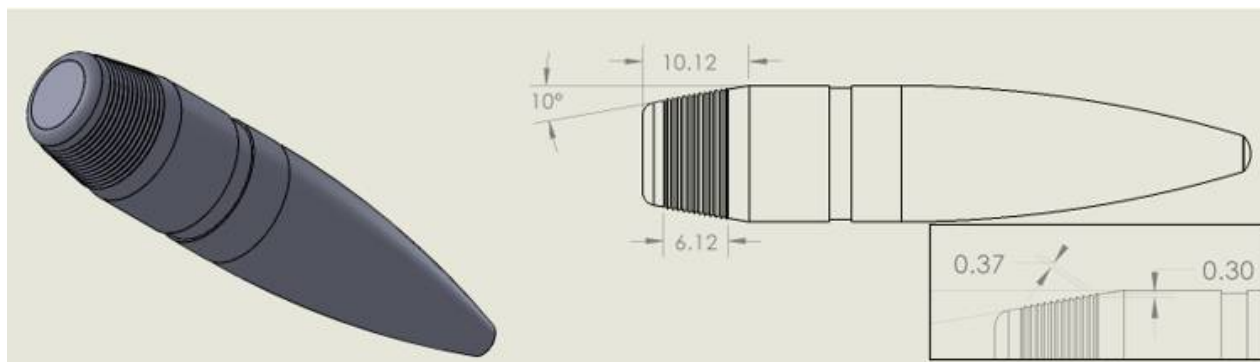


Figure 32. Boattail with riblets (mm).

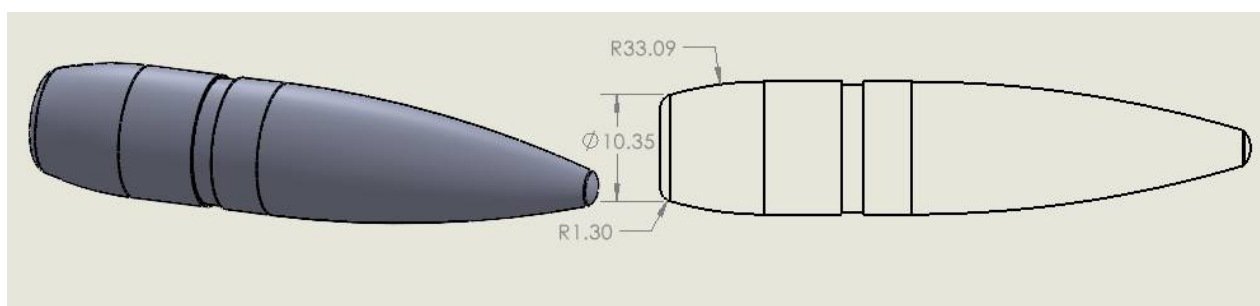


Figure 33. Arc Boattail (mm).

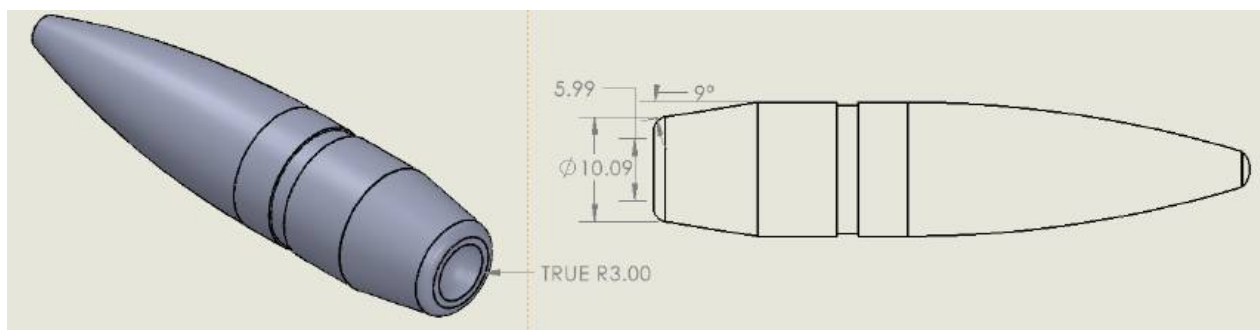


Figure 34. 2 mm depth base cavity (mm).

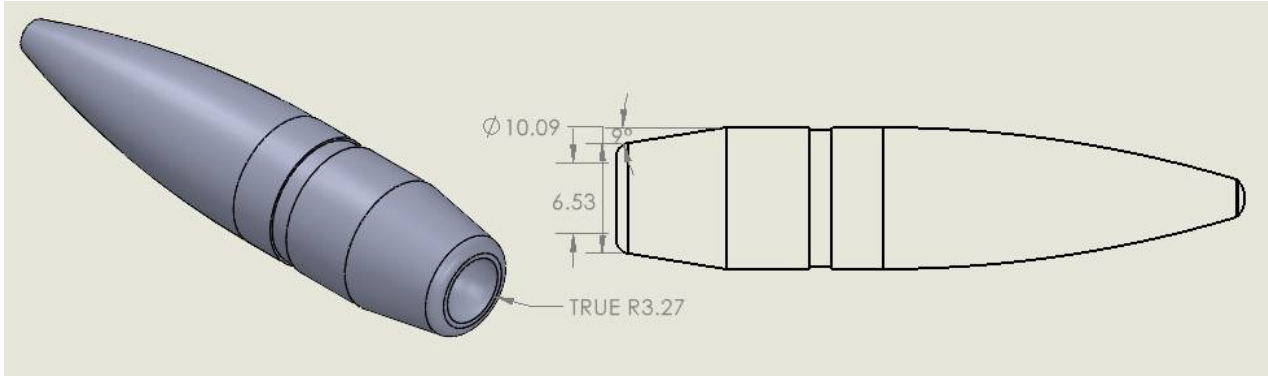


Figure 35. 4 mm depth base cavity (mm).

3.3 Flow domain and meshing

As mentioned earlier, simulations of this study involve speeds from Mach 0.6 up to Mach 2.5. Thus, the meshing should accommodate all associated aerodynamic phenomena, such as turbulence, shock waves and high wall shear stress. Therefore, meshing domain is selected to be spherical with radius that is 10 times projectile length, as shown in Figure 36. Then a cylindrical subdomain of influence is applied near the projectile to increase mesh elements in that region which appears in Figure 37. The radius of the subdomain is two times caliber size while the length is three times projectile length. Furthermore, inflation layers, of 1.2 growth rate, were generated on the surface that covers boundary layer region and satisfy the requirement of the dimensional wall displacement parameter (y^+).

The mesh is created using local sizing on surfaces with a growth rate of 1.15. As can be seen in the figures below grids consist of tetrahedral elements with prism layers. It should be noted that mesh resolution is optimized for:

1. Describing the geometry
2. High mesh quality
3. Calculating aerodynamic coefficient and flow properties accurately

4. Improving solution convergence
5. Minimizing solution time

Further details on meshing, element count, and inflation layers will be elucidated in chapter 4 in the mesh independence study.

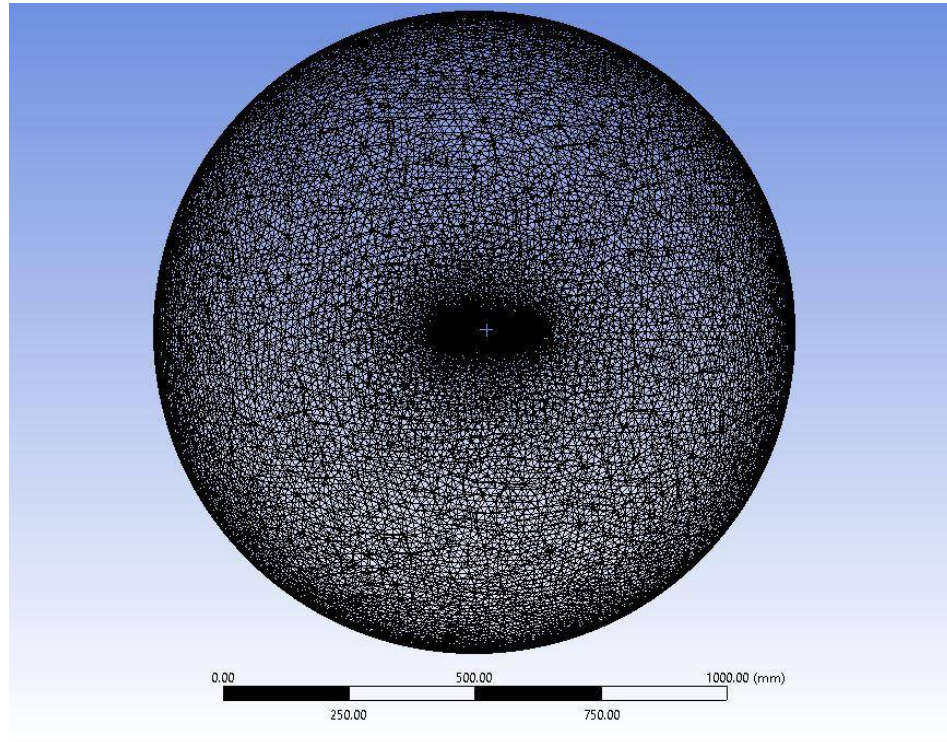


Figure 36. Outer domain mesh.

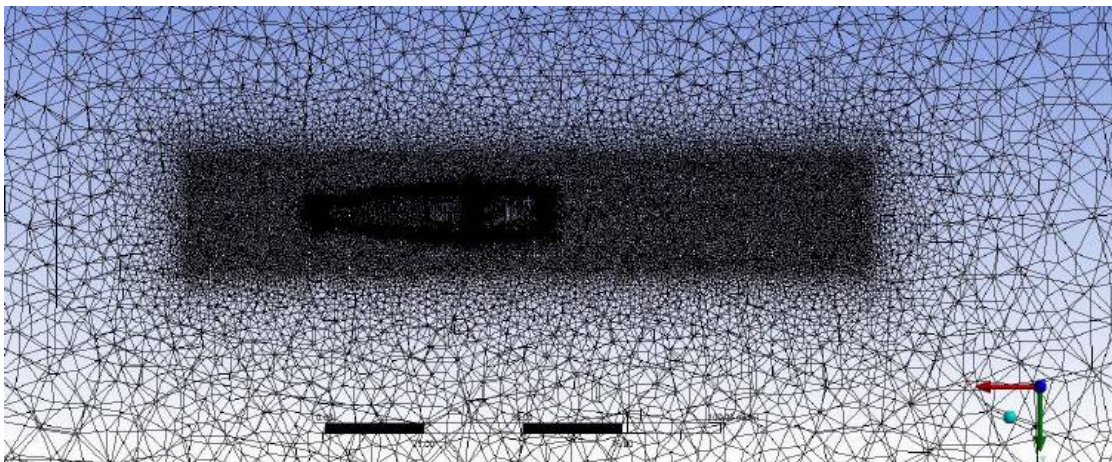


Figure 37. Domain of influence.

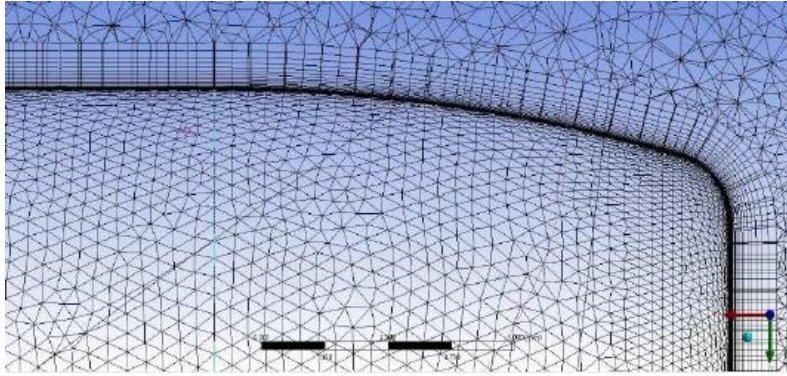


Figure 38. Mesh inflation layers.

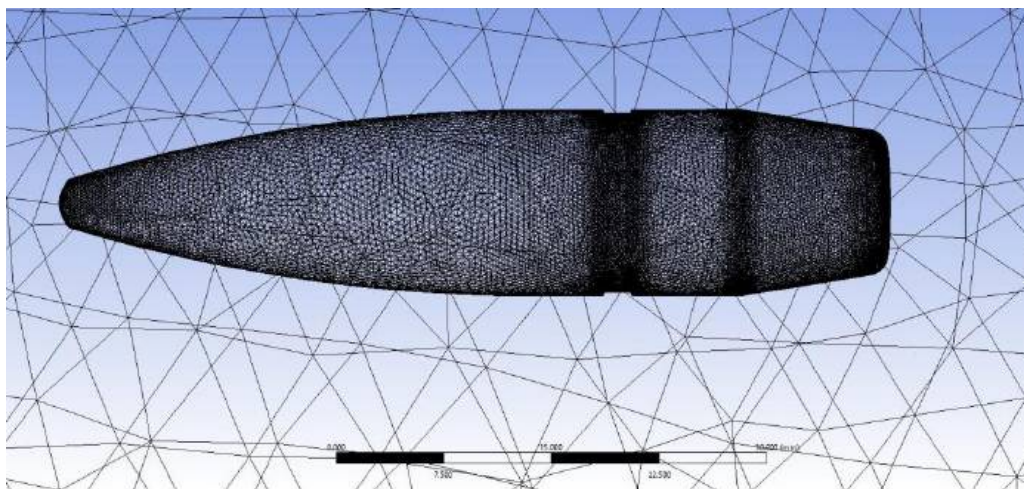


Figure 39. Original configuration surface mesh

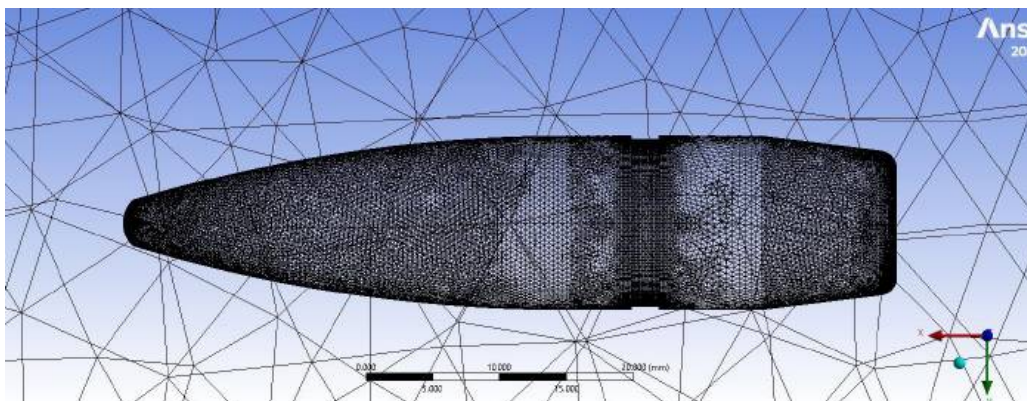


Figure 40. 7° boattail surface mesh

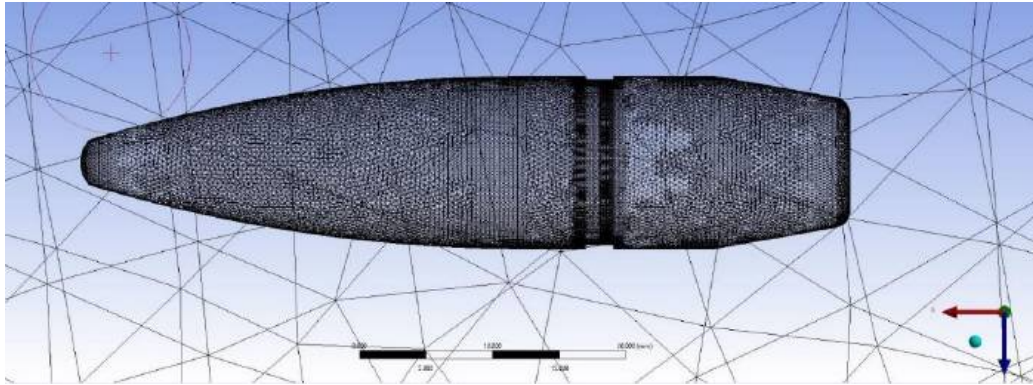


Figure 41.10° boattail surface mesh

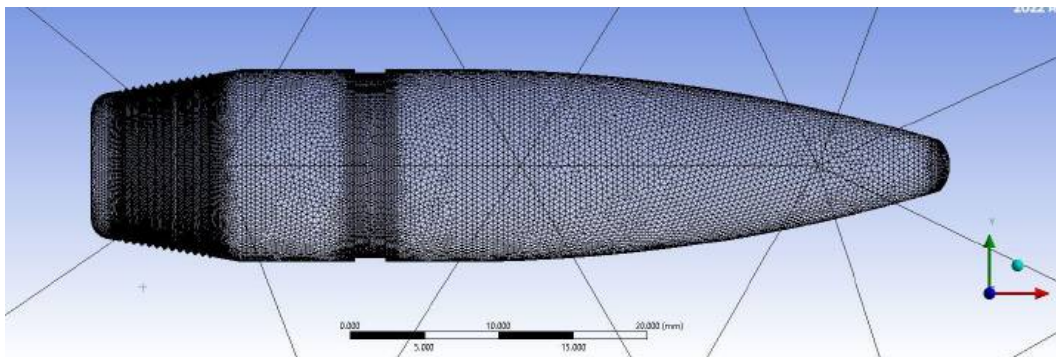


Figure 42.10° with riblets boattail surface mesh.

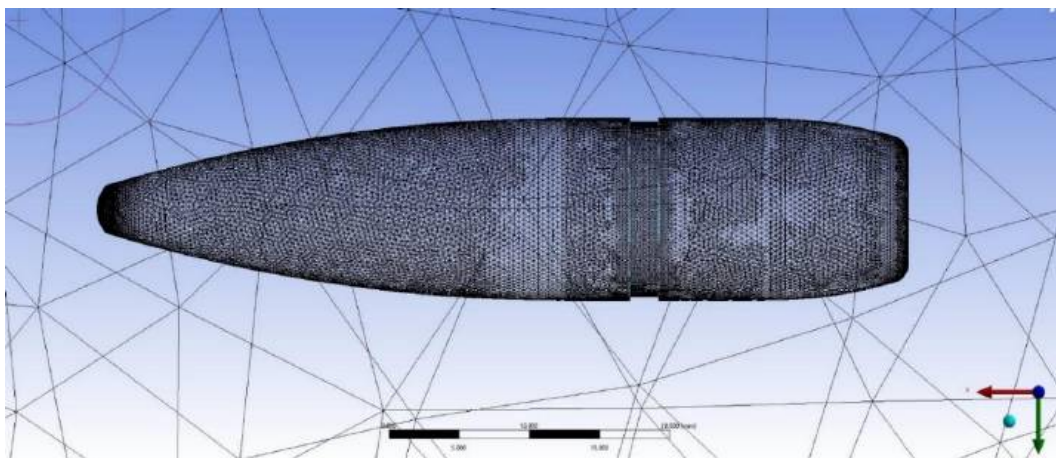


Figure 43. Curved boattail surface mesh.

