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A new motion model of rifle bullet penetration into ballistic gelatin

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ABSTRACT

An accurate description of the motion of bullets in ballistic gelatin penetration can only be given if a corresponding mathematical model is derived. In this paper, change of the effective wetted area of the bullet is studied well with the increase of angle of yaw in the penetration process. By introducing an area detached ratio and the influence of slenderness, a novel framework is proposed for drag and lift coefficients. Further, a new motion model of rifle bullet is established based on the new frameworks and validated by comparison with the results from experiment data and FEA. The comparative analysis shows that results of the new motion model have a better fit with experiment data than that of the traditional models in previous literatures and the proposed framework for drag and lift coefficients is better than the traditional ones in literatures by comparison with the numerical results. In addition, the calculation of the new motion model is in great accordance with FEA in terms of penetration depth, deflection path, yaw angle, velocity, lift force and drag force at different initial conditions. Benefitting from the motion model based on the new frameworks for drag and lift coefficients, the behavior of rifle bullet in gelatin penetration can be characterized accurately, the prediction of the distribution of energy deposited along the penetration trajectory and the potential for incapacitation of rifle bullets may become possible.

1. Introduction

By now, ballistic gelatin (hereafter referred to as gelatin) has become popular as a tissue simulant in wound ballistics [1–4] after a large number of experimental tests were carried out in different countries. That is because the gelatin is homogeneous and presents the same physical characteristics block after block. Besides, it is transparent so that any changes inside can be recorded by high-speed movies. In addition, its retarding properties are similar to those of skeletal muscle, especially 10% gelatin [5–11]. Therefore, it is significant to characterize the behavior of a bullet during gelatin penetration and understand the mechanisms acting between bullets and bionic material.

In the study of ballistic penetration problems, one of the major concerns is the penetration resistance and its mathematical model. Allen et al. [12] proposed a general model, composing of an inertia component, a viscous component and the natural strength component of the target material, as follows:

$$-m\frac{d_v}{d_t} = \alpha v^2 + \beta v + \gamma \tag{1}$$

where α, β and γ are positive constants. In some practical analysis, only the main components are selected in mathematical models of penetration to simplify the penetration problem. And the selection mainly depends on a critical velocity v_c, at which an abrupt transition is believed to occur [12]. At a very low velocity $v < v_c$, the influence of material strength is greater than others and the resistance of the bullet is assumed to be a constant [13]. Whereas the major concern is the inertial component at a very high velocity $v > v_c$ [14,15]. Some empirical models also consider the influence of more than one component [16–18]. As to the gelatin penetration, Sturdivan [19] presents a general mathematical model by considering viscous and inertia components jointly. Further, Segletes [20] introduced a rate-based strength to bridge the gap between pure viscous and pure strength-based velocity retardation models. And the mathematical model used by Peters [16–18] is a special case of Segletes'.

The yawing motion of projectiles in dense media is strikingly different from free-flight yawing motion in air and has been investigated previously from the perspective of both theoretical and experimental results [21–26]. Roecker and Ricchiazzi [21] proposed one important result, which formed the current theoretical foundation for characterizing yawing behavior of projectile in dense media. Flis [22] obtained an analytical solution to the nonlinear form of the governing equation. It can provide a relatively simple analytical form for Roecker and Ricchiazzi's numerical results and extend

