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IMPROVEMENT OF ARTILLERY PROJECTILE ACCURACY

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Range correction for spin-stabilized projectiles is now well known. This work focuses on low-cost deflection correction based on mature and simple technologies. A simple analytical approach is first used to identify relevant parameters acting on deflection. Among them, spin control, lift and static margin control have been evaluated. The deflection correction capability that they offer has been compared by means of 6 dof calculation in the case of a canard-based correction fuze. Suppressing the fuze spin can give an opportunity to increase the canard sideplane surface (and the deflection correction by extension) while limiting dynamic unstability risks.

NOMENCLATURE

g	gravity
D	calibre
S	reference surface
m	projectile mass
ϑ_l	longitudinal moment of inertia
ϑ_t	transverse moment of inertia
C_D	drag coefficient
$C_{L\delta}$	derivative of lift force coefficient
CN_α	derivative of normal force coefficient
C_{lp}	roll damping moment coefficient
Cm_δ	derivative of pitch moment coefficient
C_{mq}	pitch damping moment coefficient
$CJ\delta$	(= - $C_{np\alpha}$) Magnus moment coefficient
Ms	static margin
V	velocity
ρ_a	local air density
ξ	Complex total angle of attack $\left(\xi=\delta\cdot e^{i\cdot\psi}=a+i\cdot b\right)$
δ	total angle of attack
θ	local trajectory slope
ω_c , p	spin rate
ψ	precession angle

INTRODUCTION

Improving artillery projectile accuracy is of obvious interest in fire efficiency and contributes to optimize logistics devoted to missions. Improvement of accuracy is often associated with range extension. But range extension requires additional means, such as propellers, lifting surfaces, … and flight control systems which considerably affect the global cost. The best compromise has to be reached, taking into account, on the one hand, the accepted accuracy level (metric, decametric, …) and, on the other hand, mission cost, army needs, technological maturity, terminal effectiveness, available volume in the shell, … It is admitted that high accuracy and long range (60 – 100 km) projectiles may give good accuracy at shorter range but at excessive cost. In that context, a cost adapted solution may be preferred operationally even if the final miss distance is not as good.

This paper focuses on accuracy improvement without searching for range extension. Many physical methods can be used to correct artillery projectile trajectories in range and deflection : indirect or direct control of lift by change in spin, lift characteristics, static margin, internal mass distribution, … [1-9]

BASIC ANALYTICAL SOLUTION

It is usual to refer to simplified analytical solutions to identify the most relevant physical parameters implied in a given phenomenon. In the case of a spin-stabilized projectile, the linearized solution of the complex total angle of attack can be used to study how spin rate control, and/or lift control and/or static margin control … affect deflection, and if their combination implies cumulative or opposite effects. For a straight trajectory, a small angle of incidence, low velocity and aerodynamic coefficient variations, … a second-order differential equation for the total angle of incidence can be obtained [10-11] :

$$\boxed{\xi'' + (\alpha_1 - i\cdot\beta_1)\cdot\xi' + (\alpha_2 - i\cdot\beta_2)\cdot\xi = \alpha_3 - i\cdot\beta_3}$$

where :

$$\begin{cases}\alpha_1 = b_D + b_L - b_R \\ \beta_1 = U\end{cases} \qquad \begin{cases}\alpha_2 = -b_M \\ \beta_2 = (b_L - b_J)\cdot U\end{cases}$$

$$\begin{cases}\alpha_3 = \dfrac{g\cdot D\cdot\cos(\theta)}{V^2}\cdot(b_D + b_R) \\[2ex] \beta_3 = \dfrac{g\cdot D\cdot\cos(\theta)}{V^2}\cdot U\end{cases} , \begin{cases}b_R = B_F\cdot C_D \\ b_M = B_M\cdot C_{M\delta} \\ b_L = B_F\cdot C_{L\delta} \\ b_J = B_M\cdot C_{J\delta}\cdot\dfrac{\vartheta_t}{\vartheta_l} \\ b_D = B_M\cdot C_{mq}\end{cases}$$

and $U = \frac{\omega_c \cdot D \cdot \vartheta_t}{V \cdot \vartheta_l}$ $B_F = \frac{\pi \cdot \rho_a \cdot D^3}{8 \cdot m}$ $B_M = \frac{\pi \cdot \rho_a \cdot D^5}{8 \cdot \vartheta_t}$

The imaginary part, noted b, of the complex solution can be written as :

$$b \approx \frac{g.D}{V^2}.\cos\theta.U.\frac{1}{b_M}$$

where b is a simplified representation of the sideslip angle (yaw of repose) when precession and nutation motions are totally damped.