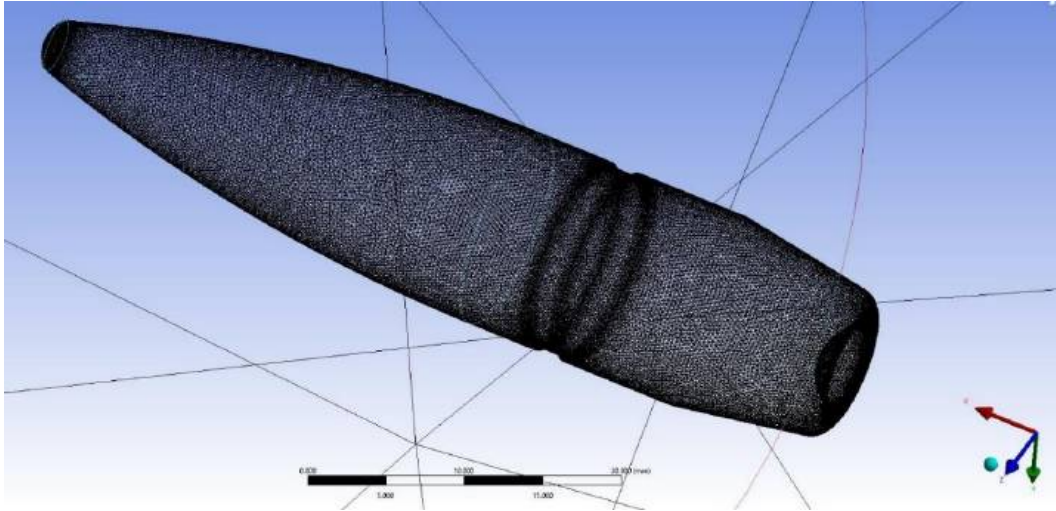


Figure 44. 2mm base cavity surface mesh.

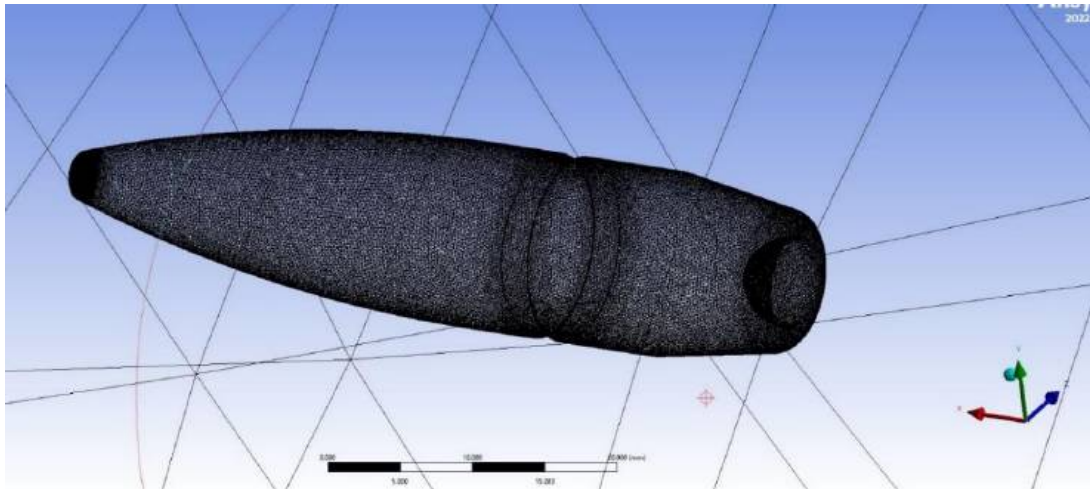


Figure 45. 4mm base cavity surface mesh.

For LES meshing, in addition to the cylindrical domain of influence, another spherical domain is added of radius 2.5 if projectile length, as appeared in Figure 47. Here the mesh count is 31 million elements. This is according to LES requirements to resolve 80% of eddies kinetic energy. Furthermore, now the meshing growth rate is 1.1. Figure 48 and Figure 49 represent the surface mesh on both the original and the riblets configurations.

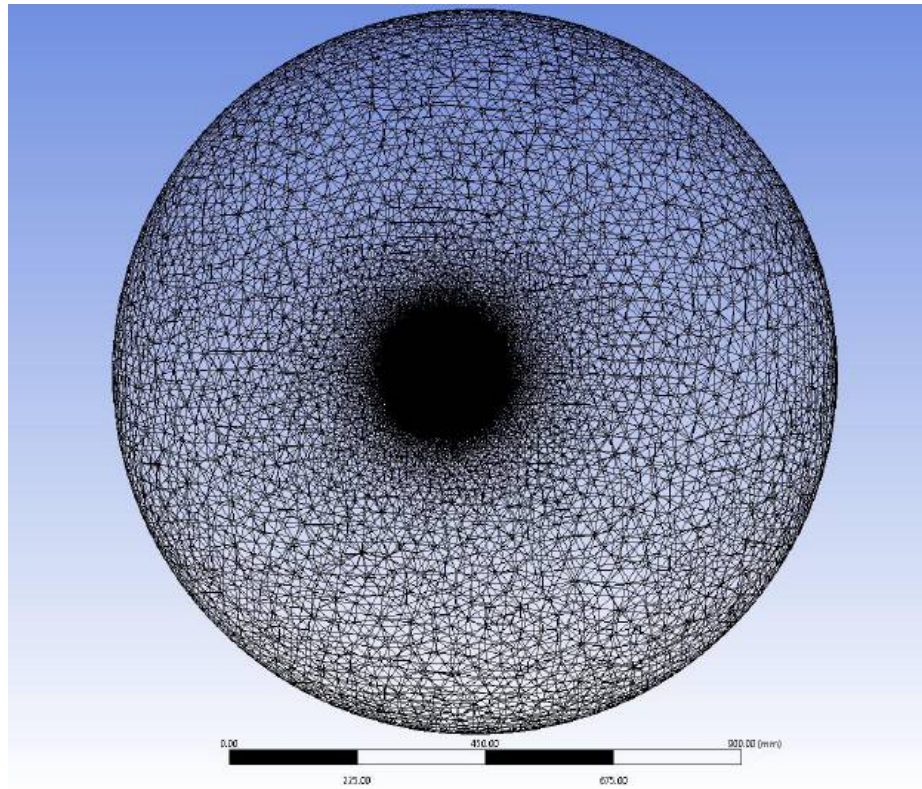


Figure 46. LES outer domain mesh.

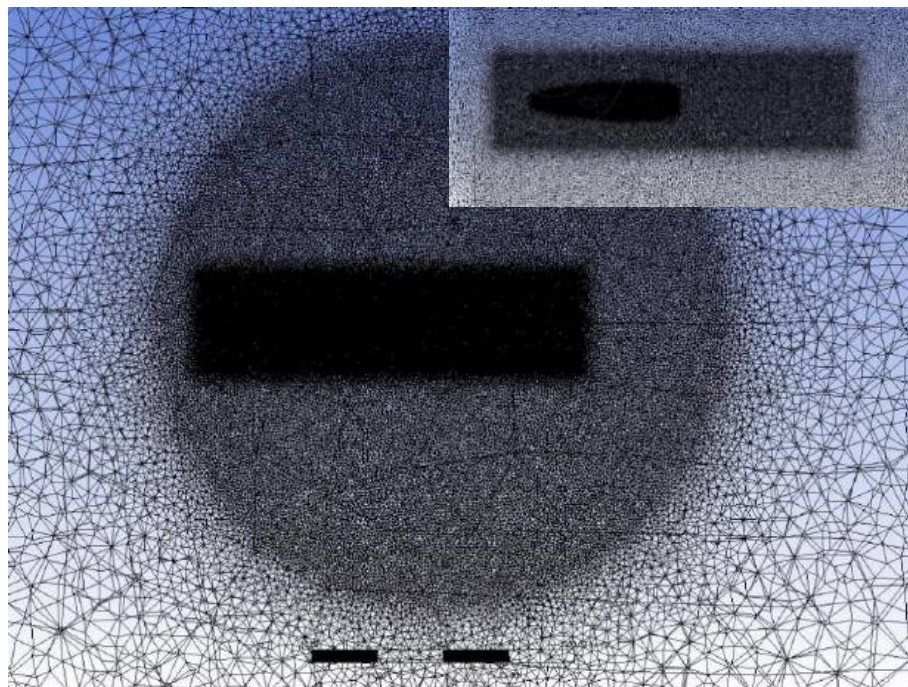


Figure 47. LES domains of influence.

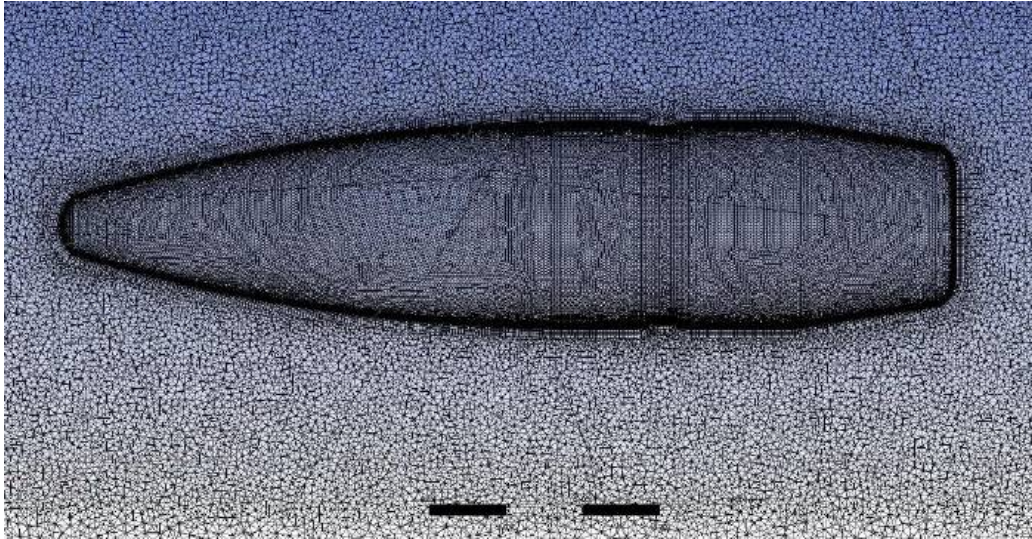


Figure 48. LES meshing of the original configuration.

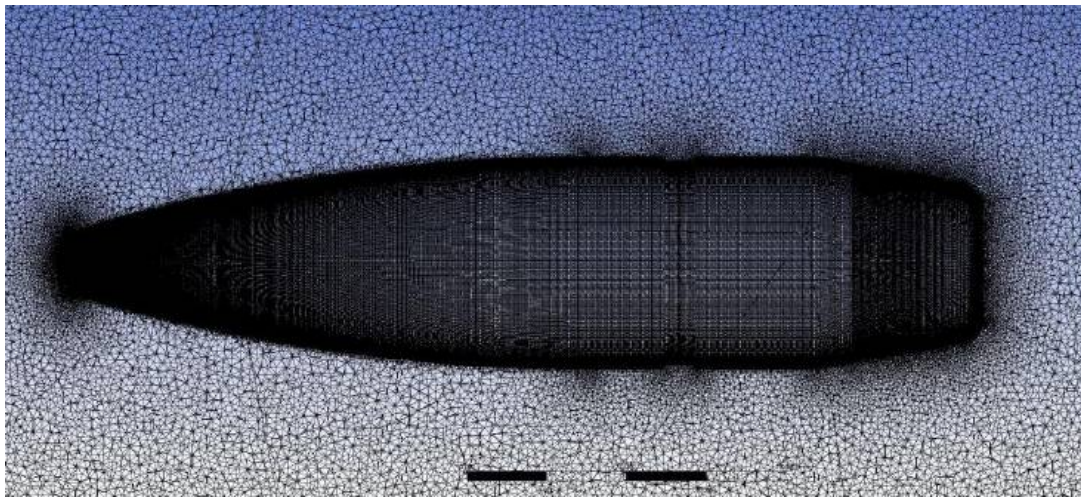


Figure 49. LES meshing of the riblets configuration.

In 6 degrees of freedom simulation the CAD model is simplified further by removing the middle groove. This facilitates the 6DoF modeling, since it involves dynamic mesh which requires high mesh quality. Moreover, low mesh resolution, of 1.5 million element count, is utilized to reduce simulation time.

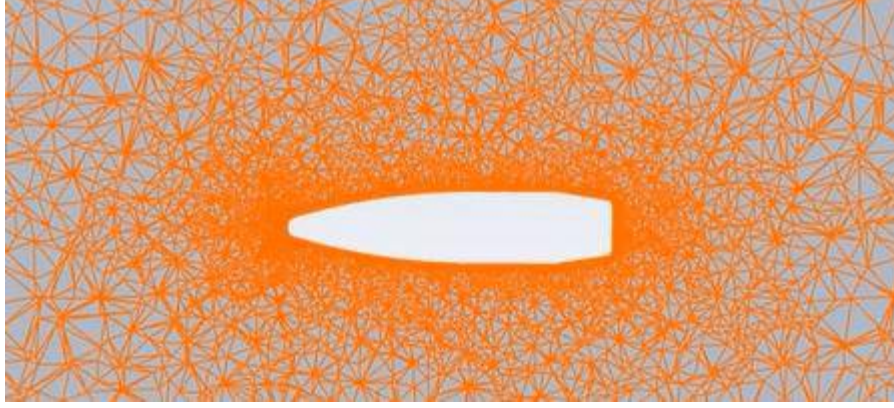


Figure 50. Mesh of the 6DoF model.

3.4 Pre-processing setups

This section explains the setups done before processing the CFD calculations. At first, RANS calculations over the different projectile configurations are carried out with freestream Mach numbers that enclose most of flight regimes. Namely at 0.6, 0.8, 0.9, 1.0, 1.1, 1.2, 1.5, 2.0, and 2.5 Mach numbers. Also, these speeds encompass most of spinning projectiles flying envelopes. In order to calculate coefficients derivatives such as $C_{L_{\alpha_0}}$ and $C_{M_{\alpha_2}}$, the simulations were conducted over zero, 2, and 4 degrees angles of attack. It is worth mentioning that with the 7 different configurations, 9 freestream speeds and 3 angles of attack, the number of simulation cases adds up to 189 cases of RANS calculations. This number does not include simulation associated with verification and during the mesh independence study.

During the computations air properties are set to sea level condition which appears in Table 5. Projectile spin rate defers at each free stream velocity so that the nondimensional rotating velocity parameter equals 0.2135 [16], defined by the relation:

$$\frac{pd}{v} = 0.2135$$

Here, p is the spin rate in rad/s, d is the projectile caliber in m, and v is the freestream velocity in m/s.

Table 6 illustrates spin rate that corresponds to each simulated Mach number.

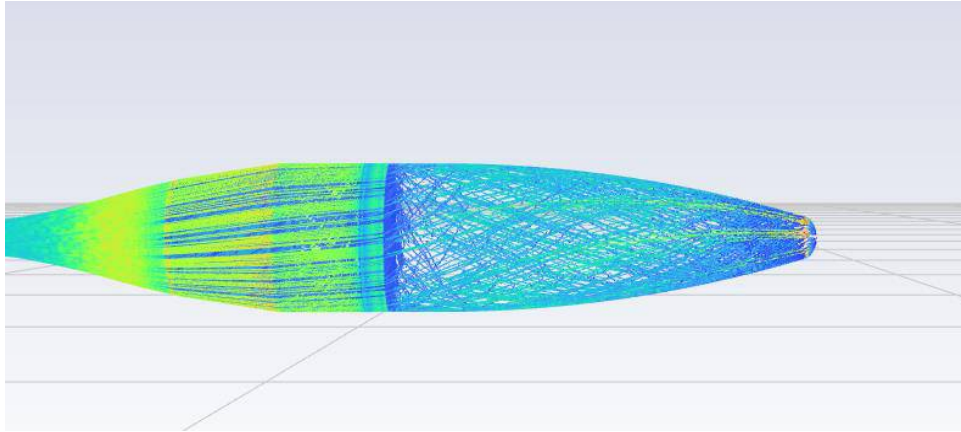


Figure 51. Streamlines around the spinning projectile.

Table 5. Sea level condition air properties [40].

Property	Value	Unit
Density (ρ)	1.225	Kg/m ³
Temperature (T)	288.16	K
Pressure (p)	101325	Pa
Viscosity (μ)	0.00001789	Kg/(m.s)
Speed of sound (a)	340.3	m/s

Table 6. Spin rate corresponding to each Mach number

Mach number	Spin rate (rad/s)
0.6	3367
0.8	4489
0.9	5050
1	5611
1.1	6173
1.2	6733
1.5	8417
2	11223
2.5	14028

ANSYS Fluent of version 2022 R1 was used for all CFD calculations. During RANS calculations, the solver was set to density based solver, since flow speed varies from subsonic to high supersonic and compressible flow is assumed. Solution Scheme is selected to be implicit and gradient terms were computed using least square cell-based method. The governing equations are discretized by the second-order upwind scheme. In the outer domain, the boundary condition is set to pressure far-field with sea level pressure and temperature. For the bullet surface, a no slip condition is set with rotating wall to simulate projectile spinning and to allow for the calculation of magnus force, magnus moment and spin damping moment. The resulted forces and moments are nondimensionalized by the parameters appearing in Table 7.

Table 7. Nondimensionalizing parameter of aerodynamic forces and moments.

Force and moment coefficient	Nondimensionalizing parameter
Drag force Coefficient (C_D)	$\frac{1}{2} \rho v^2 S$
Lift force Coefficient (C_L)	$\frac{1}{2} \rho v^2 S$
Magnus force Coefficient (C_{Np})	$\frac{1}{2} \rho v^2 S \frac{pd}{v}$
Magnus moment Coefficient (C_{mp})	$\frac{1}{2} \rho v^2 S d \frac{pd}{v}$
Overturning moment Coefficient (C_m)	$\frac{1}{2} \rho v^2 S d$
Spin damping moment Coefficient (C_{tp})	$\frac{1}{2} \rho v^2 S d \frac{pd}{v}$

In LES setups, the flow Mach number is set to 1.2 at zero angle of attack. The simulation was carried out over bullet original configuration and riblets configuration. The first configuration is selected to compare CFD results to experimental results, while riblets configuration is selected to get deeper study since it is rarely studied in the literature. At Mach 1.2, flow involves motivating phenomena such as shock wave and it is slightly low for faster calculation. Governing equations, solver setups, boundary conditions and discretization are similar to that in RANS calculations. The total simulation time was 0.00323 sec at 1e-6 sec time step. Firstly, RANS model was used to ensure convergence and check that the mesh is resolving at least 80% percent

of eddies kinetic energy, around the body. Then a URANS is conducted for gradual model complexity, before moving to LES.

In 6DoF simulation SST $k-\omega$ URANS model was used with time step of $2e-5$ sec and the total simulation time is 0.08 sec. Here, flow speed is set to subsonic with 0.6 Mach number. This speed allows the use of pressure based solver with coupled scheme which is relatively simpler than the density based. The aim of the 6DoF simulation is to assess projectile's gyroscopic stability at multiple roll rates. The initial roll rates for the five cases are: 0, 500, 1000, 2500, and 5000 rad/sec. in order to investigate the stability an initial angle of attack is set 2 degrees.

CHAPTER 4

VALIDATION AND VERIFICATION

Before proceeding into processing and numerical simulation, the initial solution will be validated and verified considering the following factors:

1. **Mesh independence study:** mesh resolution will be increased gradually until the change in drag coefficient becomes unnoticeable. This type of verification method is common on numerical prediction studies [18, 16, 43].
2. **Comparing with results from the literature:** after obtaining aerodynamic coefficients of the baseline configuration. They will be compared with existing data from literature, either numerical or experimental.
3. **Ensuring that the dimensionless distance above the wall y^+ is less than 1.0:** because of projectile high velocity in addition to spin, it is important capture flow velocity profile near the wall accurately. This also enhances the prediction of flow separation. Multiple studies suggest a value of y^+ not more 1.0 on projectile's first inflation layer [12, 18, 20, 21, 39].
4. **Convergence of forces, moments, and mass flow net flux:** to ensure solution convergence, the net flux of mass flow rate should approximately equal to zero, at the end of each simulation case ($\dot{m}_{inlet} = \dot{m}_{outlet}$). Also, the aerodynamic forces and moments should remain steady against simulation iteration before stopping the calculations.
5. **In LES, the aim is to resolve 80% of turbulence eddies near the body.** Hence, it will be ensured that $f \geq 4.8$ on most regions around the body, especially the base. This factor is explained in detail in chapter 3.

