Analysis of External Ballistics of a Projectile of Calibre 155 mm

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December 7, 2014

Abstract

The objective of this work was to propose an external geometry for a firefighting projectile named FIREND. The finite volume code Star – CCM+® is used to calculate forces and moments acting on the projectile. The characteristics of the trajectory are computed using Mathematica®. The PRODAS V3® software was used to verify and validate the models implemented.

Initially, the procedure adopted was to create a methodology for an existing ammunition that would allow to be verified and validated with the available literature. An extensive aerodynamic characterization has been done through CFD in order to establish the projectile in terms of forces and moments which depend on the angle of attack and thus feed the script for 6-DOF computation. It was concluded that the locking strap, the guiding strap and the Coriolis drift were negligible compared to the results obtained.

In the following phase six different geometries were tested, varying the length and the nose geometry. It was defined for this projectile an initial velocity is 100 m/s and the weight 10 kg, concluding that the total length would be 697.1 mm and hemispherical profile with the capacity to transport 7.5 dm³ inside. Wind tests were conducted to evaluate the projectile stability in flight. The software and analysis process developed in this work are available, being a contribution to the project FIREND.

Keywords: Firefighting projectile, projectile geometry, computation of aeroballistic coefficients, six degree-of-freedom trajectory, dynamic stability analysis.

1 Introduction

The occurrence of forest fires is unavoidable. The FIREND project arose in 2005 [1] with the ultimate aim of providing an alternative and additional way to forest fire fighting, having suffered its last upgrade in 2013 [2]. The projectile calibre changed to 155 mm. The main reason that justified this change was to increase the volume of firefighting agent to be transported inside, which happened to be three times higher.

This project consists of an artillery shell designed to fight fires, strengthening the action of the firefighters and Civil Protection. Its performance allows long distance firefighting in areas of high slope and difficult access for terrestrial means and in situations with reduced visibility, nighttime as well as under adverse weather conditions.

The FIREND Project is an opportunity to render the military a new kind of missions in peacetime, with special interest for the entire population, which certainly contribute to raising their levels of motiva-
tion and to be recognized for their work performed on behalf of the population.

This study aims to determine a geometry for a projectile and to ensure flight stability along its trajectory. This requires the use of CFD simulations, so that the coefficients of force and moment can be calculated, and also the pseudo-empirical prediction methods, as is documented in external ballistics literature. As a final goal we intend to build a software that couples results from aerodynamic analysis with the calculation of the flight trajectory using a 6 degrees of freedom approach.

2 Description

For external ballistics be understood, it is necessary to take into account several factors, including the correct nomenclature \[3\], \[4\].

Three reference frames were considered in the overall computations:
- the X Y Z referential, which is static and located at the howitzer exit, as shown in Figure 1;
- the x’ y’ z’ referential, located in the CG of the projectile, which is always aligned with the X Y Z referential;
- the x y z reference frame, aligned with the body of the projectile, and that has the same spin movement as the projectile;

![Figure 1: Referential used.](image)

Using the Star – CCM+ it is possible obtain the aerodynamic forces and moments acting on the projectile. If the gravitational force is known, the acceleration comes naturally from an algebraic operation. By definition:

\[
F_i = \frac{d (m v_i)}{dt} \tag{1}
\]
and thus,

\[
a_i = \frac{dv_i}{dt} \tag{2}
\]

By numerical integration, after setting \(\Delta t\) as a constant, it follows that

\[
v_i^{new} = v_i^{old} + \Delta t a_i \tag{3}
\]

Integration of equation 2 gives \(v_i = dx_i/dt\), which after discretization provides us the equation of coordinate position \(x_i\) of the body with time. Finally \(x_i^{new} = x_i^{old} + \Delta t v_i^{new}\) gives the discrete equation of CG position.

The rotational motion is represented with three degrees of freedom that is three angular coordinates which represent the body orientation in 3D space about its mass centre: \(\Theta = \{\phi, \theta, \psi\}\), with \(\phi\) the spin angle, \(\theta\) the pitch and \(\psi\) the yaw angle.

