USING A 3D MODEL TO ASSES PROJECTILE'S IMPACT POINTS DEVIATION DUE TO MANUFACTURING ERRORS

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This Publication has to be referred as: Trzun, Z[vonko]; Andric, M[arijan] & Vrdoljak, M[ilan] (2019). Using a 3D Model to Asses Projectile's Impact Points Deviation Due to Manufacturing Errors, Proceedings of the 30th DAAAM International Symposium, pp.0791-0799, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-22-8, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/30th.daaam.proceedings.110

Abstract

The paper describes the use of a rocket's 3D CAD model to determine the effect of nondeterministic manufacturing errors on inertial characteristics of the observed rocket. A case study was performed for a chosen unguided rocket with well-known features. For this rocket a 3D model was made, allowing simulation of different manufacturing errors such as misalignment of rocket's components, deviation of mass distribution, shape, etc. The likelihood and the extent of a particular error are gathered either from literature or directly from the manufacturer. The analysis gives a relationship between errors in production and consequent change of the rocket's geometry and inertial characteristics. The observed results are further used to predict the effect of manufacturing errors on the rocket's flight and displacement of impact points.

Keywords: unguided rockets; manufacturing errors; 3D CAD model; inertial characteristics; precision.

1. Introduction

The production of ammunition is a specific process characterized by high demands imposed on manufacturers, with strict criteria and tight tolerances. The reason for such rigorous control lies in extremely high demands that ammunition must respond to. Projectiles of today fly to distant targets 20 - 30 kilometers or even more [1], and at the same time, their expected error must not exceed a few dozens of meters (depending on the type of projectile).

Because of military, economic and humanitarian reasons, it is necessary to impose demands on manufacturers so that the weapon and ammunition of highest quality is manufactured – but on the other hand, the cost of such products must be maintained within reasonable limits. Because of the latter requirement (reduction of costs), a certain level of manufacturing errors must be accepted, and the process of designing individual manufacturing phases and associated manufacturing errors becomes a quest for the right optimum between criteria of precision and criteria of low cost [2]. This work proposes the solution of how to find such an optimum by synthesizing knowledge of 3D modeling, flight mechanics and statistics.

The problem presented in this paper has been addressed in other studies before, for example [3] and [4] where authors analyze the effect that particular disturbances have on missile behavior during flight, but always with a certain level of simplification that prevents their work to be universally applicable to any class of projectile. For example, in [3] authors identify the most influential factors that cause dispersion of projectile trajectories, especially analyzing the effect of mass imbalance. Although this paper is an excellent starting point for more extensive analysis, it refers exclusively to conventional artillery missiles and not to rockets (i.e. does not consider the problem of thrust force asymmetry). Consequently, the authors present a flight model that is suitable only for spin-stabilized artillery projectiles, etc. In [4] authors develop a flight model for non-guided missiles and also present mass imbalance as a disturbance strongly affecting the rocket's flight. But the mass imbalance is introduced exclusively by varying axial moments of inertia, i.e. under the presumption that there are no products of inertia.

In our work, a method will be presented that connects manufacturing errors with the dispersion of projectile's impact points. This is also the main contribution or difference between our research and aforementioned studies by other authors: now changes in rocket's inertial characteristics, which affect its flight so much, are presented not as a starting point of analysis, but as a consequence of specific errors occurring during production. With such approach, it is possible to identify those manufacturing errors that have the most severe impact on precision and to recommend manufacturers to which stages of production especially tight tolerances must be applied.

Our method incorporates a 3D model of a rocket with well-known characteristics, designed in CAD program and matching characteristics of the original rocket. If any manufacturing error emerges (some typical manufacturing errors will be presented in this paper), a 3D model will give exact changes in rocket's inertial characteristics that affect its flight. Also, in this paper, an advanced 6DOF flight model is shortly presented. This model is adjusted for linking with a 3D CAD model and then tracking the flight of a projectile with geometric or mass asymmetry.

As the case study, an analysis of faulty manufactured explosive head is chosen, and in the future more individual manufacturing errors will be analyzed, compared and ranked according to the effect on the final deviation of impact point.

2. Definition of a Problem

Each rocket, even if unguided and thus constructed with a limited quantity of electronic components, still remains a complex system. Producing such system requires use of many production technologies and multiple consecutive steps, each of them introducing an error of certain level which sum up and remain in the final product. A proof of such errors can be derived in two ways: either by direct measurements, or through analysis of displacement (shift) of projectile's impact point.