4.1 Mesh independence study and y^+

The aim of mesh independence study is to avoid any numerical error caused by mesh resolution. Also, the y^+ value will be assessed at each mesh. Initially a 1.3 million mesh element is created, and the value of drag coefficient and y^+ is evaluated. A 0.005 mm thickness of the inflation's first layer resulted in 1.9 y^+ value. Thus, mesh resolution is improved and first layer thickness is decreased which leads to improvement in y^+ value. Also drag coefficient becomes constant as mesh resolution increases. Table 8 presents mesh element count and first layer thickness corresponding to drag coefficient and y^+ . The simulations in the table were conducted over M33 original configuration at 1.5 Mach number and zero angle of attack.

Table 8. Mesh independence over M33 at $M = 1.5$.

Mesh Element count (million)	Inflation first layer thickness (mm)	C_D	y^+
1.3	0.005	0.384	1.9
2.4	0.005	0.379	1.9
4.6	0.005	0.367	1.9
5.4	0.003	0.363	1.2
6.1	0.002	0.363	0.8
6.9	0.002	0.363	0.8
8.7	0.002	0.363	0.8

From the above table, the selected mesh is the 6.1 million elements with 0.002 thickness of the inflation's first layer. It can be noticed that drag coefficient is not changing with mesh resolution and y^+ reached a value less than 1.0. Subsequently, the total number of inflation layers needed is 25 layers with a growth rate of 1.2. For the global domain, the mesh growth rate is set to 1.15

with local face meshing. Therefore, similar meshing method are applied to the subsequent configurations.

Figure 52 Shows y^+ on bullet surface at the maximum speed that is $M = 2.5$. Most of the surfaces have a y^+ value around 0.6. Although, at the nose it reaches a value of 2.62, the area weighted average does not exceed 0.8.

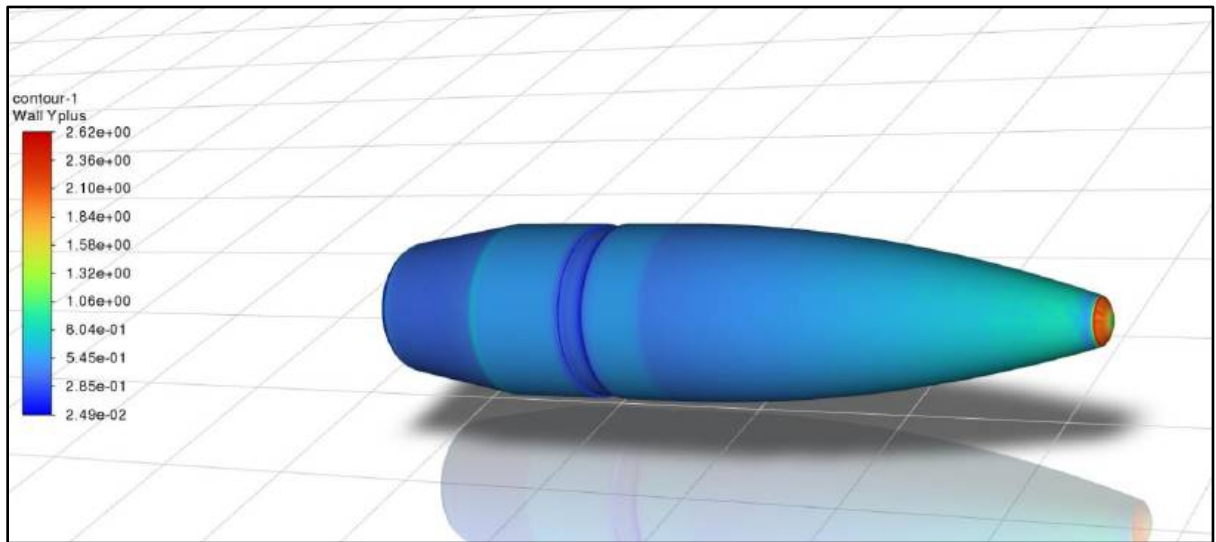


Figure 52. Wall y^+ over M33 at 2.5 Mach number.

4.2 Results validation

Results in this thesis are validated by comparing zero-yaw drag coefficient of the M33 projectile, with experimental and numerical results from the literature. McCoy conducted a wind tunnel tests ranging from 0.75 to 2.66 Mach number [44]. Also, S. Siltan studied the projectile numerically from 0.7 to 2.7 Mach numbers, where the mesh consists of 5.4 million cells [16]. The results of both researches are compared to this thesis for validation and they are appeared in Figure 53. It can be seen that CFD overpredict zero-yaw drag, especially in transonic and supersonic Mach

numbers. Furthermore, the current study predicts the value of drag coefficient better than the results from [16].

Another paper by S. Silton and S. Dinavahi investigated the M33 [32]. It concerned about the base drag. It discovered a phenomenon of negative base drag in the subsonic flow. Firstly, it was proved that this phenomenon is not numerical. Additionally, it was interpreted by the base curvature which accelerates the flow and leads to an increase in the base pressure. Thus, this work has investigated this phenomenon and compared the result with Silton and Dinavahi work. Figure 54 validates base drag at the subsonic flow regimes, and good agreement can be inferred between the two works.

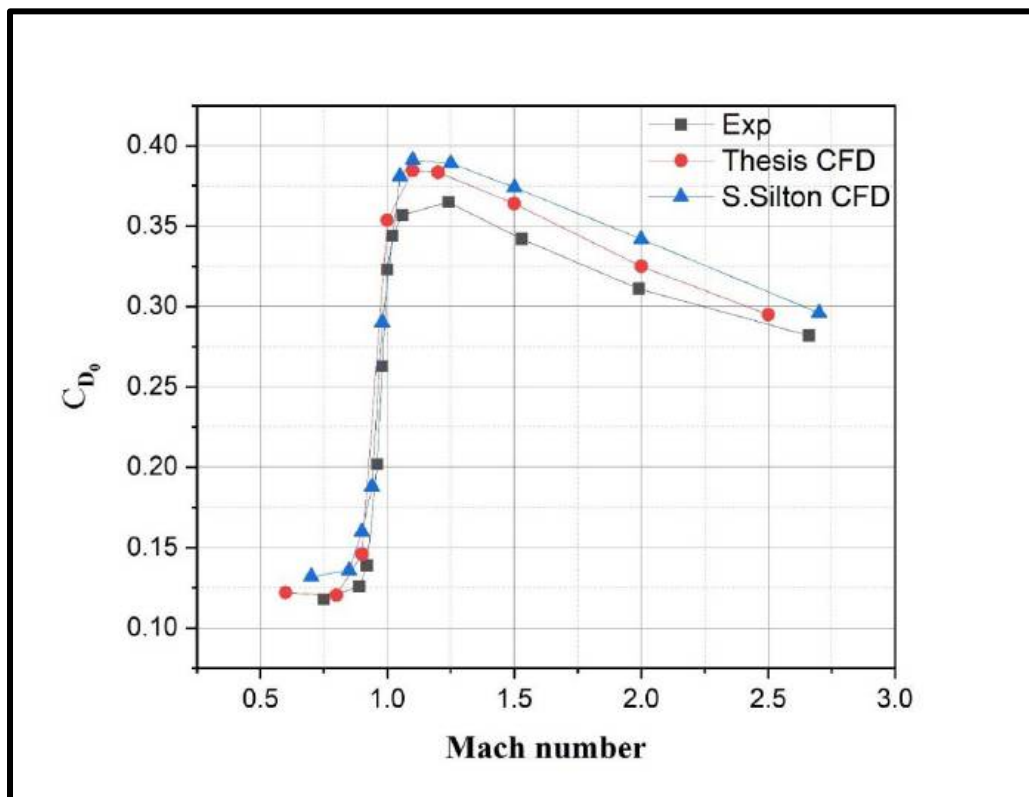


Figure 53. Zero-yaw drag comparison with experimental and numerical results.

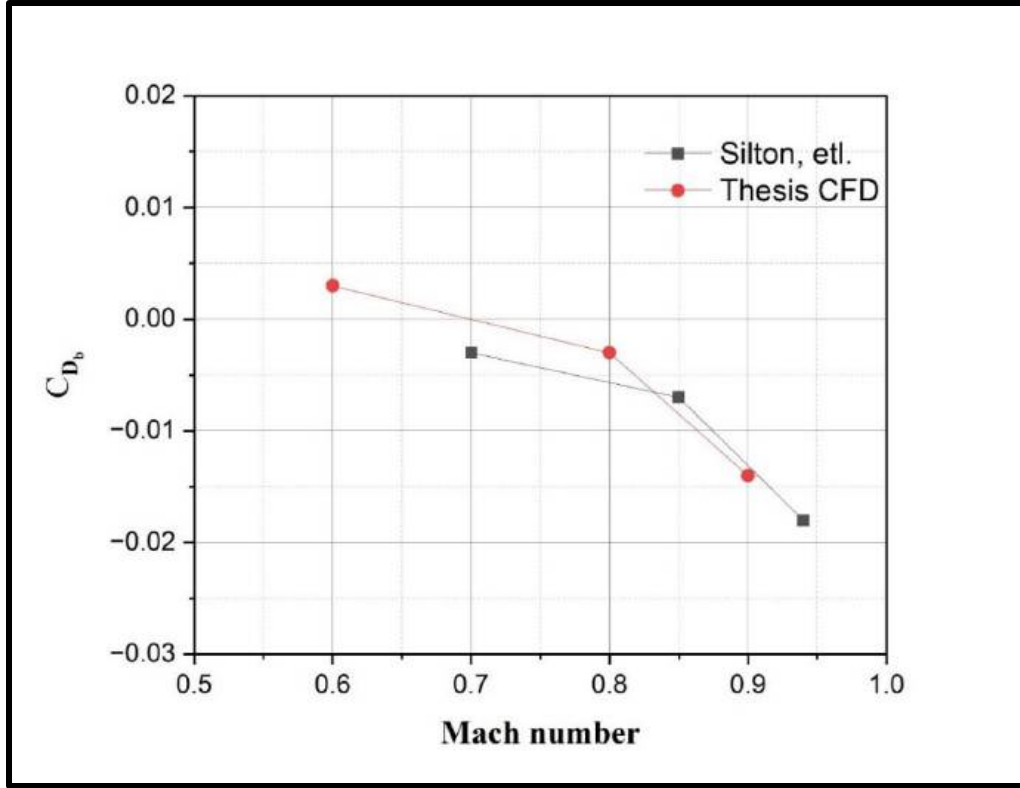


Figure 54. Base drag comparison with numerical results in subsonic flow.

4.3 Verification in LES

Because LES modelling requires substantially more time than RANS modelling, it is important to verify the pre-processing setups before proceeding into LES. As mentioned above, it will be assured that 80% of eddies kinetic energy is resolved by the mesh around the body. Returning to Table 2, integral length scale to mesh factor of 4.8 corresponds to 80% resolving. Figure 55 and Figure 56 illustrate the factor by the contour plots, for both M33 and riblets configurations. It can be seen that more than 80% of eddies kinetic energy is resolved in cylindrical sub-domain. In the base region where most of eddies energy is located, around 90% of eddies is resolved. This increases modeling credibility.

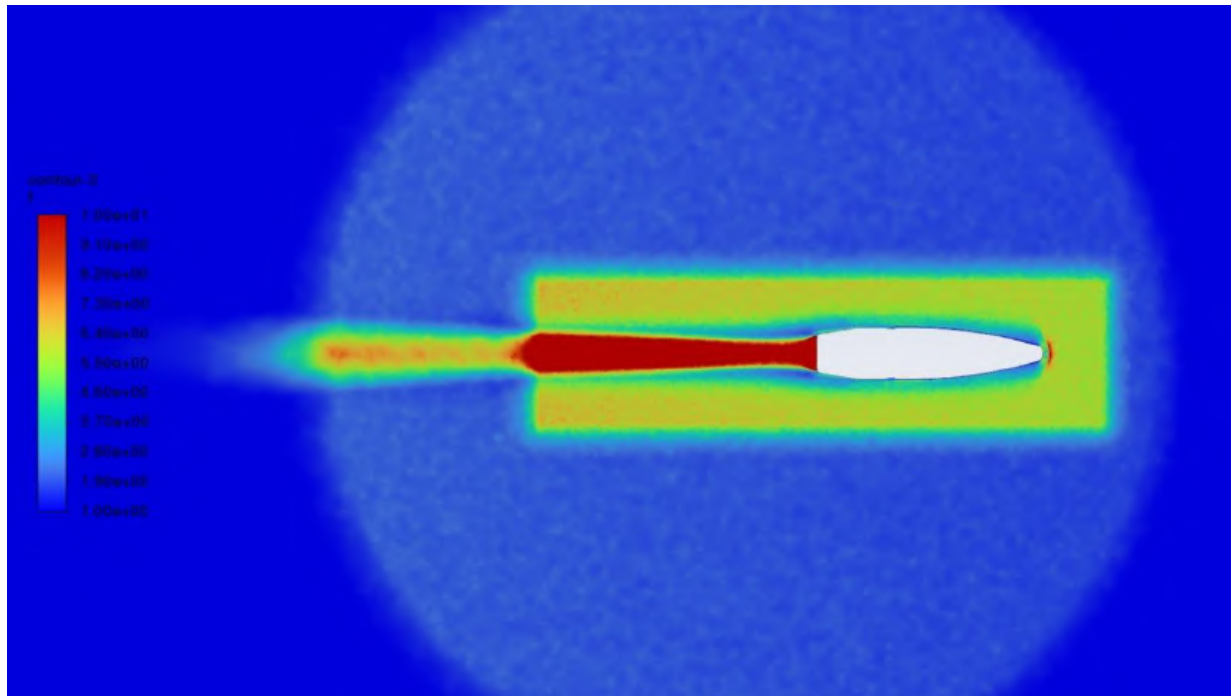


Figure 55. Integral length scale to mesh factor contour for the M33 configuration.

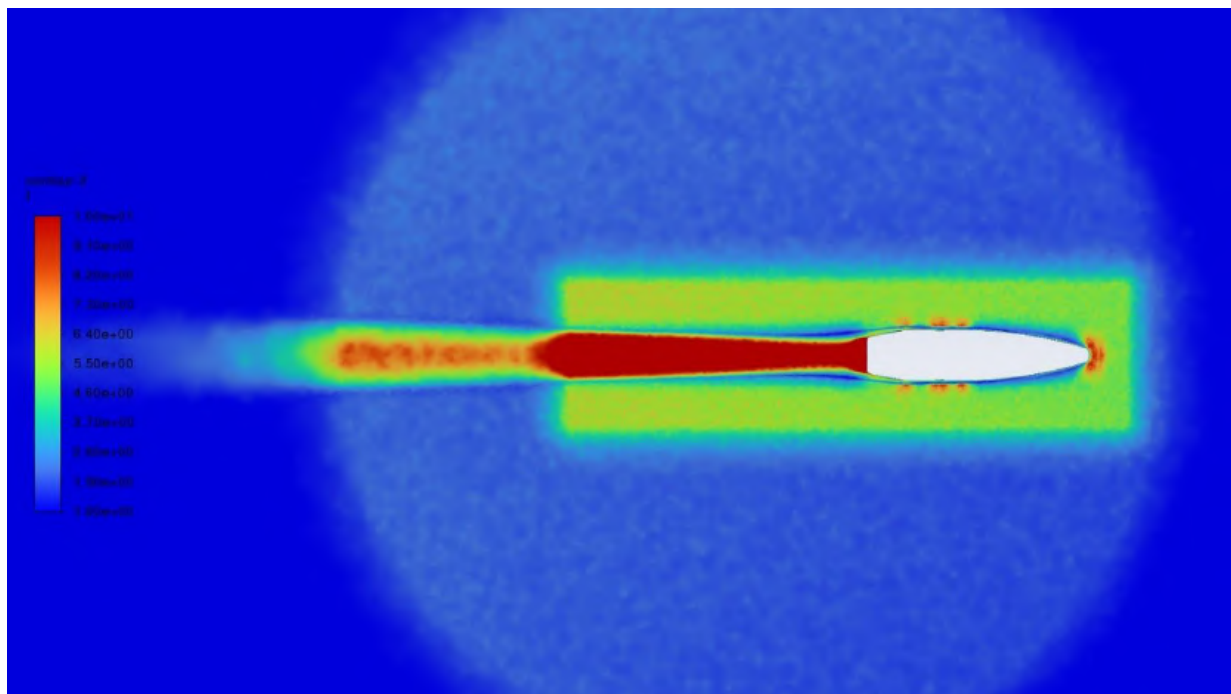


Figure 56. Integral length scale to mesh factor contour for the riblets configuration.

CHAPTER 5

RESULTS AND DISCUSSION

Comparisons between the aerodynamic coefficients of the different configurations will be conducted. First, differences in drag coefficient are investigated, which is the most affecting factor on projectile range. Next, the remaining coefficients are examined and effect of design features are highlighted. Moreover, this chapter illustrates some of air properties contours at different speeds. Also, results of the LES and 6DoF simulations are shown and discussed.

5.1 Aerodynamic coefficients comparisons

Figure 57 shows a comparison of the zero yaw drag coefficient from 0.6 to 2.5 Mach number. It can be noticed that no such configuration can provide superiorly low drag. However, for each flight regime some configurations perform better than others. In subsonic and low transonic speeds, the 10° BT performs the best and as boattail angle decreases the drag generally increases as can be seen in the M33 9° BT and 7° BT configurations. This could be referred to the larger base area. Additionally, riblets BT configuration is the highest in drag coefficient from 0.6 to 0.9 Mach number. This may be due to the larger area opposing the flow in the boattail. It worth mentioning that Arc BT was able to delay drag divergence as can be noticed at Mach 0.9.

In the transonic regime, the 7° BT is the lowest in drag which is confirmed by literature. This gives more validity to the current work. However, the remaining configurations are close to each other in drag with a slight supremacy for the LBC configuration. As the speed increases to supersonic speeds, the LBC performs better and becomes the lowest in drag at 2.0 and 2.5 Mach number. Also, it can be inferred that Arc BT is the highest in drag in the supersonic regime.

