Ballistic coefficient of a .338 Caliber Lapua Magnum VLD projectile

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Abstract

The study aims to validate the ballistic coefficient of a .338 caliber bullet projectile – Scenar. The geometry is created in CATIA V5 and then exported for meshing. The simulation is carried out at Mach 2 and a transient density-based compressible solver - rhoCentralFoam is used. The results are then validated with BC claimed by the cartridge and bullet manufacturer, Lapua. The results are also validated with the Doppler Radar experimental tests with both - the G1 & G7 drag models, carried out by Bryan Litz, an Aerospace Engineer and ballistician at Berger bullets.

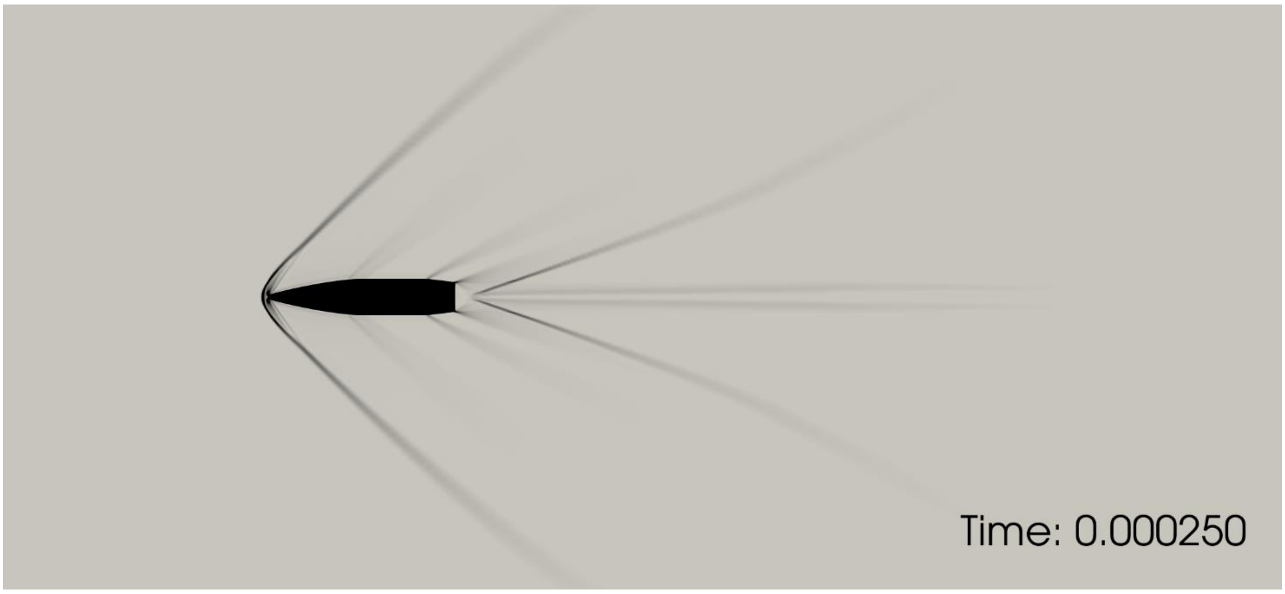


Figure 1 - Synthetic Schlieren of .338 Scenar for 2D case in Paraview

1. Introduction

1.1 Ballistic Coefficient

To put it simply in layman terms, ballistic coefficient is defined as the ability of a projectile to overcome air resistance during its flight. The higher the number, lower the retardation of the projectile. The general formula used in common engineering problems is given as

$$BC = \frac{M}{Cd \cdot A}$$

Where,

M = mass

Cd = coefficient of drag

A = cross-sectional area of the projectile

Ballistic coefficients have utmost significance in the domain of defence. The reason why ballistic coefficients are significantly important to study is because it helps to determine the projectile's trajectory, flight path and the deviations or drift caused because of wind conditions. BCs indicate how much the sniper or shooter has to adjust or offset his crosshair through telescopic sight to compensate windage and bullet drop due to gravity. This is why extensive studies are carried out on missiles & bullet projectiles because of their long flight duration and their obligations to hit the target accurately.