The orientation of the body is defined after three sequential rotations, in the previous order \(\phi, \theta, \psi\) relatively to the referential \(x’ y’ z’\). In order to analyze the motion of the projectile, only the attack angle is considered, which defined as the angle between the axis of the projectile and the flow direction of approach in the projectile frame. With no wind, this direction will be the direction of the trajectory.

The Euler equations of motion were used for the 3D rotation. These equations are written on a referential whose axis correspond to the principal axis of inertia. The referential can rotate with the body to keep unchanged the inertia moments.

The equations are:

\[
\vec{M} = \vec{\dot{H}} + \vec{R}^{-1} \vec{\dot{R}} \vec{H} \text{ or } \vec{M} = \vec{\Omega}_B^{-1} + \vec{\Omega}_R X \left( \vec{1} \vec{\Omega}_B \right) \tag{4}
\]
where

\[
\mathbf{I} = \begin{bmatrix}
I_{xx} & 0 & 0 \\
0 & I_{yy} & 0 \\
0 & 0 & I_{zz}
\end{bmatrix}
\]

(5)

\[
\mathbf{\Omega} = (\omega_x; \omega_y; \omega_z)
\]

(6)

The subscripts \( B \) and \( R \) in Equation 4 represent the body and the frame, respectively, being \( \mathbf{R} \) the rotation matrix.

The rotation matrix has 9 free variables, but considering the symmetry of the matrix, 3 of them are automatically set. Therefore, the remaining six variables are used to define three degrees of freedom of rotational movement in 3D. As such, it will be necessary to reorthonormalize the rotation matrix.

The 6-DOF trajectory was used because it is the model that best represents the physical phenomenon of ballistic flight, when we want an overall assessment, similar to what had been done in 2009 [5], when effected studies were done to calculate the trajectory of a 155 mm projectile, resorting to the aid of the software PRODAS® to calculate flight behavior.

The use of CFD methodologies to approach a problem is based on a very specific procedure. During the pre-processing, it is necessary to define the geometry of the object under study, as well as its domain, which is divided into discrete cells (the mesh) [6]. The choice of the mesh to be implemented is very important because it will have a decisive role in the solution of differential equations [7]. The CFD software allows to calculate the forces and moments at each time and report to the user [8], which depend on the angle of attack [9]. It was found that the lift increases with the angle of attack, as well as the axial force due to the Magnus effect.

The spin stabilized projectiles for L/D ratio greater than 7 (L is the length and D the projectile’s caliber) tends to be unstable unless additional components are used to ensure stability [10].

There are several factors that affect the trajectory. They are: angle and launch speed, mass and shape of the projectile, atmospheric wind, effect of Earth’s rotation, forces and moments induced by rotation and weather effects [3]. The velocity of the projectile has a direct influence on the resistance it offers in flight [11], illustrated in Figure 2.

![Figure 2: Variation of drag coefficient with Mach](image)

The following set of hypotheses to simplify the entire process is assumed:

- gravity constant along the trajectory of the projectile equal to 9.81 m/s²;
- the properties of the air are set for a standard atmosphere;
- it is considered that the projectile leaves the howitzer with an angle of attack of 0 degrees and without applied forces;
- the Coriolis force was not considered due to its low influence in short ranges;
- the surface of the projectile is considered smooth for the purposes of friction and turbulence;
- it is considered that the CG of the projectile is constant, as well as its moments of inertia, along the path.
3 Verification and Validation

The assumptions for the projectile are:

• the howitzer induces a spinning rotation to the projectile;
• charge 1 is used, therefore subsonic regime.

Another reason was to establish a methodology for use in optimization processes being the $C_D$ approximately constant in the subsonic regime, having only that the drag increases with the square of speed and air density.

The case study for verification and validation was based on the conventional ammunition M107, illustrated in Figure 3 with its main characteristics in Table 1. These tests were carried out to load 1 (minimum charge of gunpowder) which corresponds to a given rate of translation and rotation.

The mesh is a fundamental parameter to obtaining reliable results. After the convergence of the results is verified for a number of cells of approximately 6.5M, Figure 4, it was assumed that this would be the kind of refinement required to give an answer to the purpose, Figure 4.

The error obtained for the value of $C_D$ compared with the value of $C_{D,\text{theoretical}}$ to 6.5M of a mesh cell, was less than 2 %.