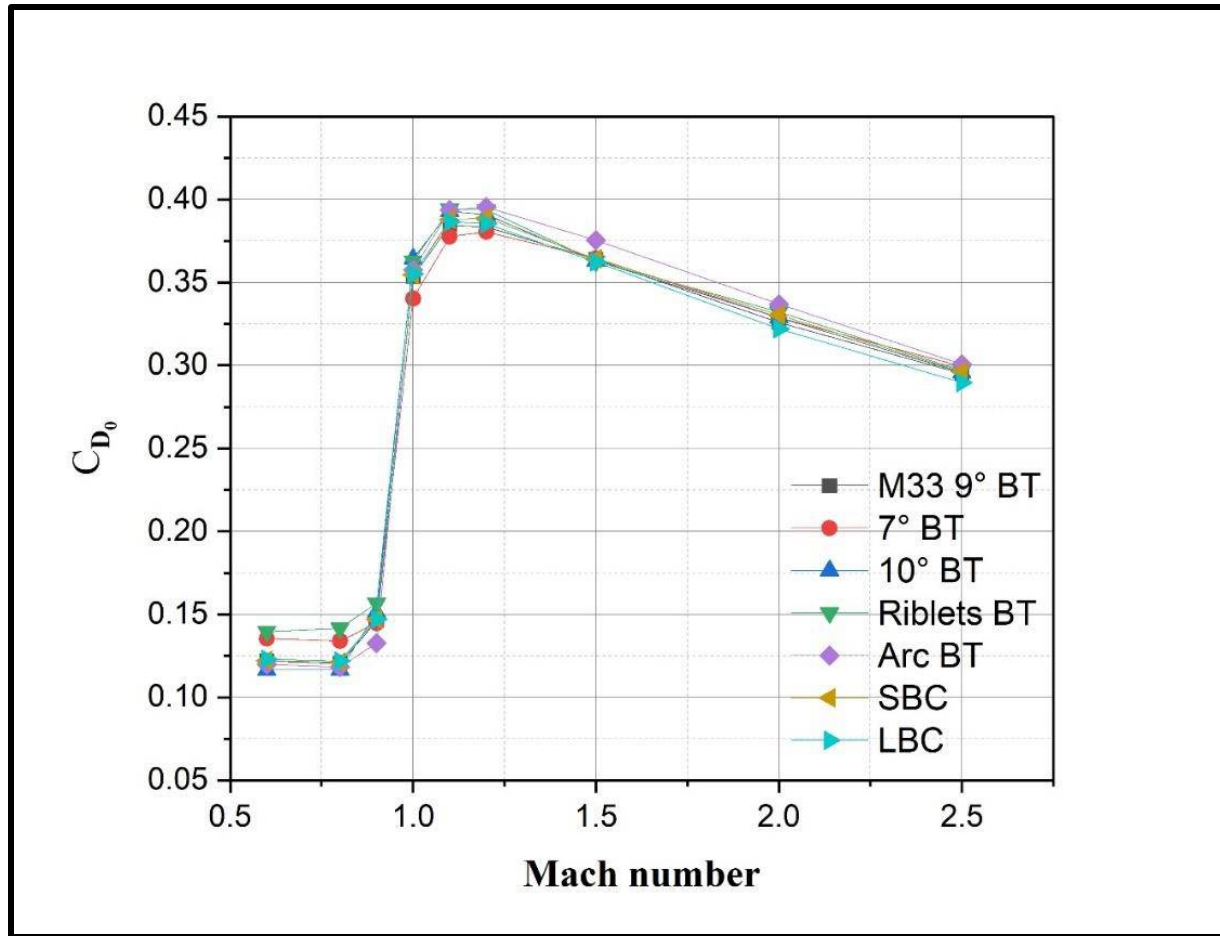


Figure 57. Zero yaw drag coefficient versus Mach number for different configurations.

The comparison of base drag coefficient appears in Figure 58. It is clear that the 7° BT experiences the largest base drag among all configurations from subsonic to supersonic. The arc BT is lowest in the subsonic base drag. However, this is not the case for supersonic speeds. Also, it can be seen that riblets BT performs well at high supersonic flows. One can interpret the high zero yaw drag and the low base drag in riblets BT by the turbulence and shock waves induced by riblets. However, the maintain flow attachment and increase pressure coefficient at the base. Examining the SBC, there is no noticeable deference compared to M33, in either zero yaw drag or base drag. In Table 9 drag coefficients are shown. Also, it represents the ratio of base drag to zero yaw drag to give more insights about them. The negative sign indicates a negative base drag.

Overall, 10° BT and riblets BT have the lowest base to total drag ratio whereas arc BT and 7° BT have the highest ratio. With respect to flow speed, the largest values of base to total drag ratio occur at Mach numbers from 1.0 to 2.0.

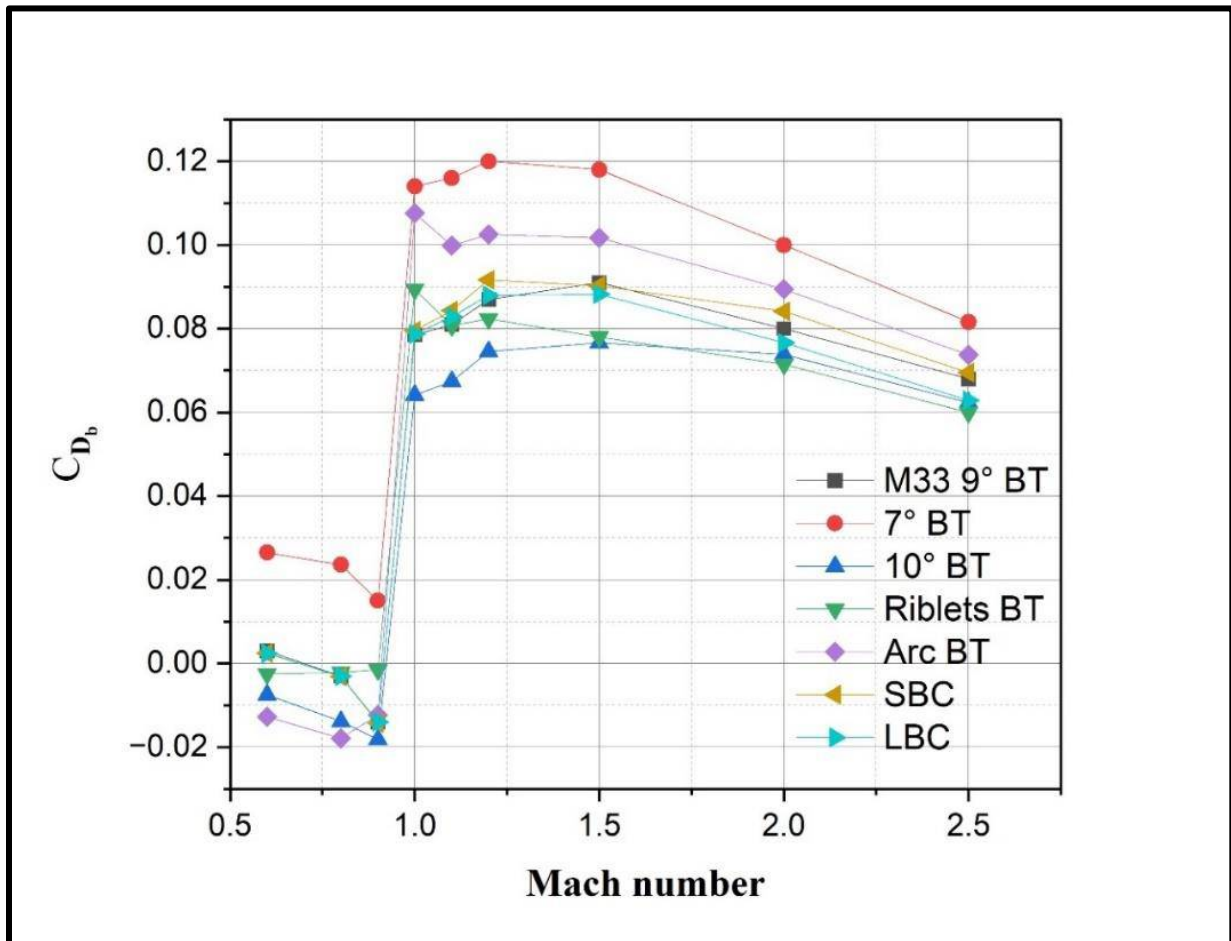


Figure 58. Base drag coefficient versus Mach number for different configurations.

Table 9. Detailed drag coefficients and coefficients ratios.

Coefficient	Configuration	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
C_{D_0}	M33 9° BT	0.122	0.120	0.146	0.354	0.385	0.384	0.364	0.326	0.295
	7° BT	0.135	0.134	0.145	0.340	0.378	0.381	0.365	0.329	0.300
	10° BT	0.117	0.117	0.151	0.364	0.393	0.391	0.363	0.329	0.296
	Riblets BT	0.140	0.142	0.157	0.363	0.394	0.394	0.363	0.332	0.297
	Arc BT	0.120	0.118	0.133	0.358	0.394	0.395	0.376	0.337	0.301
	SBC	0.122	0.121	0.147	0.355	0.388	0.389	0.364	0.330	0.296
	LBC	0.123	0.122	0.147	0.355	0.387	0.385	0.362	0.322	0.290
C_{D_b}	M33 9° BT	0.003	-0.003	-0.014	0.079	0.081	0.087	0.091	0.080	0.068
	7° BT	0.027	0.024	0.015	0.114	0.116	0.120	0.118	0.100	0.082
	10° BT	-0.008	-0.014	-0.018	0.064	0.067	0.075	0.077	0.074	0.062
	Riblets BT	-0.003	-0.002	-0.002	0.089	0.081	0.082	0.078	0.072	0.060
	Arc BT	-0.013	-0.018	-0.012	0.108	0.100	0.103	0.102	0.089	0.074
	SBC	0.002	-0.003	-0.014	0.080	0.084	0.092	0.090	0.084	0.070
	LBC	0.002	-0.003	-0.014	0.079	0.083	0.088	0.088	0.077	0.063
C_{D_b}/C_{D_0} (%)	M33 9° BT	2.46%	-2.49%	-9.59%	22.19%	21.06%	22.69%	25.00%	24.54%	23.05%
	7° BT	19.57%	17.61%	10.36%	33.50%	30.71%	31.54%	32.37%	30.41%	27.25%
	10° BT	-6.44%	-11.88%	-12.02%	17.61%	17.15%	19.07%	21.10%	22.44%	21.07%
	Riblets BT	-1.79%	-1.48%	-0.96%	24.65%	20.47%	20.92%	21.50%	21.52%	20.20%
	Arc BT	-10.59%	-15.13%	-9.27%	30.09%	25.36%	25.93%	27.08%	26.55%	24.52%
	SBC	2.01%	-2.61%	-9.70%	22.42%	21.73%	23.57%	24.78%	25.46%	23.45%
	LBC	1.95%	-2.46%	-9.53%	22.17%	21.44%	22.82%	24.36%	23.79%	21.72%

Looking at the linear lift coefficient ($C_{L\alpha_0}$) in Figure 59, the arc BT has an advantage of high lift in transonic and supersonic speeds, then comes the riblets BT. That may refer to the larger surface area of the projectile. In contrast, the effect on lift slope is minor for the SBC and LBC configurations.

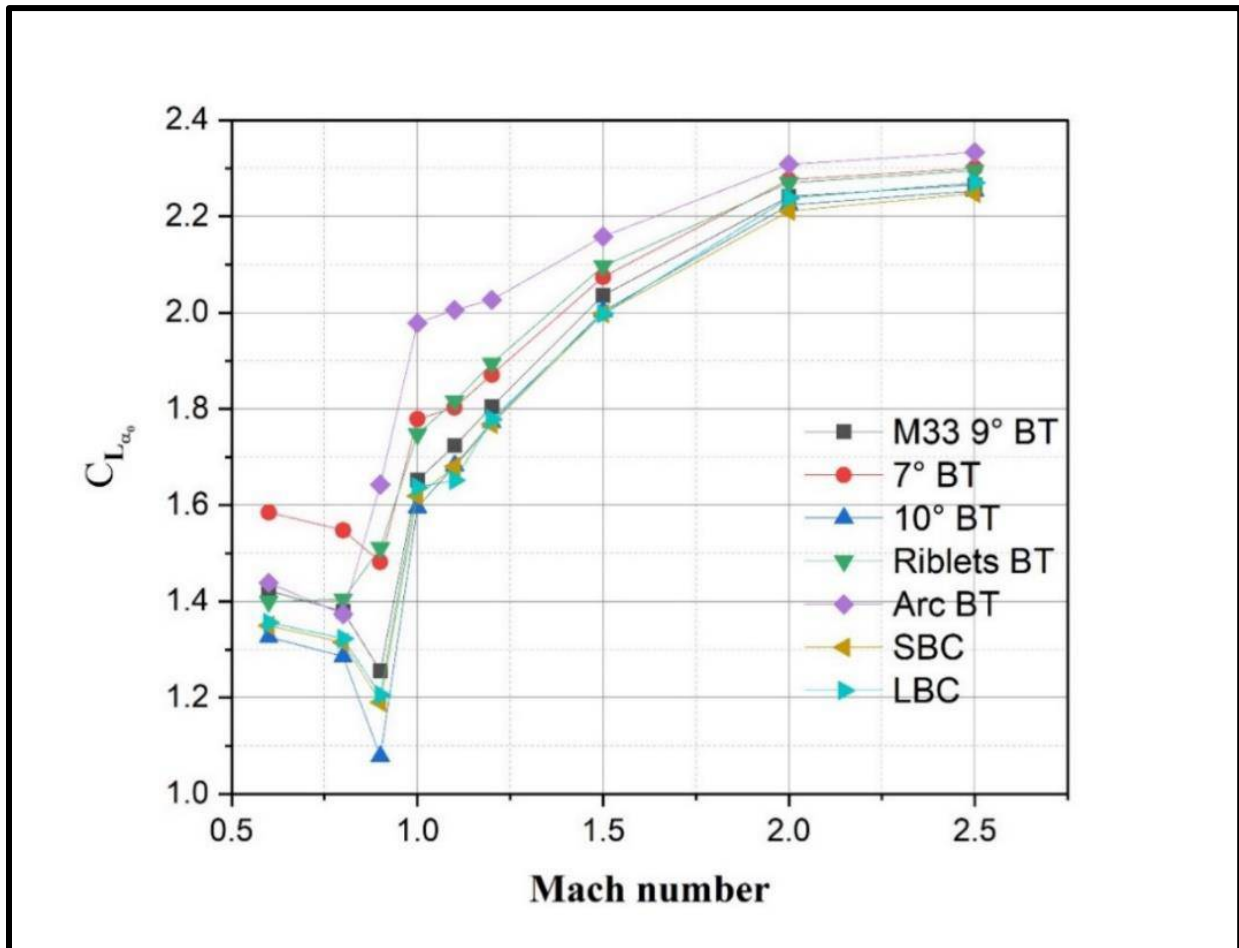


Figure 59. Linear lift coefficient versus Mach number for different configurations.

Figure 60 represents the linear overturning moment coefficient. It should be noted that at all condition the value of the moment coefficient slope is positive and this is reasonable, since spinning projectile are not statically stable. However, the degree of static stability differs among the configurations. The 10° BT experiences the largest value over most of Mach numbers. Though, Arc BT and riblets BT are high in lift slope, they have the least moment slope. This

refers to the increase in boattail surface area which leads to the change in aerodynamic center location. Likewise, this is the case for the 7° BT in subsonic speeds. Additionally, as for lift slope, base cavities have no major effect on moment slope.

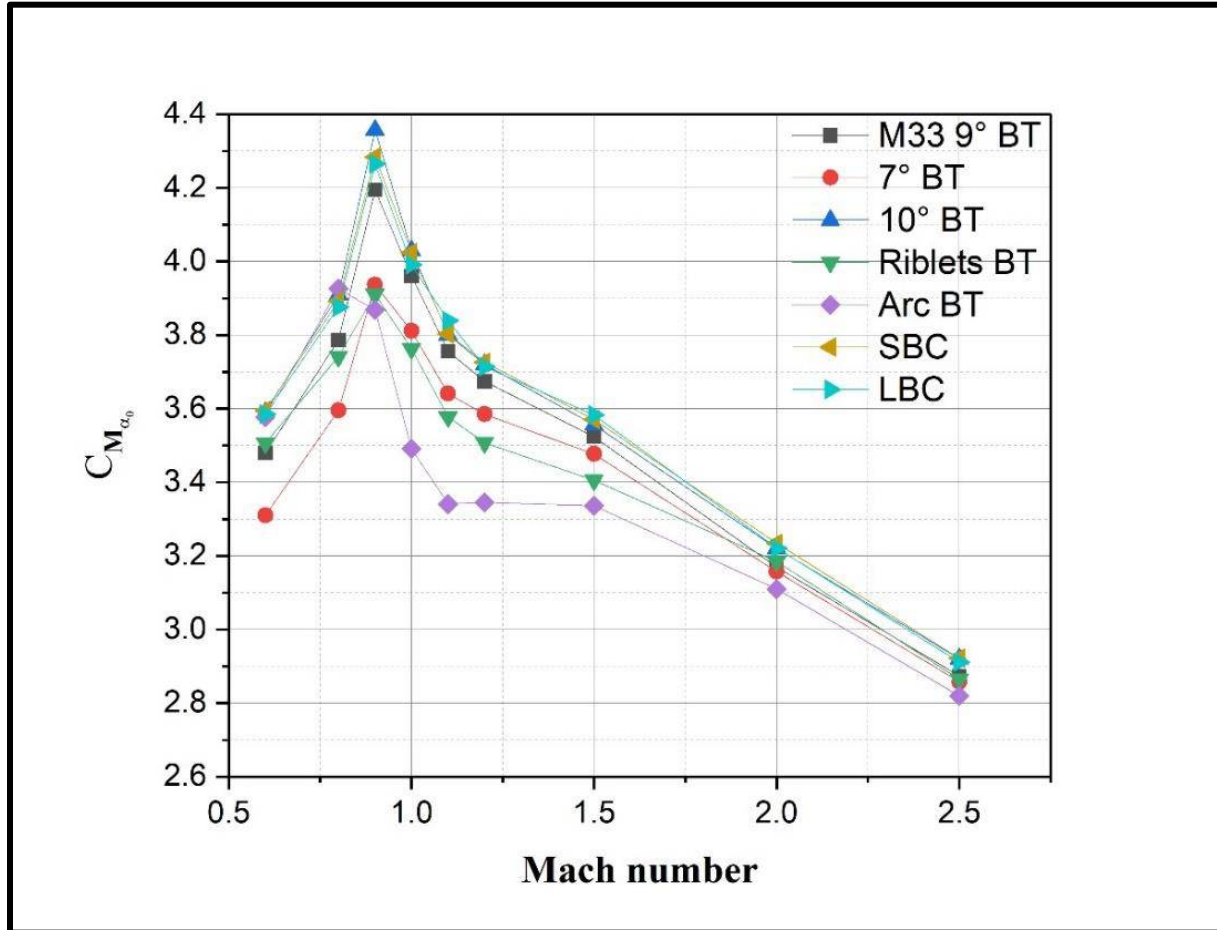


Figure 60. Linear overturning moment coefficient versus Mach number for different configurations.

The linear magnus force and magnus moment coefficients are presented in figures 61 and 62, respectively. Clearly, high magnus force is exerted on the 10° BT configuration at 0.9 Mach number. Though, the cubic magnus force coefficient is high with positive sign which opposes the

linear coefficient. More insights are appeared in the appendix. For 1.5 and higher Mach numbers differences are diminished among the configurations. Moreover, a large variation can be seen in the arc BT configuration. This can be interpreted as a nonlinearity in the magnus moment which adversely affect the dynamic stability. Also, except at Mach 0.9, linear magnus coefficients of M33, 7° BT and 10° BT behaves similarly.