By introducing U and bM into the b expression, we have :

$$b \approx \frac{2g.\cos\theta}{S.D}.\frac{p}{V^3}.\vartheta_l.\frac{1}{Cm_\alpha}.\frac{1}{\rho_a}$$

or, knowing that Cm_α = Ms. CN_α :

$$CN_\alpha.b \approx \frac{2g.\cos\theta}{S.D}.\frac{p}{V^3}.\vartheta_l.\frac{1}{Ms}.\frac{1}{\rho_a}$$

As deflection depends on the normal force intensity (which is roughly lateral for spin-stabilized projectiles without any disturbances), we can expect that, during the flight :

- an increase of CN_α implies deflection increase (all other variables remaining unchanged). It is interesting to note that this principle has already been proposed for a long range guided and steered gliding concept [12] ; substantial size gliding surfaces were located just behind the center of gravity to combine high lift and small static margin effects in order to increase b (small Ms effect) and range (if CN_α is directed vertically by appropriate steering).
- an increase of Cm_α reduces deflection (all other variables remaining unchanged).

Deflection increases (resp. decreases) when spin rate increases (resp. decreases).

All these qualitative results are going to be quantified by means of 6 dof investigations. Deflection can also be affected by a change in internal mass distribution (via ϑ_l parameter) but without any great interest for correction fuzes [1].

DEFLECTION ANALYSIS BY SIX DOF CALCULATIONS

Trajectory correction can be obtained by concepts using two kinds of actuators, one devoted to range correction (drag brakes, fig.1) and one devoted to deflection correction : sequential (fig. 2) or continuous steering determines performances, complexity and cost.

Fig. 1 : range correction fuze

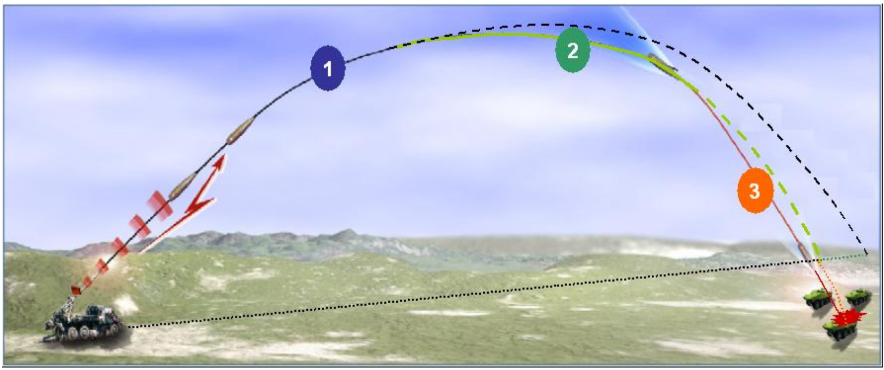

Fig. 2 : sequential range (2) and deflection(3) correction phases

Range correction is now very well known, but deflection control principles are quite specific in the case of gyroscopic projectiles. A canard based correction fuze (see *fig. 3*) has been characterized by aerodynamic computations and 6-dof flight dynamics investigations in order to analyse and hierarchize effects on deflection of the parameters previously described : spin control, dual spin concepts, static margin effects, lift effects … Fuze trajectory correction systems offer numerous advantages : among them, for instance, interchangeability and preservation of the useful content of the shell. One can propose that an acceptable correction criterion is obtained when two accuracy standard deviations in range and deflection can be corrected. Calculations consider that effectors come into action at two thirds of the non corrected reference range given in table 1.