1.2 BCs of bullet projectiles

The formula for ballistic coefficient for very small projectiles ONLY, like bullets is given by

$$BC = \frac{W}{7000 \times cal^2 \times i}$$

Where,

W = weight of bullet in grains

Cal = caliber of bullet in inches

i = bullet's form factor

& BC is the bullet coefficient in $lb/inch^2$

But in general terms while speaking, the units are dropped off.

Form factor is defined by the ratio of Cd of the test bullet to the Cd of a standard bullet.

Fig - Form factor of a typical low drag bullet.

The figure illustrates the form factor of a typical low drag bullet with the standard G1 bullet. It means that the drag of the test bullet is half of that of the G1 bullet.

1.3 Drag Models

Ballistic coefficient is a function of Cd of the bullet, hence as Cd of the bullet changes over its speed, BC changes too. Furthermore, the bullets are fired with a variety of rifles having different muzzle velocity. There are thousands of bullets out there where they all have different Cd over a wide range of velocities which makes it even more enervating and a tedious task to calculate BC of each & every bullet at every point! This is where drag models come in. All the bullets are classified into different groups referencing to a standard drag curve such as G1 or G7.

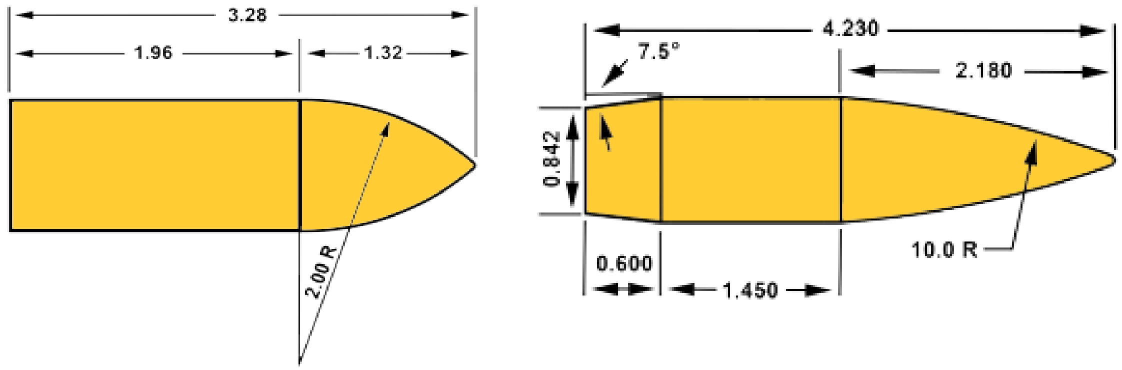


Figure 2 - Standard G1(left) and G7(right) bullets

The **G1 drag model** is a drag curve of the first standard G1 bullet - which has a flat base and an ogive of 2 calibers.

The **G7 drag model** is the drag curve of a standard modern G7 bullet - which has a tapered boat tail and ogive of 10 calibers.

The basic idea is that it's much easier to represent the drag of a class of bullets by referencing all bullets to a common standard. So, once we know the form factor you can approximate the BCs at all speeds. There is almost a dozen standard drag models but the G1 & G7 models are by far the most popular and mentioned on the product spec sheet.

Ogives are commonly referred to the curved surfaces of the nose of the projectile to make them more streamline. Ogives are the most important aspects of projectile design pertaining to ballistic and aerodynamic studies. Larger the ogive, pointier the nose, more streamline the shape. But a very large ogive radius results in dynamic instability and stands by far as one of the biggest limitations of it.

2. Problem Statement

To calculate coefficient of drag of .338 caliber projectile at Mach 2 at Standard Temperature and Pressure i.e STP conditions using compressible solver *rhoCentralFoam* and further validate the BC_1 and BC_7 coefficients.

3. Governing Equations

Unlike pressure solvers, rhoCentralFoam is a density-based solver, which means that the momentum, continuity equations are solved simultaneously rather than sequentially.