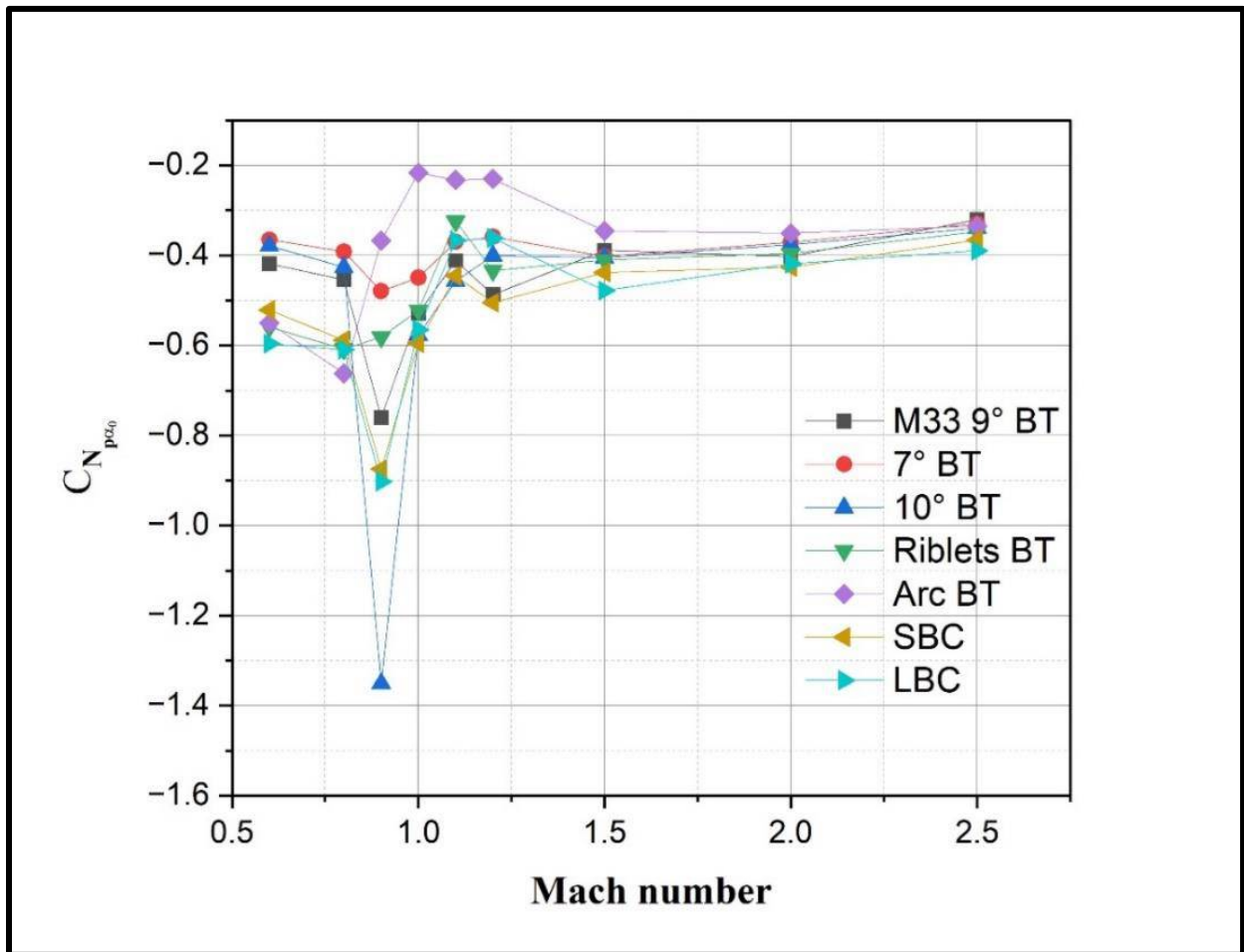


Figure 61. Linear magnus force coefficient versus Mach number for different configurations.

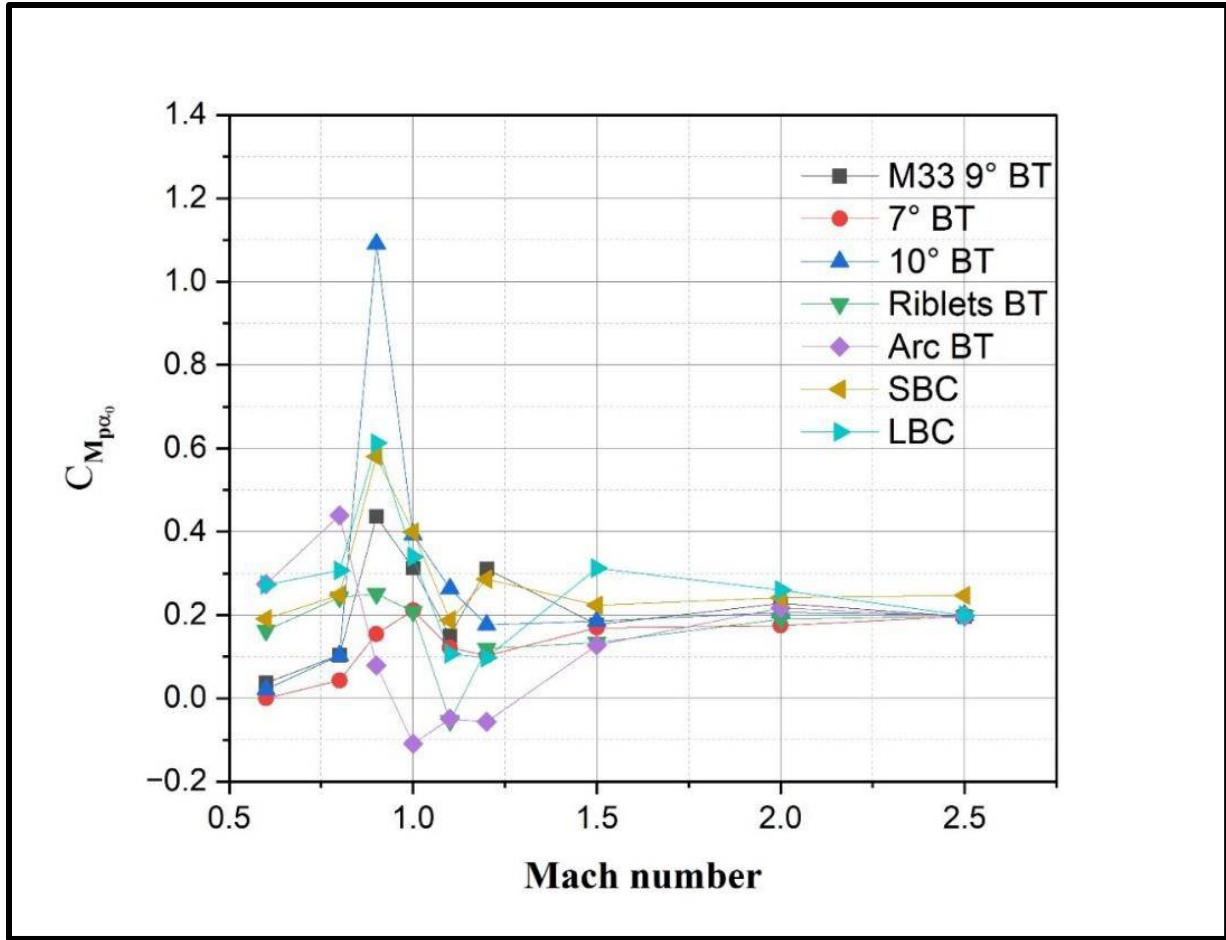


Figure 62. Linear magnus moment coefficient versus Mach number for different configurations.

A plot of spin damping moment versus Mach number is presented by Figure 63. The negative sign indicates the direction. As can be seen for all configuration, the spin damping moment coefficient decreases as Mach number increases. Though, there are some discrepancies around Mach 1.0. For supersonic regime and as speed increases, the differences in spin damping moment become noticeable. These differences can be interpreted by that the main factor of spin damping is skin friction that opposes the direction of spinning direction. Looking closely at Mach 2.5, the largest spin damping is exerted on 7° BT then arc BT then comes riblets BT. That is consistent with larger boattail wetted area for the preceding configurations. Also, this is reasonable when examining the spin damping moment in the 10° BT, which has the smallest value of spin damping

coefficient. Additionally, a very slight decrease in spin damping is noticed with angle of attack because of partial flow separation that leads to decrease in shear stress.

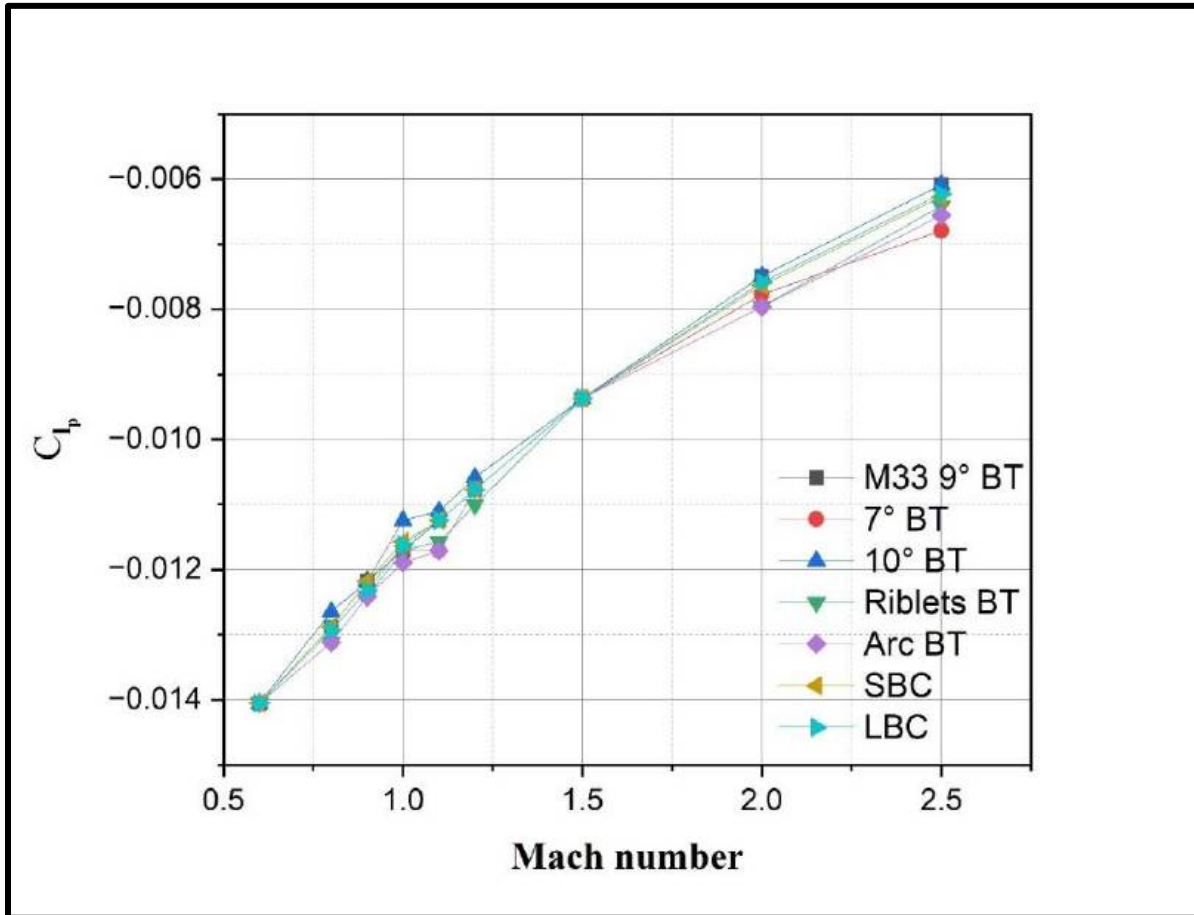


Figure 63. Spin damping moment coefficient versus Mach number for different configurations.

5.2 Flow field.

In this section, pressure coefficient along the projectiles and at projectiles bases will be discussed, to assess the differences closely. Moreover, contour plots of Mach number and pressure are presented at certain speed for every configuration.

Pressure coefficient around the body is shown in the figures below for different configurations at Mach number 0.8. A zoomed view is shown for base pressure coefficient. Summarizing,

maximum pressure coefficients at the base are tabulated in Table 10. They are arranged by the colors, where green colors indicate positive values. Darker colors mean high value in pressure coefficient. Comparing Table 10 with base drag in Figure 58, high pressure coefficients correspond to low base drag.

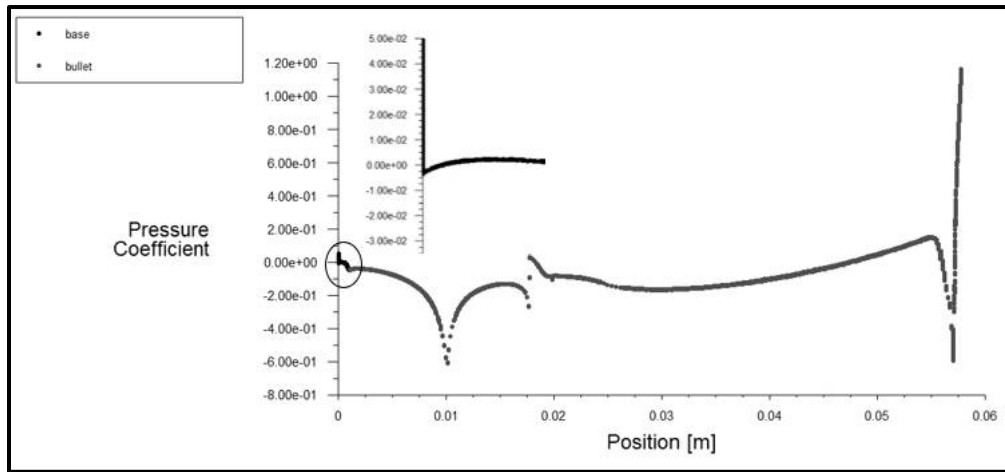


Figure 64. Pressure coefficient of M33 at Mach number 0.8.

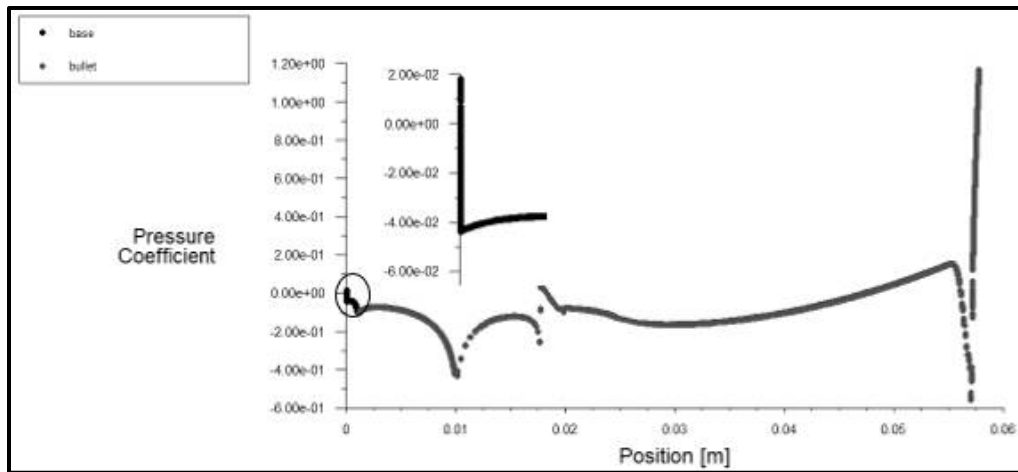


Figure 65. Pressure coefficient of 7° BT at Mach number 0.8.

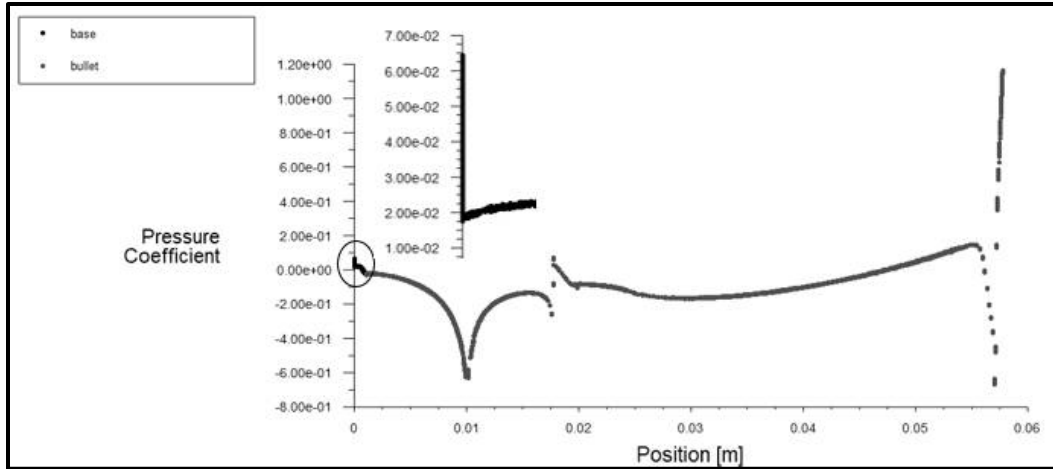


Figure 66. Pressure coefficient of 10° BT at Mach number 0.8.

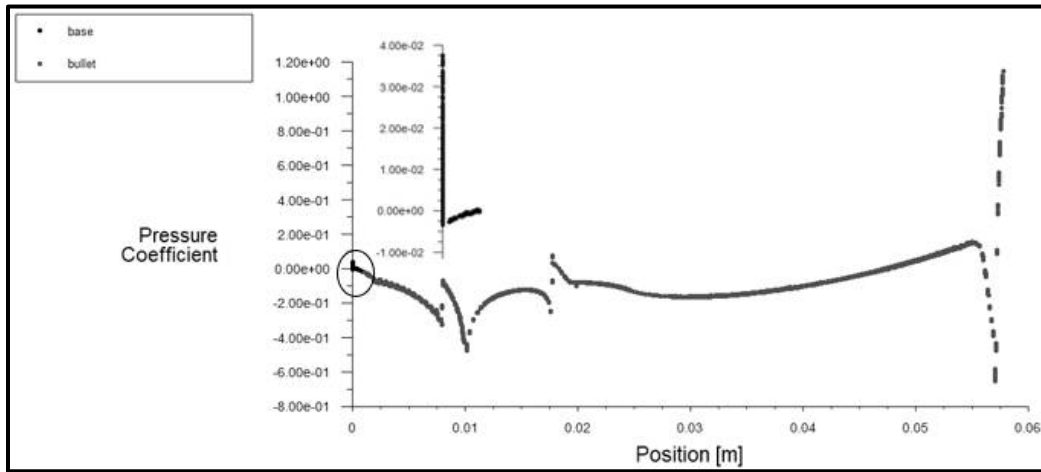


Figure 67. Pressure coefficient of riblets BT at Mach number 0.8.

Table 10. Maximum pressure coefficients at projectiles base for zero angle of attack.

Maximum base pressure coefficient									
Mach number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	0.045	0.05	0.058	-0.093	-0.088	-0.097	-0.109	-0.104	-0.093
7° BT	0.02	0.019	0.024	-0.118	-0.117	-0.123	-0.128	-0.115	-0.098
10° BT	0.06	0.065	0.062	-0.073	-0.074	-0.086	-0.108	-0.101	-0.091
Riblets BT	0.041	0.038	0.035	-0.12	-0.105	-0.109	-0.102	-0.103	-0.092
Arc BT	0.066	0.07	0.058	-0.12	-0.105	-0.11	-0.116	-0.11	-0.097
SBC	0.02	0.028	0.028	-0.107	-0.114	-0.127	-0.126	-0.124	-0.107
LBC	0.018	0.026	0.038	-0.11	-0.115	-0.122	-0.117	-0.104	-0.088

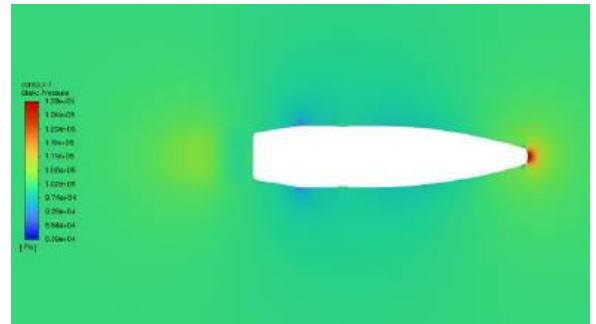
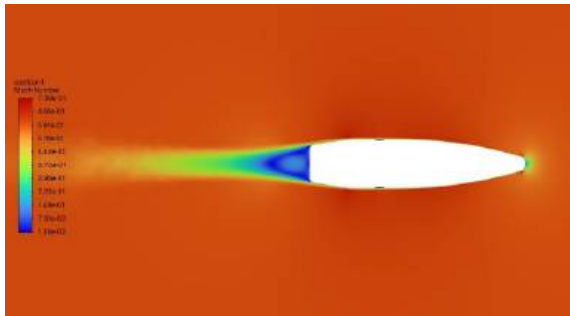
The figures below show flow field contours. Namely, Mach number and static pressure. Each table represents one configuration at 0.6, 1.0, 1.5, and 2.5 Mach numbers and at zero angle of attack. As can be seen at supersonic speed a shock wave is formed in front of projectiles. As speed increases the shock wave angle decreases. In addition, the shock wave never attaches the body, because of high nose bluntness. At Mach 1 there is no shock wave created at the nose, though an expansion wave can be noticed at the start of each boattail followed by a shock wave at the base. However, in arc BT the expansion is gradual. Furthermore, unlike other configurations where flow separates at the boattail edge, in arc BT and 7° BT the separation is delayed. Examining riblets BT, a series of shock waves occurs at boattail which explain the high drag at transonic speeds. Also, with base cavities the wake region becomes more intense and it increases for LBC.