If $\delta \vec{D}$ is the final displacement of impact point, then the sensitivity of impact point position due to particular manufacturing error can be evaluated by partial vector derivation $\partial \vec{D} / \partial p$. This derivation can be calculated by some numerical methods, for example by the finite difference method [5]:

$$\frac{\partial \vec{D}}{\partial p} = \frac{\vec{D}(p + \delta p) - \vec{D}(p)}{\delta p} \quad (1)$$

which can be further developed in a series around the matrix-vector of nominal parameter values $\mathbf{p}^0$:

$$\begin{aligned} \vec{D}(p) = & \vec{D}(\mathbf{p}^0) + \sum_{i=1}^n \frac{\partial \vec{D}}{\partial p_i} (p_i - p_i^0) + \\ & + \sum_{i=1}^n \sum_{j=1}^n \frac{\partial^2 \vec{D}}{2 \partial p_i \partial p_j} (p_i - p_i^0)(p_j - p_j^0) + \dots \end{aligned} \quad (2)$$

If partial derivations of the second and higher orders can be neglected, then expression (1) and (2) give

$$\delta \vec{D} = \frac{\partial \vec{D}}{\partial p_1} \delta p_1 + \frac{\partial \vec{D}}{\partial p_2} \delta p_2 + \dots \frac{\partial \vec{D}}{\partial p_n} \delta p_n = \sum_{i=1}^n \frac{\partial \vec{D}}{\partial p_i} \delta p_i \quad (3)$$

where

$\delta \vec{D}$ = final displacement of impact point;

δp_i = variation of parameter;

$\frac{\partial \vec{D}}{\partial p_i}$ = corresponding differential coefficient.

When analyzing the dispersion of impact point, it is apparent that it forms a certain pattern around the target, typically of elliptical shape. Also, by analyzing data from the test firing, it is possible to identify almost all disturbances leading to the final dispersion – for example, parameters related to aging barrel, inconsistent propellant or variable atmospheric conditions. But even when such an extensive analysis is completed, a certain part of dispersion remains unexplained [6]. This part of dispersion can be largely attributed to manufacturing errors, as the following analysis will show.

To minimize that part of dispersion, many efforts have been made to find the optimum between precision and cost of projectile production, but the complete solution is lacking or not being published in full. Empirical solutions are used instead, leading to tolerances too tight for some manufacturing phases and too loose for others. The clear and generally applicable method, connecting the very beginning of the production process and the final effect, is still missing.

3. A 3D CAD Model

As a part of the methodical approach to the problem, a 3D model of a rocket was created in a CAD program. A rocket of well-known features was selected as a case study, and the 3D model was designed to match the original rocket's characteristics. Figure 1 shows a 3D CAD model of a specific rocket.

Fig. 1. The cross section and a wire model of a 3D CAD modeled rocket

The entire 3D model of the rocket is divided into two main components: one is the block of solid propellant that burns during the active phase of flight, and the other is a shell that covers all other parts of the rocket. Unlike engine, shell does not change its geometrical or inertial properties during the flight meaning that the following remains constant:

- I_x, I_y, I_z = moments of inertia for a chosen coordinate system;
- I_1, I_2, I_3 = principal moments of inertia;
- $m_L, \vec{\rho}_L$ = mass of the shell and vector of its center of gravity position (relative to the tip of the rocket).

As for the block of propellant, it is modeled as a single thick-walled cylinder. The inner radius of the cylinder is r_0 , the outer radius R_0 , and so the thickness of block is $e = R_0 - r_0$. Combustion of the propellant runs at a constant speed u , simultaneously across the inner and the outer surface of the propellant block. This model of combustion is chosen because this way a constant thrust force is obtained.

Additionally, assumptions are adopted that entire block of propellant is homogeneous by its chemical, ballistic and other parameters, and also that propellant burns by layers, so as to burn one layer across the entire block surface and only then flame engages the next layer. If this is the case, then the thrust force depends solely on the surface that is in contact with flame $A(t)$. Since here the inner surface of the propellant block is continuously increasing and the outer surface is decreasing, these two effects compensate each other and therefore the thrust force remains constant until the end of combustion:

$$F_T(t) = \mu \frac{A_0}{V_0} \frac{A(t)}{A_0} u = \text{const.} \quad (4)$$

where A_0 is initial area of combustion and V_0 is initial volume of propellant. Coefficient μ is a constant, characteristic for particular propellant.