The physical model chosen for the CFD simulations in Star-CCM+® was "Coupled Flow", which is suitable for compressible flows [12]. Another advantage of this model is the robustness to solve flows with dominant source terms because the projectile has spin.

The turbulence model used was $k-\omega$ (SST version) for being suitable for situations of high adverse pressure gradient and flow rotation.

The boundary conditions of the wall were chosen high $y+$ (from 30 to 150), Figure 6, to prevent the mesh had more cells.

In Figure 6 one can observe the representation of the $y+$ along the projectile. As it can be seen the range for the values of high $y+$ was respected. There have been some exceptions for which it was not possible to guarantee the assumptions made in some areas because the flow was almost "stopped".

![Figure 3: M107 ammunition geometry.](image)

![Figure 4: Final mesh adopted.](image)

![Figure 5: Drag with the mesh refinement.](image)

<table>
<thead>
<tr>
<th>l (mm)</th>
<th>m (kg)</th>
<th>CP (mm)*</th>
<th>CG (mm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>697.100</td>
<td>43.096</td>
<td>184.04</td>
<td>458.37</td>
</tr>
</tbody>
</table>

*measured from the nose

Table 1: Features with $v = 211.8\text{m/s}$ e $\omega = 344\ \text{rad/s}$.
Simulations were performed with 0°, 2° and 4° of angle of attack because variations of $\alpha$ in flight ammunition occur mostly in this range. These values will influence the range and stability of the projectile along its trajectory. It is important to note that the coefficients of forces and moments were calculated at the CG of the projectile.

In Figure 7 can clearly be observed the influence of the angle of attack on the projectile. For 0° angle of attack can verify the symmetry of the turbulence in the wake unlike what happens at 4°, noting the variation of turbulence in the wake zone.

To analyze the trajectory it was used two softwares: Mathematica® and PRODAS®, which is a recognized ballistics commercial software. In Mathematica® it was implemented a specific own code, while in PRODAS® it was integrated the CFD results in the study of rigid body dynamics. It was established a comparison between the values of firing tables with the values obtained by different software in order to verify and validate the code implemented in Mathematica®. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>$\beta$ (°)</th>
<th>Tab (m)</th>
<th>Math (m)</th>
<th>PRODAS (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.64</td>
<td>3600</td>
<td>3549.6</td>
<td>3571.1</td>
</tr>
<tr>
<td>31.21</td>
<td>3700</td>
<td>3647.0</td>
<td>3669.9</td>
</tr>
<tr>
<td>32.99</td>
<td>3800</td>
<td>3744.3</td>
<td>3768.9</td>
</tr>
<tr>
<td>35.11</td>
<td>3900</td>
<td>3841.8</td>
<td>3868.1</td>
</tr>
<tr>
<td>37.89</td>
<td>4000</td>
<td>3939.2</td>
<td>3967.9</td>
</tr>
</tbody>
</table>

As already mentioned, the Mathematica® was used due to their valencies. A code was created so that the trajectory of the projectile could be calculated at any instant of time.

In order to complement the results obtained with PRODAS®, a code was created, mainly because the operating conditions of the new projectile can not be satisfied with this software because, for example, the future launch speed is Mach 0.3, much lower than the typical values of speed used, and this software makes interpolations of experimental data.

The other reason is the fact that the geometry can no longer be conventional and in this case, PRODAS® also is not suitable, although it is useful when it is possible to apply, making the process much quicker.

However, the code created in Mathematica® was also verified and validated with PRODAS®, using for this a speed of 200 m/s and a conventional geometry, which is available in the software library. Thus it was possible to compare the results obtained with both software. Those results are shown in Table 3.

<table>
<thead>
<tr>
<th>Variables</th>
<th>PRODAS</th>
<th>Mathematica</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_i$ (m/s)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$\omega$ (rad/s)</td>
<td>324</td>
<td>324</td>
</tr>
<tr>
<td>$\beta$ (°)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$s_{max}$ (m)</td>
<td>3236.11</td>
<td>3217.73</td>
</tr>
<tr>
<td>$t_{v00}$ (s)</td>
<td>19.91</td>
<td>19.90</td>
</tr>
<tr>
<td>$h_{max}$ (m)</td>
<td>486.16</td>
<td>485.7</td>
</tr>
<tr>
<td>$t_{hmax}$ (s)</td>
<td>9.85</td>
<td>9.84</td>
</tr>
</tbody>
</table>
As it can be seen from the results presented, both results are very similar, thus being verified and validated by the code.