M

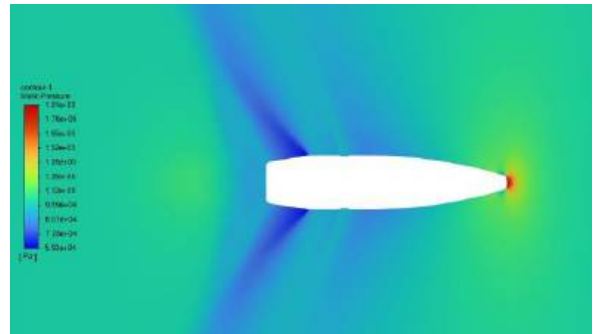
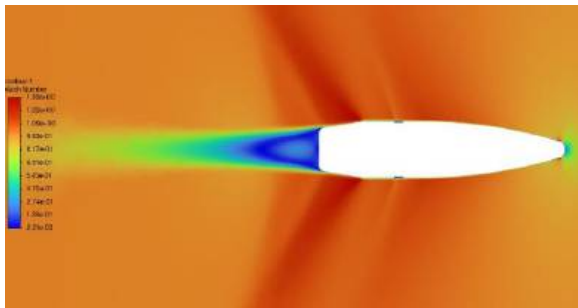
Mach Contour

Pressure Contour

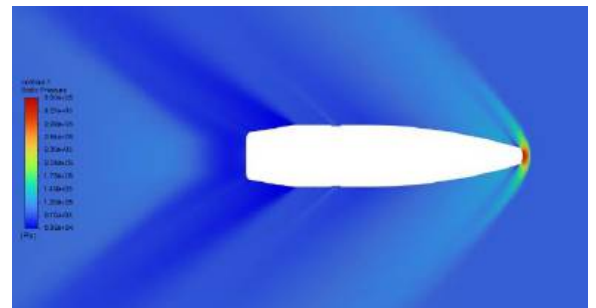
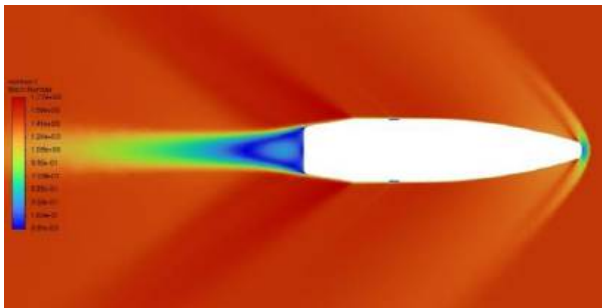
0.6



1.0



1.5



2.5

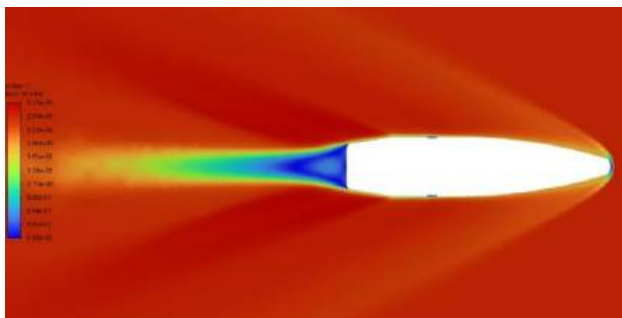


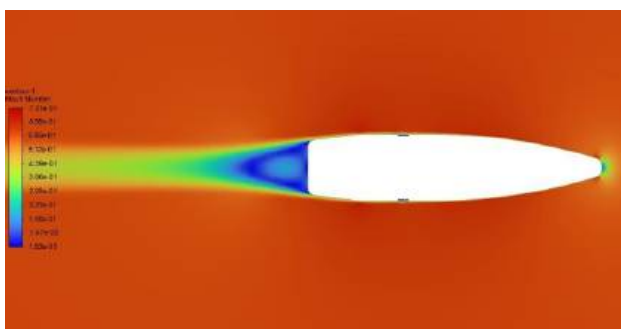
Figure 68. Pressure and Mach number contours for M33 9° BT.

M

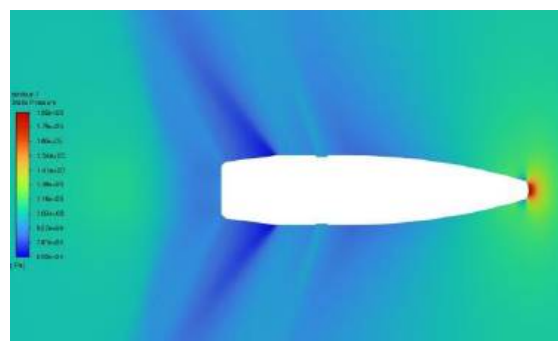
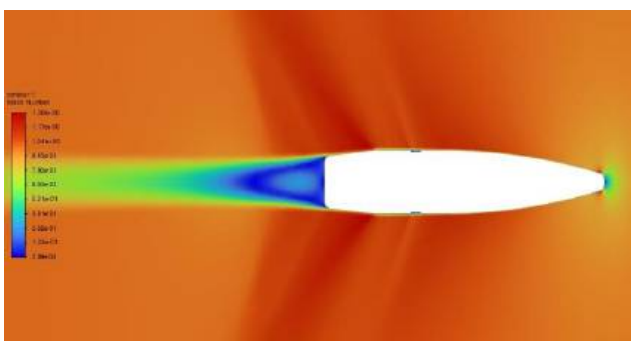
Mach Contour

Pressure Contour

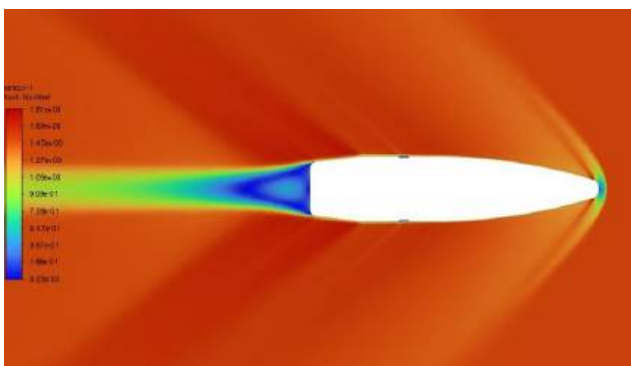
0.6



1.0



1.5



2.5

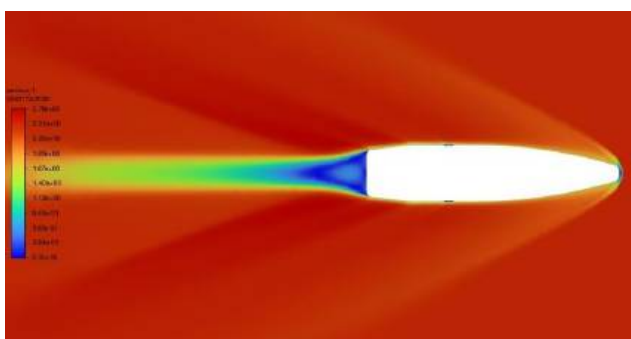


Figure 69. Pressure and Mach number contours for 7° BT.

M

Mach Contour

Pressure Contour

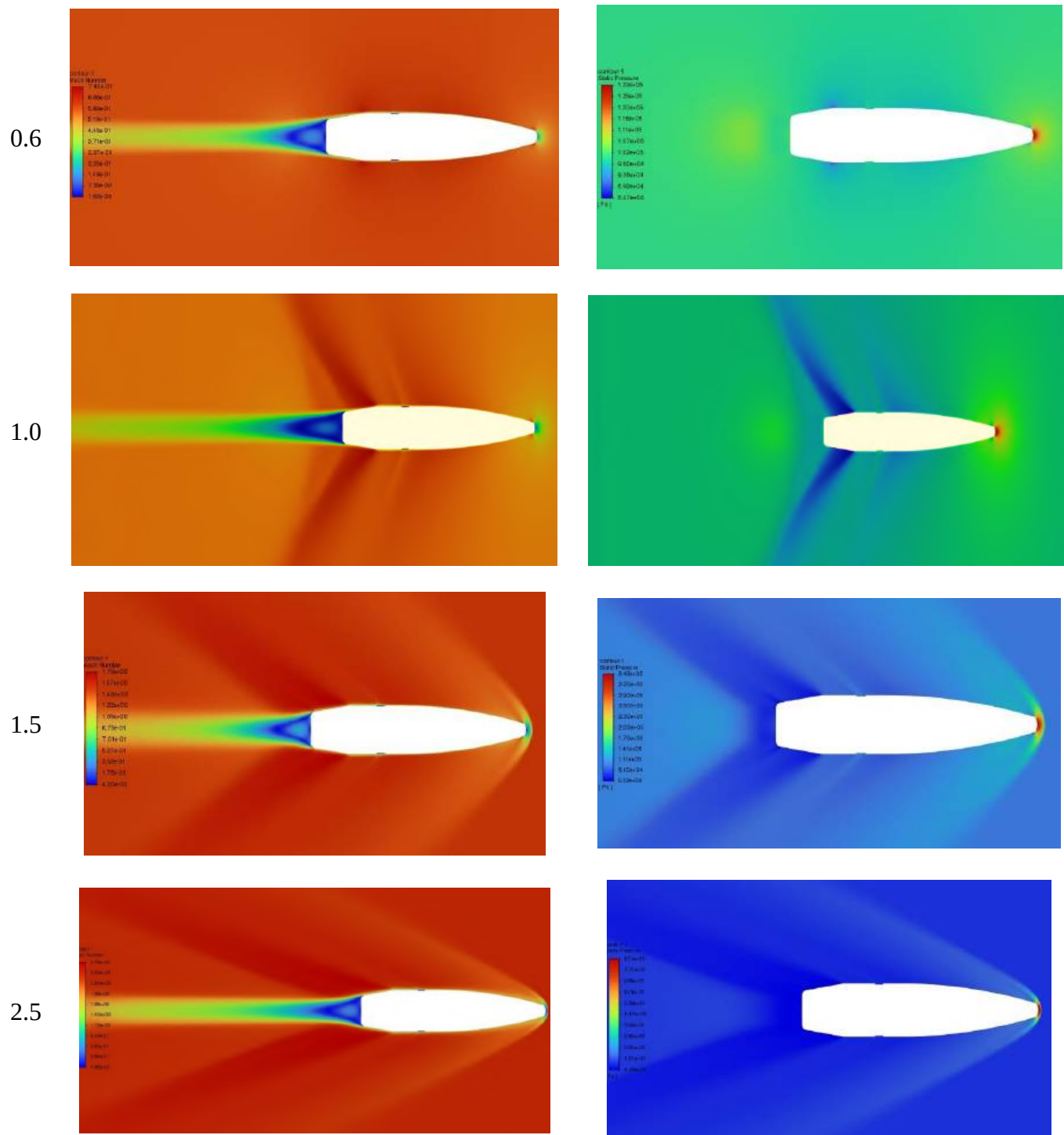


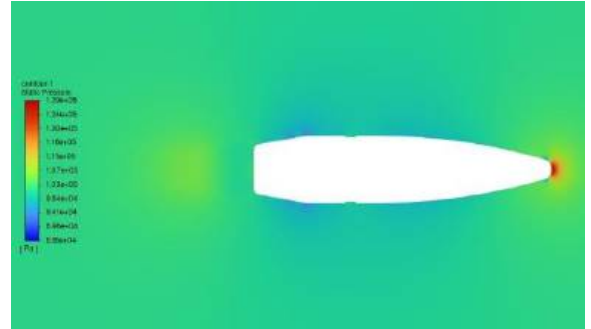
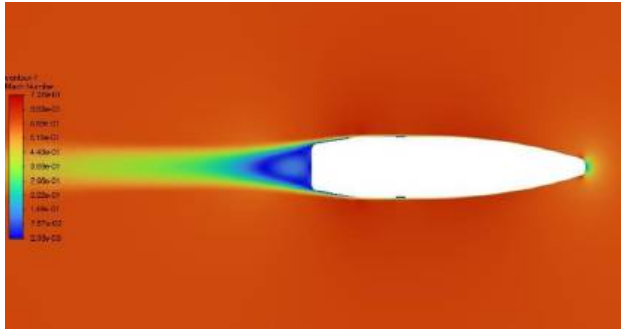
Figure 70. Pressure and Mach number contours for 10° BT.

M

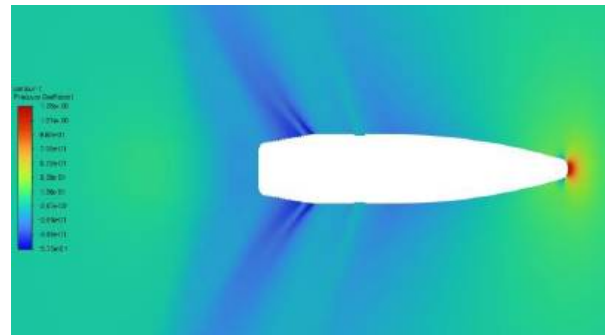
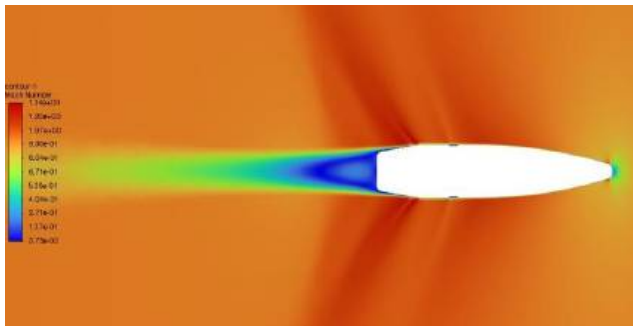
Mach Contour

Pressure Contour

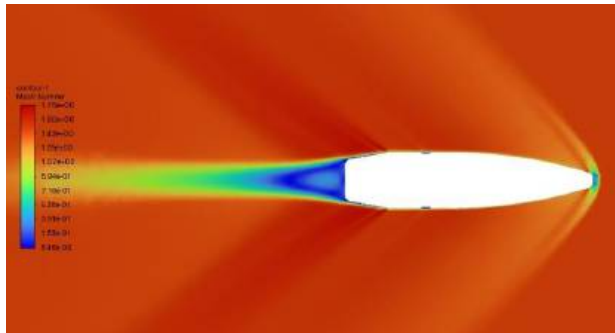
0.6



1.0



1.5



2.5

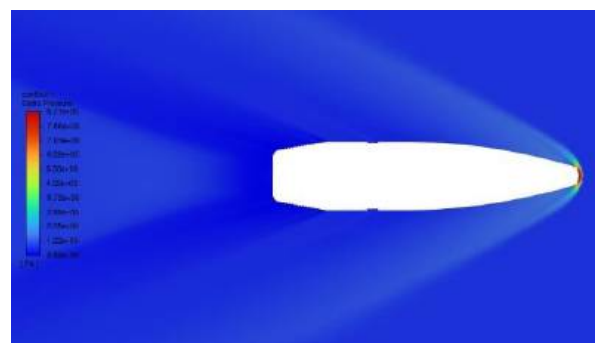
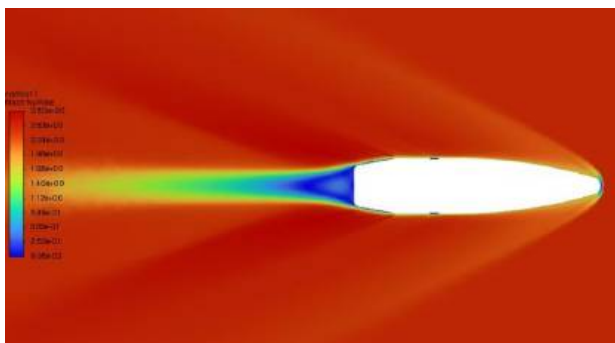


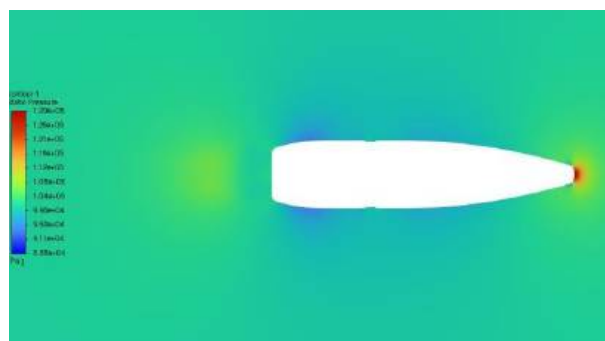
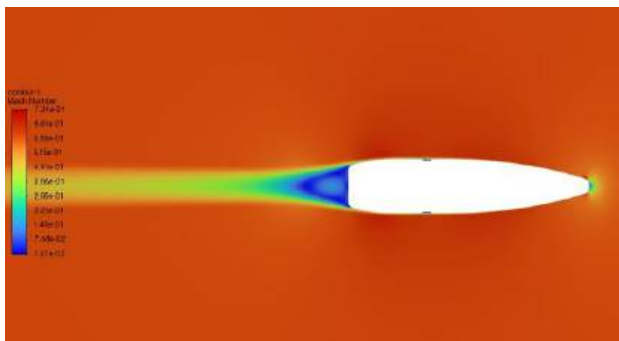
Figure 71. Pressure and Mach number contours for riblets BT.