The continuity equation for a compressible fluid is given by

$$\frac{\partial}{\partial t} + \nabla(\rho V) = 0 \tag{1}$$

The momentum equation or popularly known as Navier-Stokes equation for a viscous compressible flow is given below in x direction. The equations in y and z direction can be written in a similar format with their respective velocity and force components.

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u V) = -\frac{\partial P}{\partial x} + \rho f_x + Fx_{(viscous)} \tag{2}$$

Also, the energy equation is given by

$$\frac{\partial e}{\partial t} + \nabla.((e + P)V) = Q \qquad (3)$$

Where,

ρ = density of fluid

V = velocity of fluid (u, v and w as components in x, y and z direction respectively)

P = pressure

e = total energy per unit volume

Q = heat source

4. Simulation Procedure

4.1 Geometry and Mesh

The bullet projectile chosen for this study is the .338 caliber Lapua Magnum 300 gr Scenar. The bullet was designed keeping long range shooting in mind and other tactical uses such as penetrating ballistic armor and protective shields!

No reliable resource for the geometry of the projectile was found anywhere on the internet. The design was then obtained by the company Lapua itself by making a successful contact with a representative of the company. Thus, there is no doubt in the authenticity of the design.

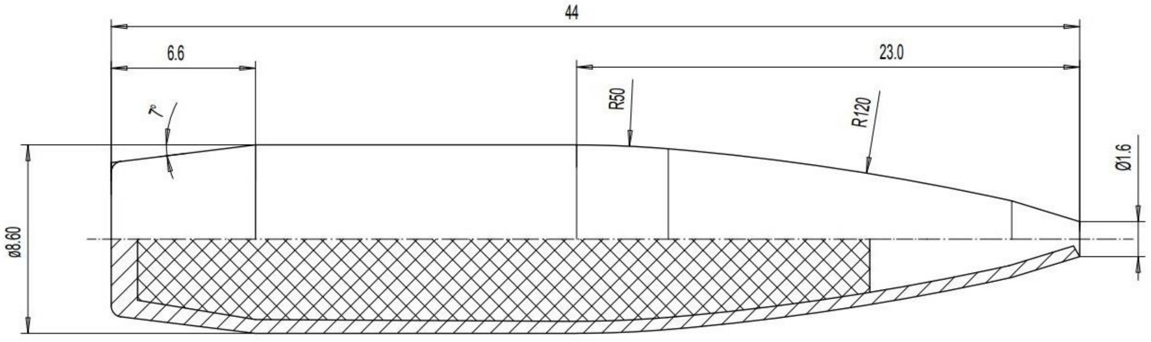


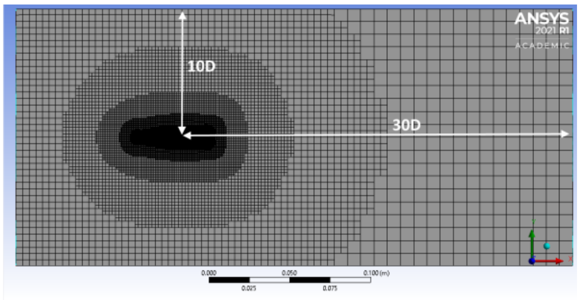
Figure 3 - Dimensions of the projectile

The bullet has tangent-secant hybrid ogive and a long 7° tapered boat tail, resembling the G7 standard bullet and making it a VLD bullet - Very-Low-Drag bullet.