Trajectory type	Range (m)	Initial velocity (m/s)	Elevation angle (mil)	Conditions at 2/3 of range			
				Mach number	velocity (m/s)	Deflection (m)	Height (m)
curved	27000	945	950	0.925	273	655	11953
Low elevation	17900	820	408	0.98	326	101	2713
Very low elevation	10580	945	100	1.71	585	11.5	317

Table 1 : reference trajectories used for 6 dof calculations

Calculations will consider that effectors are 100% efficient from this point of the trajectory to the impact (“binary” irreversible functioning).

DEFLECTION MODIFICATION BY SPIN RATE CONTROL

Spin rate control has to respect two essential conditions :
- if a spin rate decrease is chosen, it has to respect the gyroscopic stability condition which expresses the minimum theoretical spin required to compensate the destabilizing pitch moment.
- if a spin rate increase is chosen, this may favour dynamic unstability risks known to appear for some subsonic flights.

Due to this, only spin decrease on deflection is examined here (spin brake action) ; correction would then consist in decreasing deflection. In order to decrease the spin rate as much as possible, Clp increase induced by spin brakes has been acted on to reach the limit of the gyroscopic stability criterion (maximum Clp admitted).
The Clp ratio with and without spin braking may be high (table 2) and induces a significant decrease in spin (about 50% at impact, see figure 4) but it doesn't permit a substantial deflection effect (less than 40 m) even for a "favourable" trajectory.

Trajectory type	Clp ratio (with/without spin braking)	residual spin ratio (without/with spin braking)	deflection decrease at impact (m)
curved	5	2.1	37
Low elevation	6	2.17	20
Very low elevation	10	2	1.8

Table 2 : deflection decrease obtained with maximum Clp admitted

Fig. 3 : deflection canards based correction fuze

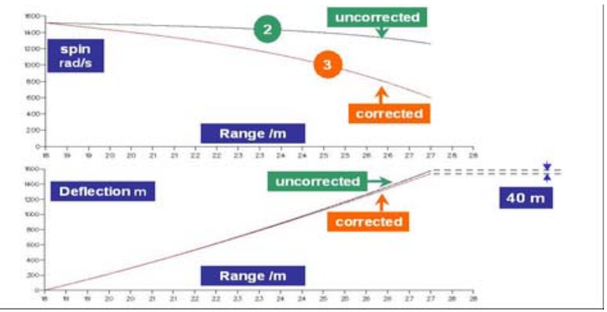

Fig. 4 : deflection correction using spin effect (maximized Clp)

DEFLECTION CONTROL INDUCED BY A CHANGE IN PITCH AND LIFT CHARACTERISTICS

Combining simultaneous low-Cmα and high-CNα to reach a high effect on deflection is not compatible with fuze effectors like canards (the static margin can't be reduced significantly enough to overcompensate the CNα increase). Fuze canards would increase Cmα and CNα simultaneously ; if taken independently, they imply opposite effects on deflection. The solution thus consists in optimizing canards (shape, location and numbers) to belong to one of either of the following opposite cases :

1/ the Cmα increase is maximized and CNα increase is minimized

2/ the Cmα increase is minimized and CNα increase is maximized.

The first case will globally reduce the normal force, and imply a deflection decrease. The second case will produce the opposite effect.

Without any aerodynamic optimisation of canards, the following results at impact have been obtained :

Trajectory type	deflection decrease (m)
curved	-154
Low elevation	-45
Very low elevation	-2

Table 3 : deflection decrease due to pitch and lift control

The deflection correction may not be appropriate for low elevation angle trajectories for which most correction devices are not efficient in general. But for curved trajectories, effectors give an appreciable deflection correction in magnitude, compatible with a two-standard deviation accuracy criterion generally admitted.

Figure 5 shows how the instantaneous change in lift and pitch characteristics affects the dynamic response of the total angle of attack. Precession and nutation modes are excited as described in the yaw rosette. This confirms that an analytical solution for b (presented as the slipside angle) has to be considered as approximated and only used for qualitative approaches.