According to these assumptions, mass and principal moments of inertia for propellant decrease during the combustion:

$$\begin{aligned} m_P(t) &= \pi l_P (R^2 - r^2) \frac{m_{P0}}{V_{P0}} \\ I_{Px}(t) &= \frac{m_P}{2} (R^2 + r^2) \\ I_{Py}(t) = I_{Pz} &= \frac{m_P}{12} (3R^2 + 3r^2 + l_P^2) \end{aligned} \quad (5)$$

where l_P is the length of propellant block, and propellant block radii R and r change during combustion at a constant rate ($R(t) = R_0 - u \cdot t$; $r(t) = r_0 + u \cdot t$; $0 \leq t \leq t_a$).

The changes shown above also impact the inertial characteristics of the entire rocket. At the same time, the center of gravity position and orientation of principal axes for propellant remain constant.

The production of the analyzed rocket is carried out through several phases and different production processes. The occurrence of various manufacturing errors can be introduced, and their effect further analyzed. A few examples of such errors are shown in Figure 2.

Fig. 2. Examples of manufacturing errors that could be simulated in a 3D CAD model

Errors mentioned in Figure 2 have been selected to give an overview of a broad spectrum of possible problems associated with the production process. For example, the explosive head will not be aligned with the central part of rocket as a result of imperfection of a bolted joint; misalignment of the propellant block and engine chamber is a result of errors in the assembly phase, etc.

Each of these errors will change rocket's inertial properties. In addition, nozzle misalignment produces lateral components of thrust force which will increase the dispersion zone even more. Similarly, if the explosive head is not aligned with the central part of the rocket (e.g. with the engine chamber) it will change its aerodynamic characteristics, introducing additional normal force and a moment of the same force around the center of gravity. This approach, where the analysis starts at the earliest stages of production, differs this work from most other analyses which start with changes of inertial characteristics, like for example in [7].

4. Model of Flight

The flight of projectile can be described by different models differing in complexity and precision. The most commonly used are the Modified Point Mass Model (MPMM) with 4 degrees of freedom, and the 6DOF model with 6 degrees of freedom. The MPMM model is a relatively simple model, particularly suitable for describing the trajectory of an axis-symmetrical projectile [8].

However, the MPMM model cannot describe rotation around transversal axes that occur as a result of normal force and its moment around the center of gravity (CG). The 6DOF model can fully describe the motion of CG and around CG and it is also suitable for describing the motion of reactive projectiles. This model follows from four basic vector equations [9]:

$$\frac{d_r \vec{r}}{dt} = \vec{V}_K \quad (6)$$

$$m \frac{d_r \vec{V}_K}{dt} = \vec{R}_A + \vec{F}_T + m\vec{g} - m\vec{a}_C \quad (7)$$

$$\frac{d\vec{H}}{dt} = \vec{M}_A + \vec{M}_F \quad (8)$$

$$\vec{\Omega} = \vec{\Omega}_E + \vec{\lambda} + \vec{\phi} + \vec{\psi} + \vec{\vartheta} + \vec{\varphi} \quad (9)$$

In (7) two external forces can be identified: the aerodynamic force $\vec{R}$ and the thrust force $\vec{F}_T$ according to (4). In equation (8) moments of both forces are shown on the right. To solve these two equations, it is needed to find all possible changes in inertial characteristics, including changes of CG position and tensor of inertia. Derivation of angular momentum for chosen coordinate system can be written in a matrix form, with matrices noted with bold symbol:

$$\dot{\mathbf{H}}_0 + \tilde{\mathbf{\Omega}}_G \mathbf{H}_0 = -\tilde{\mathbf{V}}_0 \tilde{\mathbf{\Omega}} \rho_C m + \mathbf{M}_0 + \tilde{\rho}_C \mathbf{g} m \quad (10)$$

where $\tilde{\mathbf{\Omega}}_G$ is a skew-symmetric matrix which consists of angular velocity components, ρ_C is a center of gravity position and $\mathbf{M}_0$ is a moment of external forces. If the origin O for applied coordinate system is at the center of gravity ($\rho_C = 0$), then (10) takes a simpler form:

$$\dot{\mathbf{H}}_0 + \tilde{\mathbf{\Omega}}_G \mathbf{H}_0 = \mathbf{M}_0 \quad (11)$$

Solving (11) is complicated for bodies that not only change their angular velocity during the flight, but also their inertial characteristics ($m, \rho_C, \mathbf{I}$). Furthermore, for dynamically unbalanced projectiles, principal axes do not coincide with axes of the outer surface symmetry.

One solution is to solve equations in a coordinate system linked to principal axes (in the “frame” coordinate system, F), but then all aerodynamic coefficients must also be transformed because they are linked to the outer geometry of projectile. To simplify solving of the equation, a new coordinate system is introduced, called geometrical coordinate system (G): its axes coincide with axes of symmetry or remain parallel to them. Both frame and geometrical coordinate systems have origin in the center of gravity.