Specifications –

- Caliber = 8.6 mm (.338 inch)
- Total length = 44 mm
- Weight = 19.4 gm (300 grains)

The bullet was designed in CATIA V5 and was then exported as a step file(.stp). The flow domain is a cylinder with a cushion of 10D in radial direction and 30D in backward direction which seems sufficient for developing full flow conditions



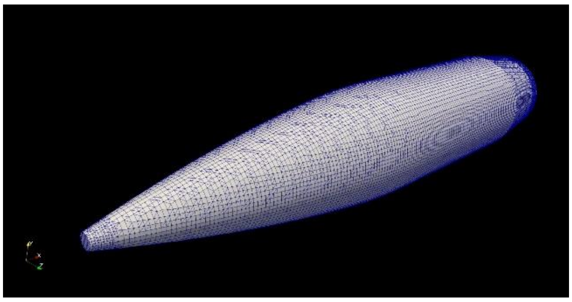


Fig. 4 – Mesh flow domain *Fig. 5 – Surface mesh over the bullet*

The flow domain was meshed using ANSYS meshing utility and Cutcell method was adopted to obtain a structured grid over the whole domain. Face sizing of 0.25 mm was implemented over the surface of the bullet. Growth ratio was set to 1.05 to enable a slower growth rate of cells as well as to have more no. of smaller cells in the near wall region. Inflation layers were also adopted on the surface to resolve boundary layers. The thickness of the first layer of the grid cells was calculated by keeping y+ value as 90 at 1.85×10^6 Re.

The initial test was run on a coarser mesh with the details below (Table 1) and finer mesh was adopted based on the results of coarser mesh discussed in the results part. The mesh was then exported into .msh format and later converted into OpenFOAM readable format by the "fluent3DMeshToFoam" utility.

Mesh	Face sizing	Growth rate	y+ value	Cell count
Coarse	0.5 mm	1.1	130	357k
Fine	0.25 mm	1.05	90	1 million

Table 1

The case was run parallelly with the mpirun command and hence was decomposed into 4 domains with the help of decomposeParDict located in system folder of the case directory. At last, the decomposed solution was reconstructed with the “reconstructPar” command for further post-processing in Paraview.

4.2 Initial and Boundary Conditions

The general boundary conditions and parameters for the simulation are as follows –

- Temperature - 300K
- Velocity - 686 m/s (Mach 2)
- Pressure - 1,00,000 Pa
- Adiabatic index - 1.4
- Viscosity - 2e-5 kg/m.s

The boundary conditions used for all the patches are as follows

Parameters / Names	U	T	P
inlet	fixedValue	fixedValue	zeroGradient
outlet	inletOutlet	inletOutlet	waveTransmissive
projectile	noSlip	zeroGradient	zeroGradient
boundary	supersonicFreestream	inletOutlet	zeroGradient

Table 2

4.3 Solver

The solver being used here is rhoCentralFoam which is a transient compressible-density based solver. Initial tests were also conducted using sonicFoam which had fairly accurate results but had poor shock capturing capability. Hence, rhoCentralFoam was finalised as the UserGuide suggested the same [2]. No turbulence model has been applied to the case and hence it is set to laminar in the "turbulenceProperties" file.

5. Results and Discussions

In Fig. 6 and Fig.7 we can see pressure and velocity contours respectively at the final timestep. The pressure contours clearly show a strong stagnation point in front of the nose of projectile. A low-pressure region is also created behind the bullet. The huge pressure difference between the front and rear of the bullet indicates a high pressure/form drag and that it is major contributor of drag.