4 Results

Some initial conditions that have a major role in the design of the projectile and scope of the intended purpose were imposed. These are shown in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Initial conditions of operation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>v_i (m/s)</td>
</tr>
<tr>
<td>FIREND</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The initial velocity and the total mass of the projectile have undergone significant changes. These aim to conceive the projectile FIREND with a material which makes the entire process more economical and that the pressures and temperatures developed inside the shell are much lower, so that the new material supports them.

It were created and analyzed six geometries, varying the total length of the projectile and the shape of his nose. The first 3 nose cone versions have a varying length, while the other have a hemispherical nose, Table 5.

<table>
<thead>
<tr>
<th>Table 5: Different geometries tested.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomenclature</td>
</tr>
<tr>
<td>version 1</td>
</tr>
<tr>
<td>version 2</td>
</tr>
<tr>
<td>version 3</td>
</tr>
<tr>
<td>version 4</td>
</tr>
<tr>
<td>version 5</td>
</tr>
<tr>
<td>version 6</td>
</tr>
</tbody>
</table>

Both parameters that were changed have the same purpose: to increase the ability of material to be transported inside the projectile, when compared with conventional M107 ammunition.

The concept of hemispherical nose dates back to the FIREND 105 mm Project. Giving this same concept, applied to the same overall projectile’s length, the carried material is to be increased to the double of the one used on the conical profile ammunition.

In order to test and to establish a comparison between different geometries, some parameters remained unchanged. The speed used was 100 m/s and tested simulations into a launch angle of 60°, as it is more susceptible to the instability of the projectile.

However, it should be noted that other parameters such as the total length, CG, CP, undergone changes in geometry to geometry, these parameters also have a leading role in the stability analysis of the projectile.

Based on tests performed for six different geometries in order to select the geometry that best fulfilled the requirements for the new 155 mm FIREND’s projectile, geometry version 4 was selected. It was found that this is the most stable geometry by analysis of the variation of the angle of attack during the trajectory, compared with various geometries analyzed for different wind speeds, and also according to the value of the registered gyroscopic stability. The results obtained are shown in Table 6.

In Table 5 it can be seen that the parameter of gyroscopic stability is only satisfied for three of the created versions, being version 4 one of these. This provides a greater capacity to carry material inside and therefore, with regard to this aspect, is the better choice.

<table>
<thead>
<tr>
<th>Table 6: Different limits as a function of wind speed for geometry version 4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>v_{wind} (m/s)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>+20</td>
</tr>
<tr>
<td>-20</td>
</tr>
</tbody>
</table>
For this geometry the maximum angle of attack achieved in a situation without wind, never exceeds 5.6°, while in a situation where there is the presence of a crosswind (magnitude of 20 knots) the angle of attack already reaches values of 10°. However, these maximum are achieved when the projectile starts its descending phase in the trajectory, when the travel speed of the projectile registers its minimum, then returning to low values of angle of attack. It means that its behavior returns to a stabilize level in the stage which is prior to his arrival at the ground. The variation of angle of attack along the trajectory can be seen in Figures 8, 9 and 10.

In Figure 11 one can observe the new location of the CG and CP in geometry version 4.

Using the software Star – CCM+®, all simulation methodology developed for conventional ammunition M107, in the previous chapter, was applied in this new configuration of the projectile, i.e., in the FIREND 155mm geometry. Thus, the final mesh got approximately 7M cells, present in Figure 12 like the mesh implemented for the M107 ammunition in the previous section. Also the parameters implemented in Star – CCM+® were the same.

With the results of the aerodynamic characteristics for the three angles of attack analyzed (0°, 2° and 4°), under the imposed conditions, the curves of forces and moments acting on the projectile were traced in order to observe the tendency. These results are shown in Tables 7 and 8 and the characteristics curves are shown in Figures 13 and 14. It is important to note that the moments were calculated at the CG of the projectile.