By introduction of this new coordinate system, a new 6DOF model is derived (called G6DOF), which makes it easier to describe projectiles with asymmetry of geometrical and inertial characteristics than “classical” 6DOF. For the same reason, G6DOF makes it easier to connect a 3D CAD model with a model of flight of asymmetric projectile.

5. Connecting the 3D CAD Model with G6DOF

For this paper, one manufacturing error will be analyzed: the misalignment between axes of symmetry for the inner and outer surface of the explosive head.

Explosive head is manufactured through impression-die forging which gives good precision, but still requires further processing to achieve a finished part [10]. If subsequent machining is not adequate or even omitted (as often for cavity or inner surface of explosive head) then a dynamic imbalance will appear as Figure 3.

Fig. 3. Misalignment of explosive head's inner and outer surface

Figure 3 shows a significant thickness variation of explosive head's wall at various positions. Principal axes do not coincide with axes of symmetry of the outer surface. Figure 4 shows resulting misalignment between axes of geometrical symmetry for inner surface (indexed "U") and outer surface (indexed "V").

This misalignment is simulated by two angles: δ_{BG} and φ_{BG} , which combined give a spatial angle between two axes of symmetry.

Transformation matrix from inner to outer surface coordinate systems is:

$$\begin{aligned} \mathbf{L}_{VU} &= \mathbf{L}_x(\varphi_{BG}) \cdot \mathbf{L}_z(\delta_{BG}) = \\ &= \begin{bmatrix} \cos(\delta_{BG}) & \sin(\delta_{BG}) & 0 \\ -\cos(\varphi_{BG})\sin(\delta_{BG}) & \cos(\varphi_{BG})\cos(\delta_{BG}) & \sin(\varphi_{BG}) \\ \sin(\varphi_{BG})\sin(\delta_{BG}) & -\sin(\varphi_{BG})\cos(\delta_{BG}) & \cos(\varphi_{BG}) \end{bmatrix} \end{aligned} \quad (12)$$

Fig. 4. Misalignment of explosive head's inner and outer surface

Once the particular manufacturing error is defined, a 3D model gives changes of rocket's inertial characteristics – a shift of CG and changes in inertia tensor. The information is directly included in G6DOF. Now becomes possible to

calculate transformation matrix between any of the two coordinate systems of interest – for example matrix $\mathbf{L}_{FG}$ gives transformation from rocket's geometrical coordinate system (G) into the frame coordinate system (F). Now becomes possible to determine variables needed to calculate projectile trajectory: for instance, angular momentum and angular speed (needed to solve (8) and (9)) are transformed as

$$\begin{aligned}\mathbf{H}^F &= \mathbf{L}_{FG} \mathbf{H}^G \\ \boldsymbol{\Omega}^F &= \mathbf{L}_{FG} \boldsymbol{\Omega}^G\end{aligned}\tag{13}$$

and inertia tensor gets transformed as

$$\begin{aligned}\tilde{\mathbf{p}}_C^F \mathbf{V}_O^F m + \mathbf{I}^F \boldsymbol{\Omega}^F &= \mathbf{L}_{FG} \left(\tilde{\mathbf{p}}_C^G \mathbf{V}_O^G m + \mathbf{I}^G \boldsymbol{\Omega}^G \right) \\ \mathbf{I}^F &= \mathbf{L}_{FG} \mathbf{I}^G \mathbf{L}_{GF}\end{aligned}\tag{14}$$

where application of Steiner's rule can be omitted since both coordinate systems (G and F) have origin in the center of gravity. All required input parameters for G6DOF flight model come from the 3D CAD model.

6. Results for Case Study

Boundaries of impact points zone (a short term "*impact zone*" will be used) are analyzed for rocket of following characteristics:

- Caliber $d = 122 \text{ mm}$;
- Mass $m = 66 \text{ kg}$;
- Length $L = 2700 \text{ mm}$;
- Range used for the case study: 15000 m .

6.1. Centre of Mass Position

Rocket's center of gravity shifts along axes of geometrical coordinate system x_G , y_G and z_G , although by very small extent for realistically expected angles $0^\circ \leq \delta_{BG} \leq 1^\circ$. For instance, if $\delta_{BG} = 0.1^\circ$, displacement along x_G axis is less than $1 \times 10^{-2} \text{ mm}$ and even at the very edge of observed interval ($\delta_{BG} = 1^\circ$) displacement only reaches a value of $5 \times 10^{-2} \text{ mm}$.