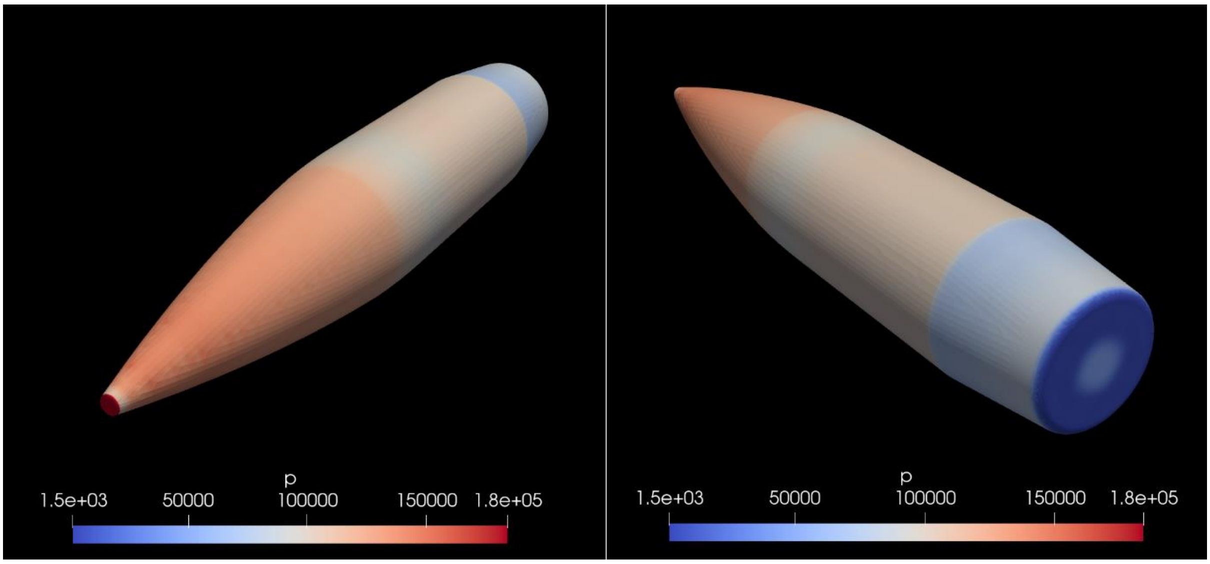


Fig. 6 – Pressure contours over the bullet surface

The velocity contours show a high velocity region over the ogive. Also notice the shockwaves being generated at the front of nose and at the tail of the bullet.

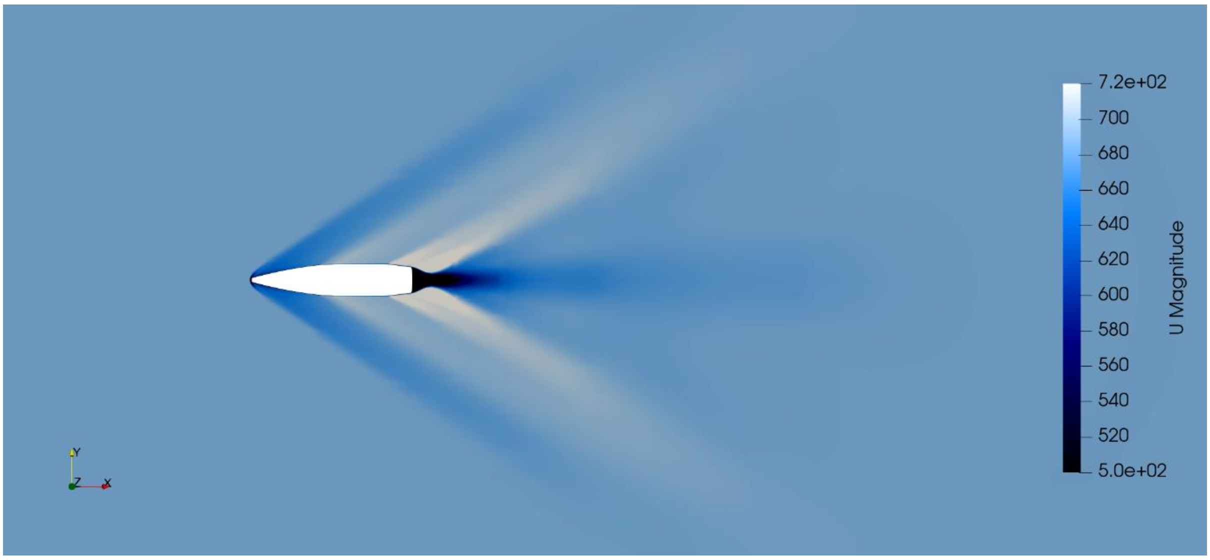
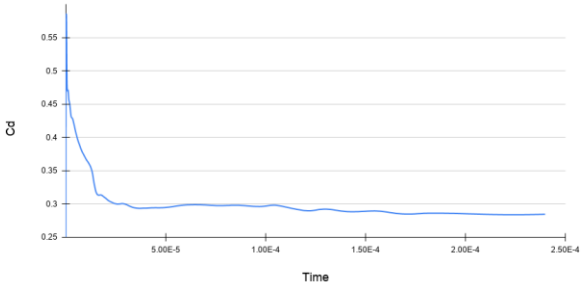