<table>
<thead>
<tr>
<th>α (°)</th>
<th>Magnus (N)</th>
<th>Lift (N)</th>
<th>Drag (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.173</td>
<td>0.011</td>
<td>-17.044</td>
</tr>
<tr>
<td>2</td>
<td>0.192</td>
<td>7.106</td>
<td>-17.836</td>
</tr>
<tr>
<td>4</td>
<td>0.706</td>
<td>13.616</td>
<td>-19.173</td>
</tr>
</tbody>
</table>
Table 8: Results of moments in the CG with $\alpha$.

<table>
<thead>
<tr>
<th>$\alpha$ (°)</th>
<th>Pitch (N.m)</th>
<th>Yaw (N.m)</th>
<th>Roll (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.003</td>
<td>0.043</td>
<td>-0.062</td>
</tr>
<tr>
<td>2</td>
<td>-2.154</td>
<td>0.043</td>
<td>-0.062</td>
</tr>
<tr>
<td>4</td>
<td>-4.411</td>
<td>0.013</td>
<td>-0.062</td>
</tr>
</tbody>
</table>

As can be seen in Figure 13, increasing the angle of attack causes large changes in the lift and in particular, in pitch, by varying these parameters in an approximately linear way. In the case of the lift, which for $0°$ angle of attack was virtually nil, at $4°$ shall be of considerable value. The same goes with the pitch, resulting of pressure distribution along the projectile.

![Figure 13: Variation of the forces with $\alpha$.](image)

Figure 14: Variation of the moments with $\alpha$.

Similar to the analysis performed for the trajectory of the projectile with $60°$ of launch angle, after having defined the final geometry to adopt, additional tests were also conducted for other launch angles, especially for $30°$ and $45°$. As was done previously, it was now found the influence of wind at 20 knots in projectile either in the positive direction, but also in the negative sense. The results are shown in Table 9.

Table 9: Limits to wind for FIREND 155 mm with $\beta = 60°$.

<table>
<thead>
<tr>
<th>$v_{wind}$ (m/s)</th>
<th>$X_{max}$ (m)</th>
<th>$h_{max}$ (m)</th>
<th>$z_{max}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>766.99</td>
<td>353.79</td>
<td>-27.5</td>
</tr>
<tr>
<td>+20</td>
<td>744.94</td>
<td>349.62</td>
<td>-5.3</td>
</tr>
<tr>
<td>-20</td>
<td>760.18</td>
<td>349.07</td>
<td>-42</td>
</tr>
</tbody>
</table>

5 Conclusions

The main conclusions are the following:

- The value of the forces and moments acting on the projectile depend significantly on the angle of attack. For $\alpha = 0°$ all moments and forces are practically inexistent, except drag and roll;
- The maximum angle of attack reached by the projectile along its trajectory is directly dependent on the launch angle;
- It was found that it would not be possible to increase the length of the projectile, ensuring its stability in flight as described in the literature.
- For the initial conditions imposed for the release of the projectile, the hemispherical profile is more stable than the conical profile. With this new profile in addition to respect the stability parameter, also significantly increases the amount of load to be carried inside the projectile;
- Were also carried out simulations taking into account the wind speed and it was concluded that the most critical situation in order to unsettle the flight of the projectile is to crosswind with positive direction. It was shown that the 155 mm projectile FIREND would be more likely to unsettle when subjected to wind than the M107;
- It was also concluded that the lateral deviation suffered by the projectile has a strong dependence on
the time of pitch, and the higher the value the first derived of this moment, lower the amount of lateral deviation of the projectile. It also presents some influence in variation of the angle of attack so that the larger the lateral deviation greater will be the variation of angle of attack.

- A process was established, verified and validated, which allows to characterize in a structured and sequential way the specificities of a munition with regard to external ballistics. This methodology will be of great importance in future developments of the project. It should be noted that even if this form is considered, many other aspects such as the interior of munition or the material which is manufactured have implications in the mass, in moments of inertia, in CG, among others.

- According to the methodology and parameters defined, it’s expectable to obtain aerodynamic and external ballistics results lower than 2%.

References