A shift along axis y_G is only slightly larger. For $\delta_{BG} = 0.5^\circ$ displacement is $\Delta y_G = 0.03 \text{ mm}$. Since $\delta_{BG} > 0.5^\circ$ is unrealistic to expect, the assumption can be adopted that angle δ_{BG} would not cause any center of gravity displacement.

6.2. Middle Point of Impact Zone

The effect of analyzed manufacturing error is further observed on rocket's trajectory and position of impact point. Shooting at 15000 m distant target is analyzed. The trajectory of the rocket is simulated by G6DOF model of flight, and inertial characteristics of the rocket are acquired from 3D CAD rocket model. The results are compared with firing tables for analyzed rocket.

If no manufacturing errors are present, G6DOF model gives a range of exactly 15000.7 m and also a drift of 76.5 m to the right, if looking from a firing position. These results match the firing tables' data. For various values of δ_{BG} ($0^\circ \leq \delta_{BG} \leq 1^\circ$) a middle point of impact zone shifts only minimally, so for further analysis it is assumed that observed manufacturing error has no impact on middle point of impact zone.

6.3. Span of Impact Zone

Boundaries of impact zone can be estimated if angle δ_{BG} is kept constant, but radial angle φ_{BG} varying inside the interval $\varphi_{BG} = 0^\circ - 360^\circ$. Then the impact zone obtains its characteristic elliptical shape. Figure 5 shows boundaries of impact zone for $\delta_{BG} = 1^\circ$:

Fig. 5. Boundaries of impact zone for $\delta_{BG} = 1^\circ$, $\varphi_{BG} = 0 - 360^\circ$

The observed misalignment gives an impact zone of relatively small size: for instance, if $\delta_{BG} = 0.3^\circ$ impact zone takes an elliptical shape spreading only 17.5 m along range (or along the target line) and 13 m perpendicular to that line. The increase of δ_{BG} results with the increase of impact zone, approximately with linear dependence as shown on Figure 6:

Fig. 6. Span of impact zone for various δ_{BG} angles

The comparison of impact zones for various δ_{BG} shows that impact zone grows, but the middle point remains constant. Figure 7 presents following cases: $\delta_{BG} = 0.1^\circ$, $\delta_{BG} = 0.3^\circ$ and $\delta_{BG} = 1^\circ$. The rapid increase of impact zone is evident:

Fig. 7. The augmentation of impact zone for increasing δ_{BG} angle

Impact zone for $\delta_{BG} = 1^\circ$ spans dozens of meters, which clearly shows why such projectiles should be discarded as production write-off. In further research a comprehensive study will also be made to analyze combined effect of all manufacturing errors occurring simultaneously. The most promising method for such analysis is the Monte-Carlo simulation [11].

7. Conclusion

In this paper a method is presented that connects manufacturing errors with dispersion of impact points as a final consequence.

A 3D model of a rocket of well-known characteristics was created in a CAD program, designed to match the original rocket. Now the occurrence of various manufacturing errors can be introduced, and their impact further analyzed, because model gives exact changes of rocket's inertial characteristics (a shift of CG and changes on inertia tensor) that are afterward included in 6DOF flight model.

As for the model of flight, a new coordinate system (geometrical c.s.) is introduced and a new 6DOF model is derived (G6DOF). This model makes it easier to describe projectiles with geometrical or mass asymmetry, comparing to classical 6DOF.

The analysis points to following conclusions:

- 1) Misalignment of inner and outer explosive head's surfaces, modeled through the angle between their axes of symmetry δ_{BG} , causes only insignificant shift of the middle point of impact zone;
- 2) Contrary to that, there is a linear and a significant augmentation of the impact zone along with the increase of the δ_{BG} angle;
- 3) Complete estimate of the impact zone follows from a simulation involving not only the angle δ_{BG} , but also the radial angle φ_{BG} . Only when both variables are introduced, exact boundaries of the impact zone can be defined.

For particular manufacturing error (misalignment of explosive head's inner and outer surface), it is shown that even for a relatively large misalignment ($\delta_{BG} = 0.5^\circ$) impact zone remains relatively small, suggesting that for this stage of production loose tolerances could be accepted. A maximum tolerance of 0.5° for angle of misalignment can be therefore recommended, assuring that span of the impact zone is kept within narrow boundaries (less than 30 meters for range and 22 meters for drift).

A similar analysis is required for each step of the overall manufacturing process. A combination of 3D CAD model and 6DOF model of rocket flight can be used to select adequate tolerances, ultimately leading to the rocket of satisfactory precision and at the same time low manufacturing cost.

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