Fig. 7 – Velocity Contours at middle section of domain

The solution was initially run, setting maxCo as 0.2 in the controlDict file for the solution to be stable. And as you can notice in the residuals chart (Fig. 9) there is a sudden increase in order of 10 near timestep 0.00002 seconds. This is because the maxCo was increased from 0.2 to 0.6 in order to save computational power as well as time. The residuals continued dropping below 1e-6 which are industrially acceptable standards.

The endTime was set to 0.00024 and Cd was found to be nearly constant at 0.2811 (Fig.)



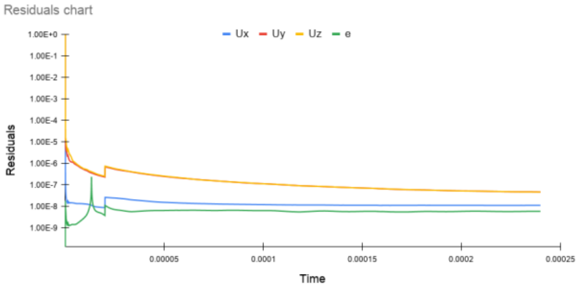


Fig. 8 – Cd of bullet vs. time

Fig. 9 - Residuals

At Mach 2, Cd of a standard G1 bullet is 0.593 and Cd of a standard G7 bullet is 0.298[1].

Therefore, as discussed above in introduction, the calculation of G1 and G7 form factor as well as ballistic coefficients will be as follows

$$i_1 = \frac{Cd\ of\ projectile}{Cd\ of\ G1} \qquad i_7 = \frac{Cd\ of\ projectile}{Cd\ of\ G7}$$

$$i_1 = \frac{0.2811}{0.593} \qquad i_7 = \frac{0.2811}{0.298}$$

$$= 0.4740 \qquad = 0.9432$$

The corresponding BCs will be

$$BC_1 = \frac{W}{7000 \times cal^2 \times i_1} \qquad BC_7 = \frac{W}{7000 \times cal^2 \times i_7}$$

$$= \frac{300}{7000 \times 0.338^2 \times 0.4740} \qquad = \frac{300}{7000 \times 0.338^2 \times 0.9432}$$

$$= 0.7814 \qquad = 0.3933$$

The Cd of the projectile was found out to be 0.312 for coarse mesh. The BCs are after calculating in a similar fashion as above.

The Lapua product catalog 2020[3] contains BCs for Scenar and many other projectiles not for every velocity but for different velocity ranges.

Bryan Litz, an Aerospace engineer and ballistician at Berger bullets have conducted several experimental Doppler Radar tests on more than 500 most popular bullets of all time. His book, Ballistics for Long range shooting [1] contains the average BC_1 & BC_7 from 450 m/s to 910 m/s. The following are the final results when compared with both the sources

Ballistic coefficients	Lapua Catalog	Bryan Litz	Coarse mesh (% error)	Fine mesh (% error)
BC_1	0.726 - 0.756	0.764	0.713 (6.67%)	0.7814 (2.27%)
BC_7	0.368+	0.392	0.358 (9.6%)	**0.3933 (0.33%)**