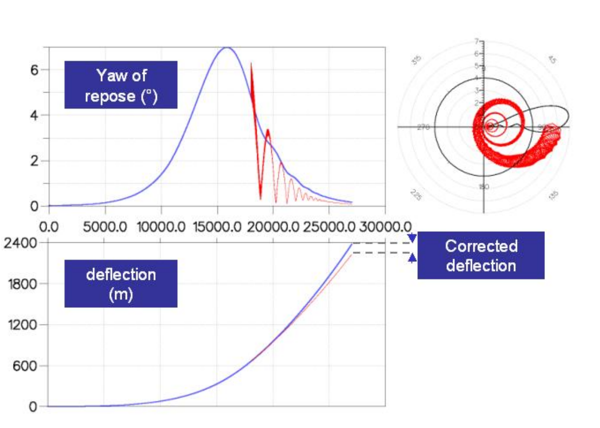

Fig. 5 : deflection correction using change in lift and static margin after

DUAL SPIN CONCEPTS

Spinning canards may introduce undesirable contribution to dynamic unstability. For this reason, their sideplane surface can be severely restricted and, as a consequence, their potential effect on deflection would be limited.

A relative spin between the platform (typically a fuze) supporting the canards and the rest of the shell can be profitably introduced. In particular, dual spin enables an increase in lifting surfaces and avoids dynamic and gyroscopic stability problems that the non-dual spin configuration might imply.

If the longitudinal inertia ratio between the spinning main body and the canard platform equals typically 20, the gyroscopic stability consumption is about 9% if the platform doesn't rotate (fig. 6). In that case, the undesirable suspected consequence on Magnus effect can be avoided by liberating the rotation of the canard platform with an acceptable gyroscopic stability consumption. This enables the use of large lifting surfaces and the amplification of deflection correction capability. Consumption decreases linearly with the canard platform spin rate [13].

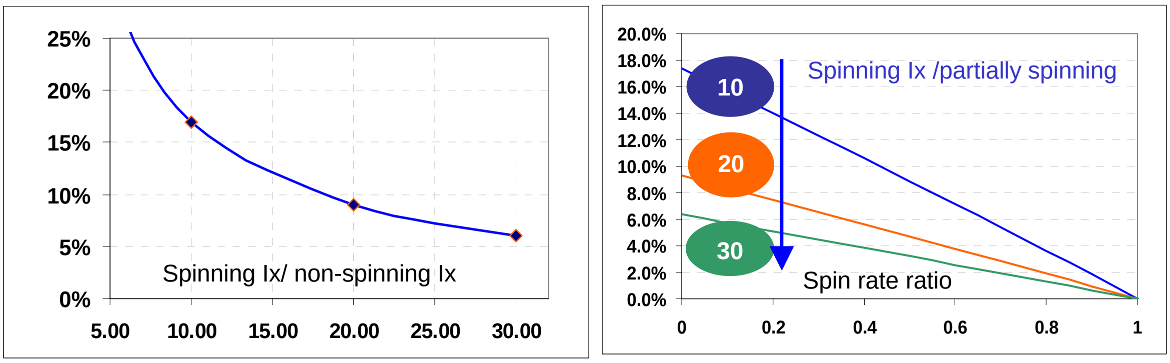

Fig. 6 : Global gyroscopic stability consumption by suppressing (partially or totally) canards spin

CONCLUSION

Deflection correction capabilities obtained with spin control, direct lift and pitch control, … have been evaluated and hierarchized for a canards-based fuze. A change in direct lift and pitch characteristics seems to offer significant deflection correction, roughly compatible with a two standard deviation in accurary correction, such criterion being generally admitted. It appears that spin control is not efficient enough for primary deflection control even for the minimum spin admitted by the gyroscopic stability criterion. Spin control can then only be used for secondary correction mode.

For a low-cost correction kit with “binary” effectors, it is essential to avoid crossed effects : that means that range correction effectors shouldn’t affect deflection, and deflection effectors shouldn’t affect range. Using two kinds of effectors (drag brakes for range correction and very low drag lifting surfaces) can be a good solution.

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