M

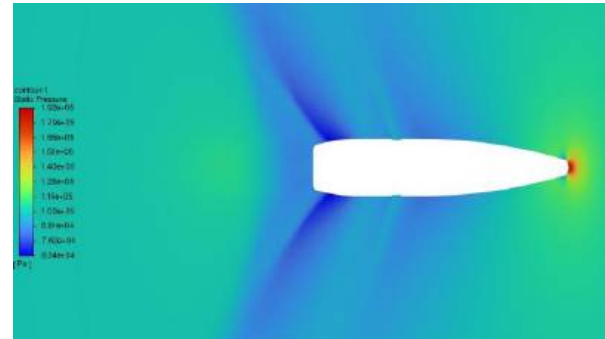
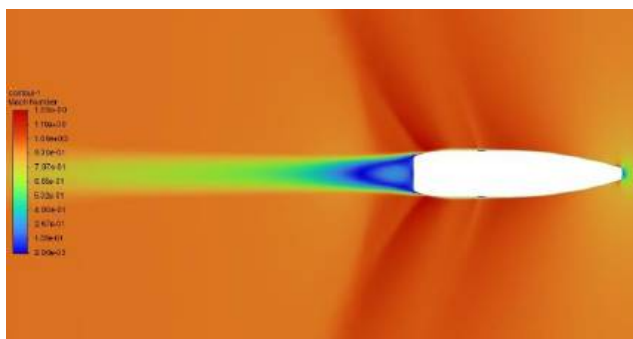
Mach Contour

Pressure Contour

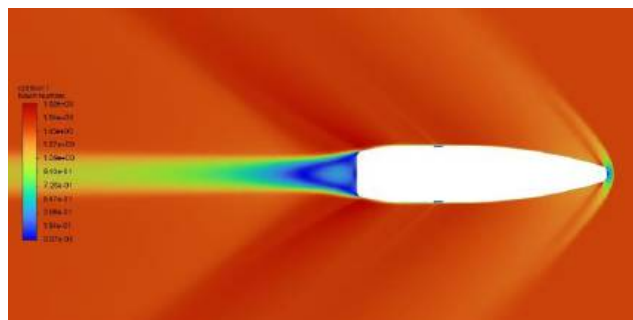
0.6



1.0



1.5



2.5

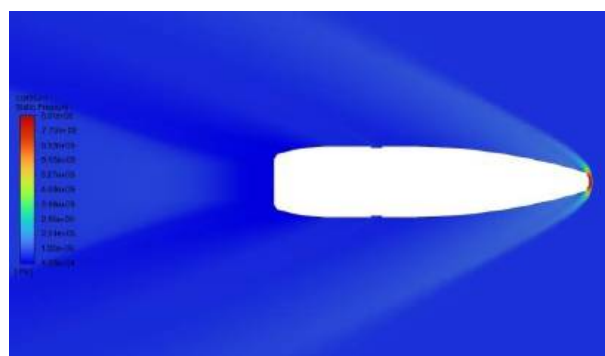
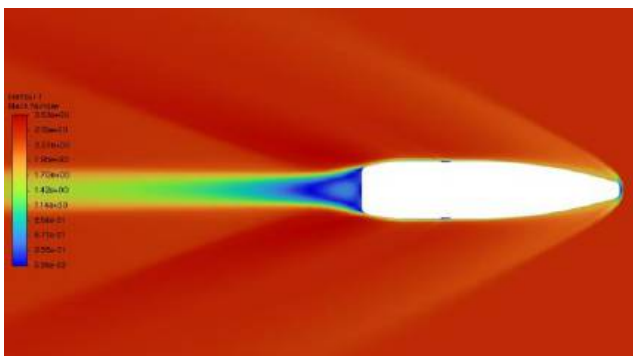


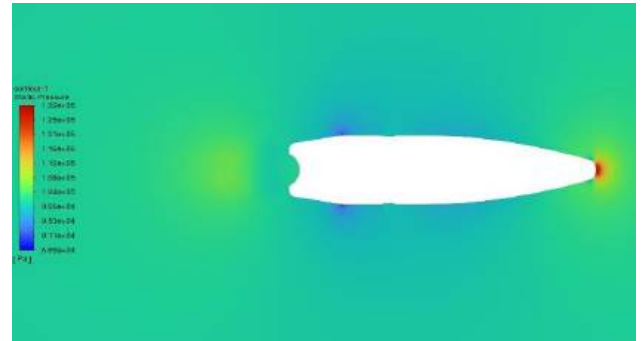
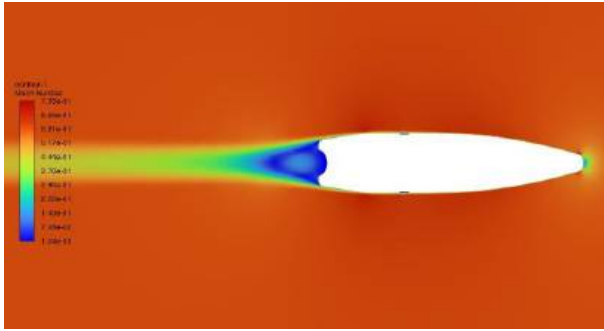
Figure 72. Pressure and Mach number contours for arc BT.

M

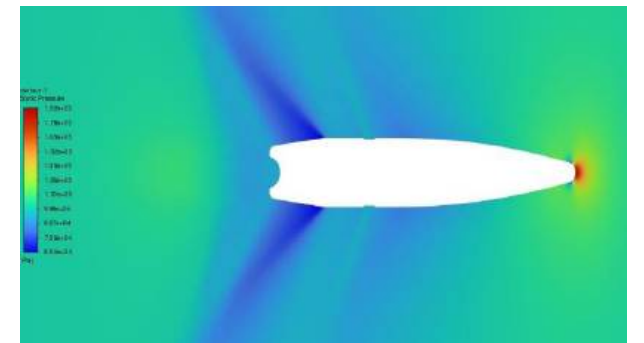
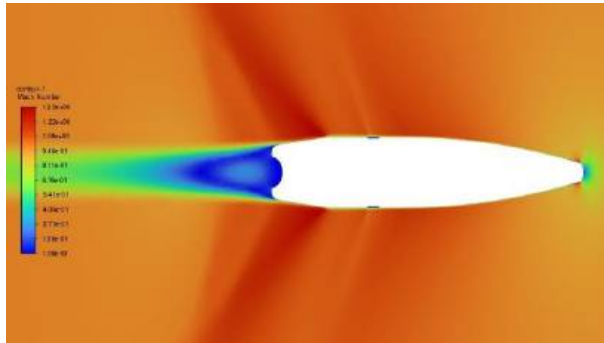
Mach Contour

Pressure Contour

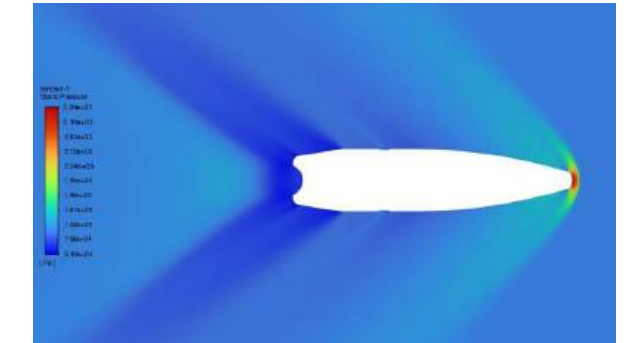
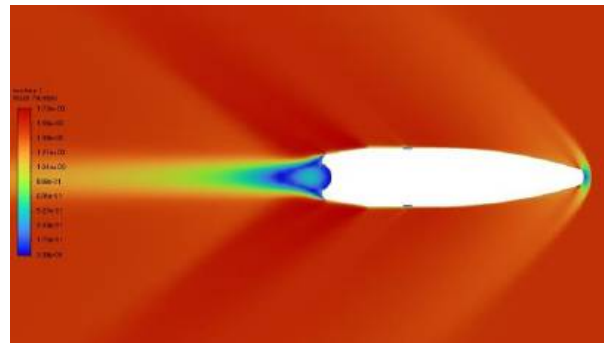
0.6



1.0



1.5



2.5

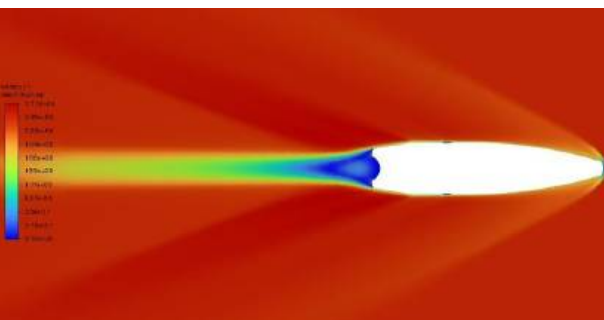


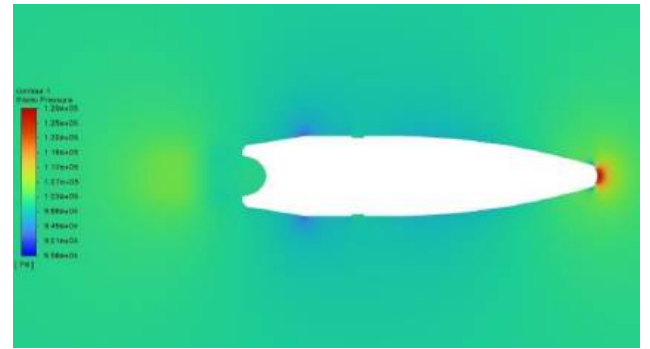
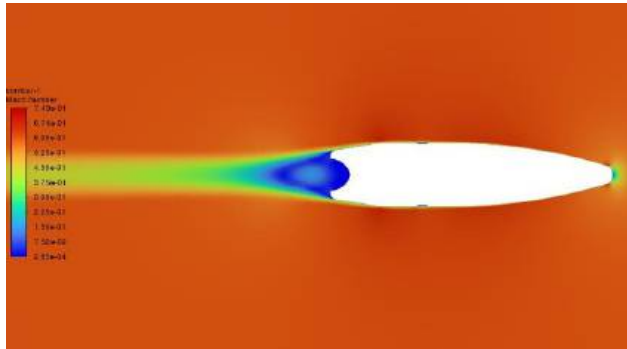
Figure 73. Pressure and Mach number contours for SBC.

M

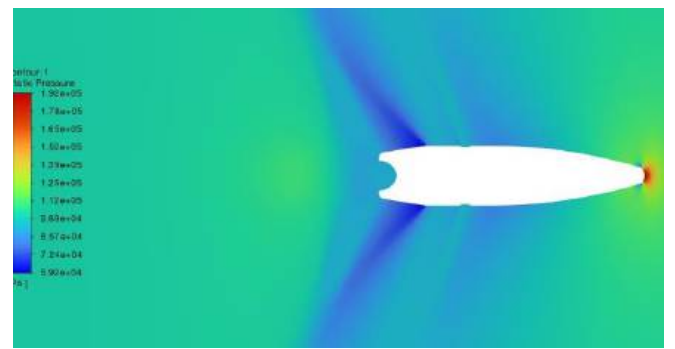
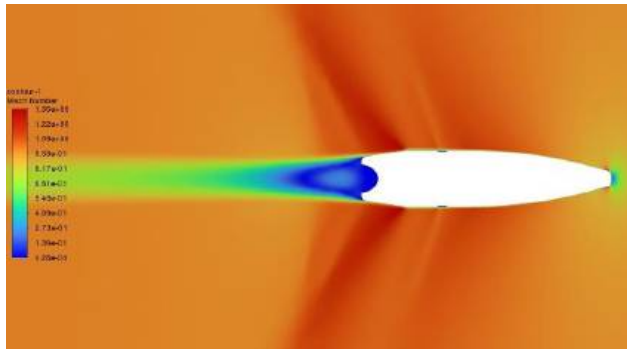
Mach Contour

Pressure Contour

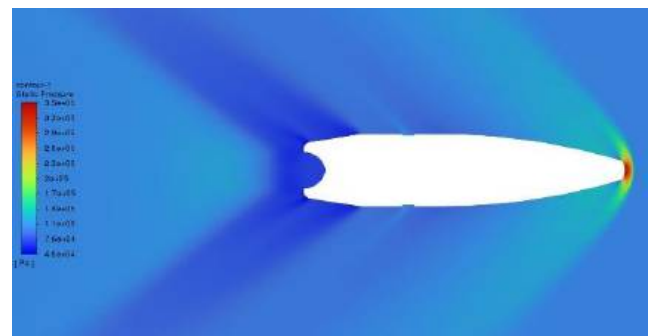
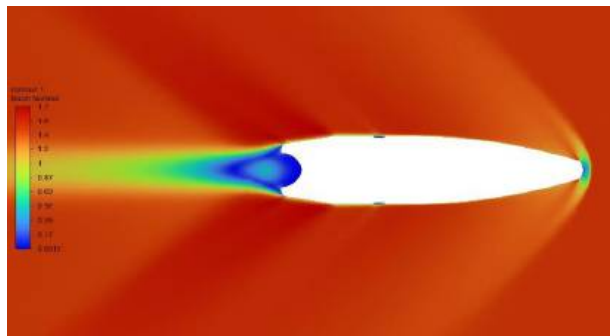
0.6



1.0



1.5



2.5

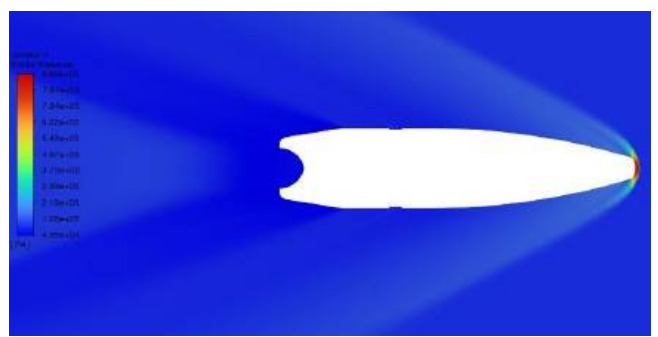
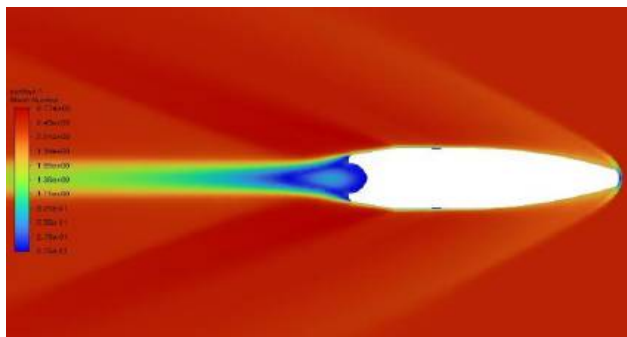


Figure 74. Pressure and Mach number contours for LBC.

5.3 LES results

In large eddy simulation two cases were conducted, over M33 9° BT and Riblets BT. Since angle of attack is zero, the computed coefficients are C_{D_0} , C_{D_b} and C_{l_p} . The remaining coefficients are zero because of body symmetry. LES showed a better accuracy than SST k- ω model as appeared in Table 11. The difference in zero yaw drag between LES estimation and experiment is 1.64 %, while it is 3.01 in URANS. For spin damping moment coefficient, RANS and URANS SST k- ω estimated a value that is almost double of LES estimation.

Table 11. URANS and LES results comparison.

Turbulence model	Configuration	C_{D_0}	C_{D_0} Error	C_{D_b}	C_{l_p}
URANS (SST k- ω)	M33 9° BT	0.376	3.01%	0.0807	-0.0109
	Riblets BT	0.391		0.0757	-0.011
LES (WALE)	M33 9° BT	0.371	1.64%	0.104	-0.00501
	Riblets BT	0.386		0.775	-0.00703

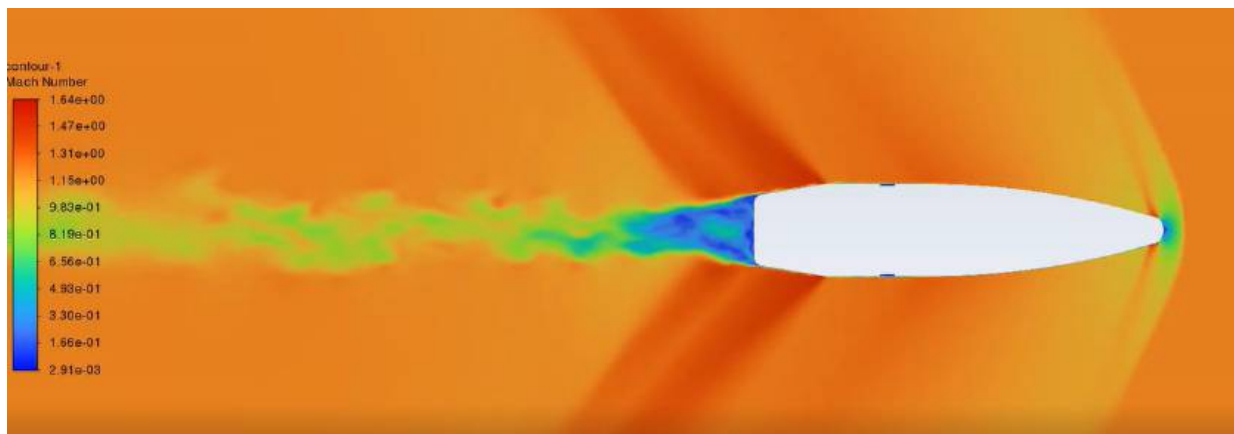


Figure 75. Mach number contour of LES over M33 9° BT at M = 1.2.

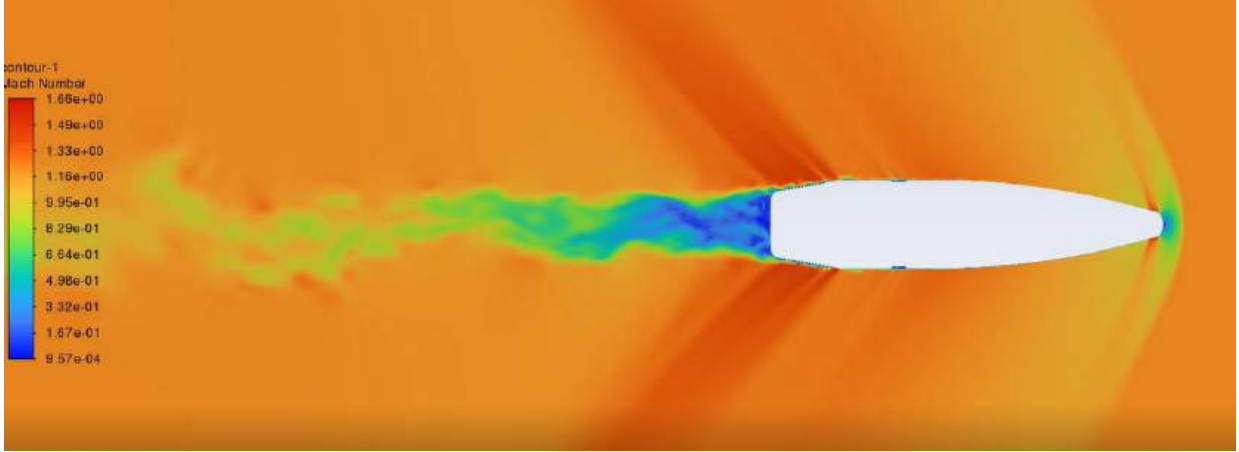


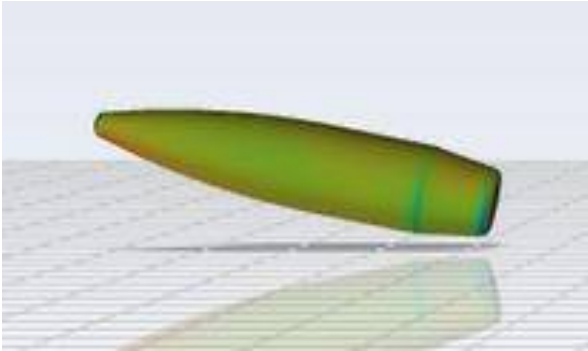
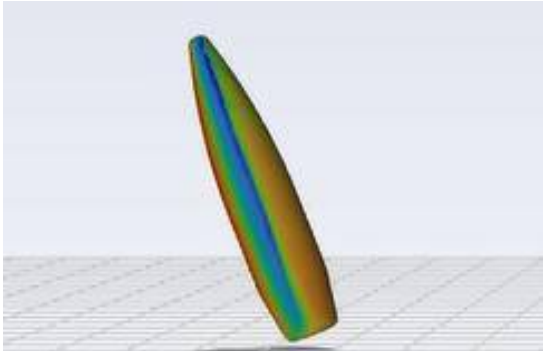
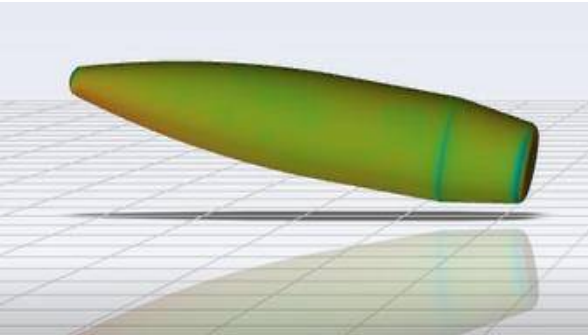
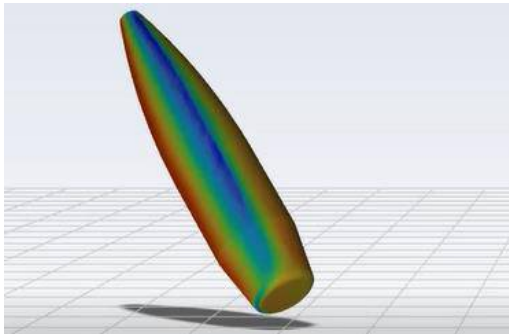
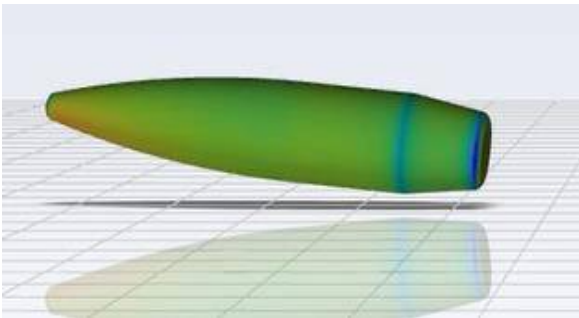
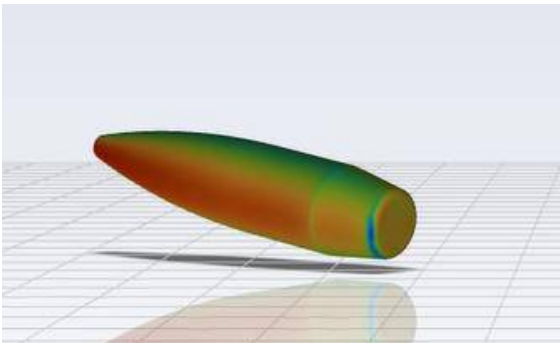
Figure 76. Mach number contour of LES over riblets BT at $M = 1.2$.