Table 3

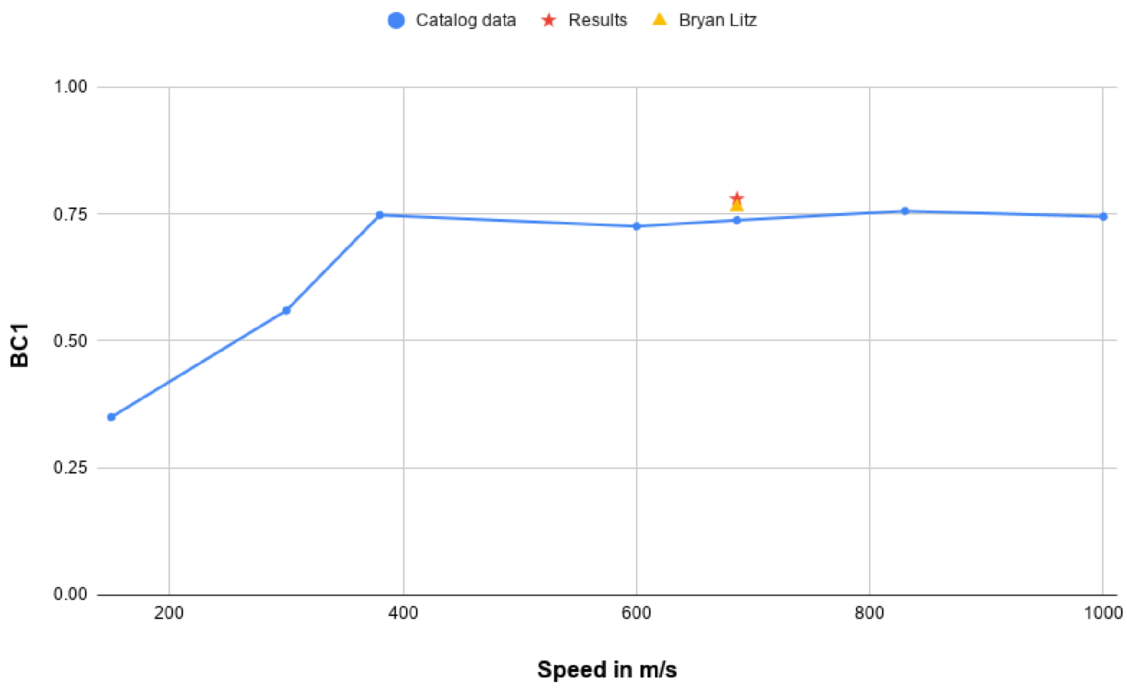


Fig. 10 – Final results comparison

The .338 caliber Lapua Magnum projectile Scenar fits better with G7 drag model and hence utilising G7 BC would lead to more accurate results than G1 BC for practical purposes. The calculated BC_7 has erred only by 0.33% if compared with the value of Bryan Litz's, though it is an average over a range of velocity. Although, BC_1 doesn't lie in the exact range, the value is very close to the range.

There are several other ways to calculate an approximate form factor of bullets design parameters or section densities. The form factor of 300gr Scenar is 0.956[1]. Therefore,

$$0.956 = \frac{Cd\ of\ Scenar}{Cd\ of\ G7}$$

$$Cd\ of\ Scenar\ =\ 0.956 \times 0.298$$

$$= 0.2848$$

Which is very close to our obtained Cd – 0.2811 resulting an error of 1.31%

A 2D case study is feasible and well suited for studying shock-waves since it demands very fine mesh around the body. A 2D case was also setup just to demonstrate the shock capturing capability of OpenFOAM. Refer Fig. 1 for Synthetic Schlieren of .338 Scenar.

6. Conclusions

1. The results obtained have thus been validated with both the sources and proves that OpenFOAM can accurately calculate drag of bullet projectiles even at high speeds and eventually help us determine ballistic coefficients at various speeds. The difference in errors could be twisting effect of bullet-Magnus effect during its flight, along with Coriolis effect and different atmospheric conditions during tests.
2. Since many times, experimental data or complete data is not available while buying ammos, and a single BC value doesn't match over the whole range of velocities, professional shooters can use OpenFOAM to calculate their own BCs according to their own rifle's muzzle velocity and have an upper hand over others in rifling competitions.

Acknowledgements

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References

1. Litz Bryan, Applied Ballistics for Long range shooting, 3rd edition, 2015, ISBN 978-0-9909206-1-8, Page 408, 418
2. OpenFOAM User Guide
3. Lapua, Product catalog, 2020, Page 18