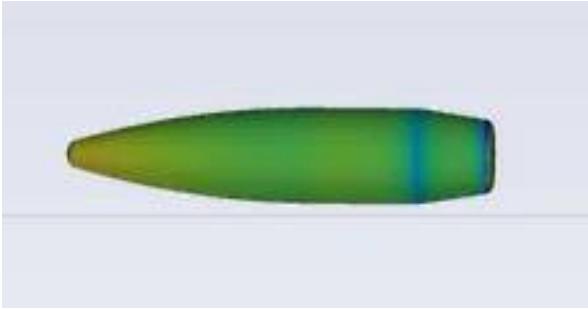
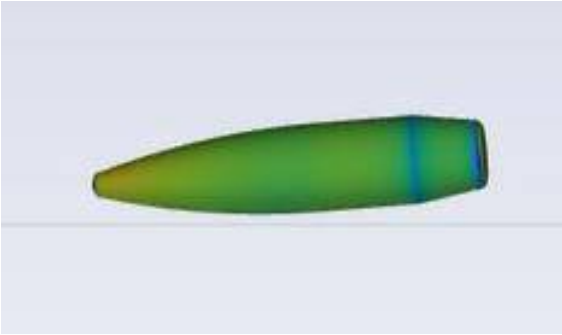
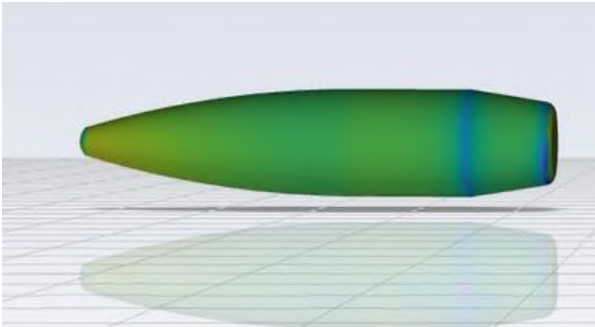
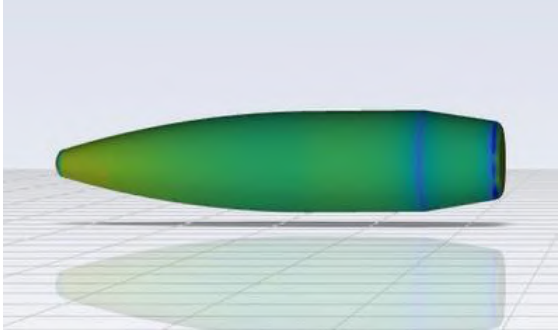
5.4 6DoF simulation

The aim of six degree of freedom simulation is to assess the gyroscopic stability of the projectile. Here, different spin rates are set as an initial condition. The dynamic behavior of the projectile is illustrated in Table 12. It is shown at 0.025 second and at 0.035 seconds simulation time. As expected, at zero spin rate the projectile is not stable and angle of attack propagates. As spin rate increases the propagation of angle of attack is delayed and some degree of stability is gained. At 2500 rad/s, the projectile start to be stable. However, a propagation of angle of attack is noticed at 0.035 s. At 5000 rad/s the projectile become gyroscopically stable.

It is important to mention that bullets are fired at zero angle of attack and for nominal trajectories angle of attack does not exceed 1 degree. Therefore, even for slow spins rate, projectile stability is not exactly as described here. The reason is that in initial conditions angle of attack is set to 2 degrees to evaluate the stability in shorter simulation time.

Table 12. M33 dynamic behavior for different initial spin rate at 0.025 and 0.035 second of simulation time.

P (rad/s)	At 0.025 sec	At 0.035 sec
0		
500		
1000		

2500		
5000		

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

This thesis discusses the aerodynamic characteristics of spinning projectiles, aiming to optimize projectiles boattails to enhance aerodynamic performance. At the beginning, general information and definitions were introduced. Then, short history of the evolvement aerodynamic analysis and projectile design was reviewed. Also, extensive reviews of numerical analysis and design variations were shown.

It is discussed that the name of spinning projectiles is derived from the technique of stabilizing in which gyroscopic stability is induced by spinning. Also, the calculation of main aerodynamic forces and moments are elucidated. They are drag force, lift force, magnus force, magnus moment, overturning moment, and spin damping moment. In the literature, there are many boattailing and range extending techniques that are discussed here. Thus, some techniques are modified and implemented in this work. Exclusively, design variations on projectile boattail and base are considered. This includes varying boattail angle, use of riblets, use of arced boattail, and introducing two different sizes of base cavity. The selected projectile for the study is M33 12.95 mm caliber projectile.

The analysis in this thesis is done by computational fluid dynamics CFD where the flow is three dimensional, compressible, viscous, and involves supersonic speed in some cases. ANSYS fluent is utilized to solve the governing equations. They include continuity equation, three momentum

equations, energy equation, ideal gas equation and equation of state. The speed varies from subsonic to subsonic, where the angle of attack is set to 0° , 2° and 4° .

Firstly, results were validated by comparing with experimental and numerical results from the literature. Furthermore, a mesh independence study is done for verification and a value of y^+ was ensured to be less than 1. Then RANS calculations were carried out over all design configuration. In addition, LES model was used over M33 and over riblets BT configurations at Mach 1.2. Moreover, to investigate projectile stability, coupled CFD and six degree of freedom simulation was conducted at various spin rates.

It was found that every configuration has good performance at certain speed with regard to zero yaw drag. Also, the 10° BT configuration is the lowest on drag on most speed envelopes. A non-linearity in magnus moment was noticed for arc BT in which it is consistent with a similar configuration in the literature. Additionally, the base drag is the lowest in riblet BT at supersonic speeds whereas it is the lowest in the arc BT at subsonic speeds. An 11.8 % was achieved in base drag reduction with the riblets BT at supersonic speed, when compared to the original configuration. With respect to zero yaw drag the LBC was performed the best at 1.5, 2.0 and 2.5 Mach numbers, with a drag coefficient of 0.2896 at 2.5 Mach number while it is 0.295 for M33 original configuration. Thus, this thesis recommends the implementation of riblets BT and LBC configurations, especially for projectiles traveling at supersonic speeds. Moreover, In LES the estimation was found more accurate than URANS models, when comparing to experimental results. It is shown that the error in drag prediction is reduced from 3.01% to 1.64% when LES is used. However, the required time to perform an LES is greater than that of RANS model by about 100 times, which indicate the infeasibility for industrial applications. Regarding, 6DoF simulation, it was inferred that projectile stability noticeably increases with spin rate.

6.2 Future work

After investigating multiple design of boattails and base, some remarks can be noted. Low drag was observed at 10° boattail angle though it increases in transonic speed. In this regard, it is suggested to increase the boattail length from 0.78 cal to 1.0 cal. For the riblets BT configuration, riblets seemed to have undesirable effects were noticed in speeds less than 1.5 Mach number. Therefore, an amendment may be made by submerging the riblets so that they do not directly interfere the flow. Additionally, the boattail angle can be modified to be 12° which results in higher adverse pressure gradient, where riblets become more beneficial. Also, at 12° boattail angle base area decreases, resulting in lower base drag.

In arc BT, smaller base area can be utilized and investigated, since the separation is delayed and occurs gradually. Comparing SBC with LBC, a greater decrease in zero yaw drag was observed in LBC. However, it is suggested to study a combination of LBC with modified riblets. Also, other active techniques can be studied, such as base injection, and combined with passive techniques that is introduced in this work. Lastly, LES can be carried out over more cases since it showed more accurate results.

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Appendix

Tabulated Aerodynamic coefficient

C_{D_0}									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	0.122	0.1204	0.146	0.3537	0.3846	0.3835	0.364	0.326	0.295
7° BT	0.1354	0.134	0.14475	0.3403	0.3777	0.3805	0.3645	0.3288	0.2995
10° BT	0.1165	0.1165	0.15123	0.3643	0.39287	0.3909	0.363	0.3289	0.2957
Riblets BT	0.1397	0.1416	0.1568	0.3627	0.3942	0.39377	0.3628	0.33234	0.297
Arc BT	0.1199	0.1183	0.1327	0.3576	0.3936	0.39535	0.3755	0.3369	0.3008
SBC	0.12226	0.1212	0.147	0.3547	0.38792	0.3888	0.36426	0.33037	0.29632
LBC	0.12306	0.12182	0.14696	0.3552	0.38665	0.3854	0.36225	0.322	0.2896
C_{D_b}									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	0.003	-0.003	-0.014	0.0785	0.081	0.087	0.091	0.08	0.068
7° BT	0.0265	0.0236	0.015	0.114	0.116	0.12	0.118	0.1	0.0816
10° BT	-0.0075	-0.0138	-0.0182	0.06415	0.067365	0.07456	0.0766	0.0738	0.0623
Riblets BT	-0.0025	-0.0021	-0.0015	0.0894	0.0807	0.08236	0.078	0.07152	0.06
Arc BT	-0.0127	-0.0179	-0.0123	0.1076	0.09983	0.1025	0.1017	0.08944	0.07376
SBC	0.00246	-0.0032	-0.0143	0.07952	0.0843	0.09163	0.09026	0.08412	0.0695
LBC	0.0024	-0.003	-0.014	0.07876	0.0829	0.08795	0.08825	0.0766	0.0629
$C_{D_{\delta^2}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	3.1187	3.3197	3.0366	5.7449	6.1553	4.3087	6.2373	6.6477	7.7967
7° BT	3.693	4.013	3.878	5.827	6.443	4.555	6.935	6.278	4.091
10° BT	2.79	2.967	2.831	5.4	5.815	4.227	4.186	5.991	2.79
Riblets BT	2.544	2.872	3.242	5.499	6.106	4.091	1.97	5.581	3.939
Arc BT	2.708	2.897	3.332	7.148	6.668	4.288	5.745	6.525	4.891
SBC	3.985	3.98	3.139	5.597	6.036	4.493	4.645	6.086	5.097
LBC	4.703	4.317	3.213	5.967	6.233	4.259	10.73	5.499	3.426

$C_{L_{\alpha_0}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	1.423	1.379	1.256	1.652	1.724	1.805	2.036	2.241	2.266
7° BT	1.585	1.548	1.482	1.779	1.803	1.871	2.074	2.276	2.3
10° BT	1.326	1.286	1.078	1.596	1.683	1.772	2.003	2.224	2.253
Riblets BT	1.4	1.405	1.512	1.748	1.817	1.894	2.096	2.27	2.295
Arc BT	1.439	1.374	1.643	1.978	2.006	2.027	2.158	2.308	2.333
SBC	1.35	1.315	1.191	1.619	1.68	1.768	1.998	2.211	2.248
LBC	1.356	1.323	1.206	1.638	1.652	1.779	1.998	2.238	2.27
$C_{L_{\alpha_2}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	-39.19	-17.24	15.67	17.24	7.836	-0.0009	3.134	29.78	28.21
7° BT	-42.79	-16.46	2.037	3.918	6.269	4.701	9.404	20.38	32.91
10° BT	-33.7	-14.11	53.76	18.81	5.955	8.307	8.62	20.38	34.48
Riblets BT	-41.69	-24.14	-10.35	14.11	-1.568	-0.0009	-8.904	11.75	25.55
Arc BT	-56.35	-32.45	-57.68	3.604	-24.84	-27.12	-6.741	17.24	25.7
SBC	-1.019	15.36	42.85	27.04	15.83	9.796	15.75	28.92	35.89
LBC	18.81	27.12	46.71	21.63	29.31	10.66	13.32	33.23	38.87
$C_{N_{p\alpha_0}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	-0.4182	-0.4543	-0.7602	-0.5288	-0.4115	-0.4876	-0.3891	-0.4025	-0.3198
7° BT	-0.3654	-0.3915	-0.4796	-0.4495	-0.3699	-0.3587	-0.4021	-0.3712	-0.3296
10° BT	-0.3784	-0.4265	-1.3508	-0.5770	-0.4571	-0.4007	-0.4048	-0.3757	-0.3399
Riblets BT	-0.5593	-0.6080	-0.5813	-0.5218	-0.3240	-0.4339	-0.4102	-0.3956	-0.3475
Arc BT	-0.5504	-0.6618	-0.3672	-0.2163	-0.2324	-0.2299	-0.3453	-0.3509	-0.3343
SBC	-0.5208	-0.5883	-0.8745	-0.5953	-0.4456	-0.5054	-0.4377	-0.4260	-0.3657
LBC	-0.5963	-0.6094	-0.9026	-0.5653	-0.3672	-0.3616	-0.4782	-0.4184	-0.3900

$C_{N_{p\alpha_2}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	-25.70	-12.55	7.34	12.85	-14.68	14.68	-22.02	0.00	-18.36
7° BT	-13.95	-9.11	-2.94	-11.01	-43.32	-60.19	-16.89	-14.68	-21.29
10° BT	-63.89	-50.30	29.37	22.02	-1.47	-12.48	-25.70	-22.02	-29.37
Riblets BT	-36.71	-13.21	-7.34	26.43	-31.93	14.68	0.73	-19.46	-6.61
Arc BT	-22.02	-7.34	-96.16	8.44	10.65	-31.57	-24.96	-18.72	-9.18
SBC	25.70	47.73	18.36	13.95	7.78	7.34	-13.58	5.58	-5.51
LBC	29.66	26.43	35.97	8.07	-21.88	-42.95	5.73	6.97	20.56
$C_{M_{\alpha_0}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	3.479	3.787	4.194	3.961	3.756	3.674	3.524	3.169	2.874
7° BT	3.31	3.595	3.937	3.811	3.641	3.585	3.477	3.157	2.858
10° BT	3.59	3.91	4.357	4.03	3.801	3.72	3.556	3.22	2.921
Riblets BT	3.506	3.742	3.911	3.763	3.578	3.507	3.406	3.184	2.865
Arc BT	3.577	3.926	3.868	3.491	3.341	3.345	3.336	3.11	2.82
SBC	3.595	3.892	4.284	4.024	3.803	3.726	3.571	3.234	2.922
LBC	3.585	3.876	4.265	3.991	3.839	3.714	3.583	3.221	2.911
$C_{M_{\alpha_2}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	39.97	18.81	-14.11	-25.86	-14.11	-2.353	-0.0017	29.0	15.67
7° BT	37.46	14.11	-3.92	-12.54	-10.19	-2.353	-10.19	-9.406	-11.76
10° BT	33.7	13.32	-51.73	-29	-15.68	-13.32	-6.271	-3.92	-11.76
Riblets BT	42.32	29	14.89	-15.68	-0.00168	2.193	22.73	-11.76	-0.0014
Arc BT	57.21	35.27	71.32	-14.27	29	33.62	21.16	-1.569	-6.898
SBC	-14.89	-28.37	-49.61	-42.32	-16.46	-10.97	-12.23	-19.2	-23.9
LBC	-39.03	-41.93	-53.29	-34.41	-32.13	-12.54	-15.68	-26.65	-22.26

$C_{M_{p\alpha_0}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	0.0371	0.1037	0.4368	0.3126	0.1498	0.3109	0.1776	0.2281	0.1968
7° BT	0.0	0.0433	0.1543	0.2111	0.1219	0.1024	0.1693	0.1749	0.1977
10° BT	0.0215	0.1027	1.0913	0.3925	0.2632	0.1760	0.1852	0.2062	0.2004
Riblets BT	0.1632	0.2424	0.2505	0.2080	-0.0538	0.1199	0.1337	0.1896	0.1986
Arc BT	0.2742	0.4388	0.0794	-0.1091	-0.0488	-0.0559	0.1273	0.2169	0.1968
SBC	0.1905	0.2480	0.5799	0.3990	0.1874	0.2863	0.2233	0.2417	0.2467
LBC	0.2728	0.3071	0.6126	0.3396	0.1070	0.0975	0.3126	0.2601	0.1995
$C_{M_{p\alpha_2}}$									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	30.10	16.15	-9.91	-22.02	3.67	-40.38	13.95	0.00	14.68
7° BT	11.01	7.19	-4.41	7.34	45.88	75.60	22.39	16.15	2.86
10° BT	61.69	45.15	-36.71	-42.95	-23.86	2.57	28.63	12.48	11.75
Riblets BT	47.73	21.29	14.68	-22.02	60.37	-10.28	21.29	31.57	17.73
Arc BT	9.55	-6.61	114.89	-29.37	-42.58	11.75	26.06	-2.94	-1.84
SBC	-46.25	-33.51	-24.23	-23.49	-22.76	-14.68	14.17	0.37	-14.76
LBC	-36.71	-33.41	-40.74	-13.07	17.69	38.91	-28.78	-11.38	8.07
C_{l_p}									
Mach Number	0.6	0.8	0.9	1	1.1	1.2	1.5	2	2.5
M33 9° BT	-0.0141	-0.0129	-0.0122	-0.0117	-0.0112	-0.0108	-0.0094	-0.0075	-0.0061
7° BT	-0.0141	-0.0131	-0.0124	-0.0117	-0.0117	-0.0108	-0.0094	-0.0078	-0.0068
10° BT	-0.0141	-0.0126	-0.0122	-0.0112	-0.0111	-0.0106	-0.0094	-0.0075	-0.0061
Riblets BT	-0.0141	-0.0131	-0.0124	-0.0117	-0.0116	-0.0110	-0.0094	-0.0080	-0.0064
Arc BT	-0.0141	-0.0131	-0.0124	-0.0119	-0.0117	-0.0108	-0.0094	-0.0080	-0.0066
SBC	-0.0141	-0.0129	-0.0122	-0.0116	-0.0112	-0.0108	-0.0094	-0.0076	-0.0063
LBC	-0.0141	-0.0129	-0.0123	-0.0116	-0.0112	-0.0108	-0.0094	-0.0076	-0.0062

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1. H. Khormi and S. Alfifi, “Multi-element airfoil analysis for NACA 0012 using computational fluid dynamics,” AIAA SCITECH 2022 Forum, Jan. 2022.
2. H. Khormi, H. Fairaq, T. Alhaddad, and W. Abdelrahman, “Feasibility of Developing Hybrid Electric General Aviation Aircraft,” AIAA SCITECH 2022 Forum, Jan. 2022.