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Nomenclature

α, β, γ	positive constant
ψ	angle of yaw
ψ_1	maximum angle of yaw in the narrow channel
ψ_D	angle of yaw in damped oscillation phase
$\dot{\psi}$	yawing angular velocity
$\ddot{\psi}$	yawing angular acceleration
δ	angle of incidence
ρ	media density
a	area detachment ratio
A_0	cross-sectional area of rifle bullet
A_{eff0}	effective wetted area at $\psi = 0$
A_{eff}	the effective wetted area of bullet
A_{eff1}	the maximum effective wetted area of bullet in narrow channel
A_{eff90}	the maximum effective wetted area of bullet in second phase
C_{L_0}, b_1, b_2	constant used in the lift coefficient
C_L^*	lift coefficient
C_D^*	drag coefficient
C_D	a constant, expressing the influences specific to head-shape of the bullet
$C_{D_0}^*$	a drag coefficient at $\delta = 0$
C_{DA}	damping coefficient
C'	symbol of function
$C_{m_\psi}^*$	overturning moment coefficient
d_0	a detached diameter
d	diameter of the bullet
D	drag force
D_{ref}	reference diameter
e	the length to a diameter ratio
f	ratio of length of bullet to length of ogive head
F_D	drag force
H	length of ogive head of bullet
J	symbol of function
J_q	transverse moment of inertia
l_0	length of rifle bullet
L	lift force
line-0,line-1	tangent line at the separation point
M_1	overturning moment
M_2	damping moment
Δs	increment of wetted area
s	instantaneous penetration
S_{ref}	reference area
t	time after impact
v_c	critical velocity
v	instantaneous velocity
x, y	displacement of bullet in X and Y coordinates
$\dot{x}$, $\dot{y}$	velocity of bullet in X and Y directions
$\ddot{x}$, $\ddot{y}$	acceleration of bullet in X and Y directions

their analytical solution of the linear governing equation. Furthermore, Weinacht and Cooper [23] presented a complete set of analytical solutions for the linear and nonlinear yaw growth of a projectile impacting and traversing dense media.

Mo et al. [27] presented a surface pressure model to predict the translational and yawing motion of rifle bullets in gelatin penetration. The resultant force and moment on a projectile were achieved through numerical integration of surface pressure, and the trace of a projectile was calculated by solving spatial motion equations deduced from the mass center motion equations and Euler equations. Liu et al. [28] established a two-dimensional motion model and investigated the model parameters of rifle bullets penetrating gelatin very well [29]. Compared with several useful penetration formulas in previous work, no or less research has paid attention to the relationship between the lift and drag coefficients exerted on a bullet and the angle of yaw in the gelatin penetration. Roecker [25] gave the trend of drag coefficient C_D^* with the varying of the angle of yaw, while Sellier et al. [26] derived the relationship based on external ballistics, as follows,

$$C_D^* = C_{D_0}^* \cdot \left(1 + C' \cdot sin^2\psi\right) \tag{2}$$

where $C_{D_0}^*$ is a constant within the observed range of velocities and C' is a linear function of the relationship between the length of projectile and the caliber. However, Sellier et al. [26] made the remarks that Eq. (2) is only valid for small angles of yaw up to 20°, and the integration of the differential equation above the value of 20° never gives a real value. To the best of our knowledge, it is very difficult to find the available correlation to describe the lift coefficient. The closest useful assumption is the formula for rigid gyro-stabilized projectile in Reference 30, which is defined as :

$$C_L = C_{L_0} \cdot cos^2\psi \cdot \sin(2\psi) \tag{3}$$

where C_{L_0} is a constant. Despite the limitations of Eq.(2) and little verification of Eq.(3) in gelatin penetration, a motion model was established by Liu et al. [28] based on Eq.(2) and Eq.(3). The comparison of calculated results of Liu et al.'s model [28] is unsatisfactory with his experiment data.

In order to accurately predict the translational and yawing motion of rifle bullets in gelatin penetration, we theoretically study the changing of the effective wetted area of rifle bullets in the penetration progress and propose new frameworks for drag and lift coefficients. Further, a new motion model for bullet penetrating gelatin is established based on the frameworks and validated by comparison with the experiment data and the previous model in Ref. 28. The calculated results of new frameworks for drag and lift coefficients are validated by simulated results and compared with the older models found in Sellier et al. [26] and Nestor [30]. The comparative analysis is also made between results of new motion model and simulated results in terms of penetration depth, deflection path, yaw angle, velocity, lift force and drag force at different initial conditions. In our proposed motion model, it is assumed that the bullet is not broken and its gravity and rotation are ignored in the process of penetration. Because of the high velocity of rifle bullets, the influence of inertial component of resistance is only concerned. Fit parameters used in the motion model are determined from one case of FEA simulation results.

2. Theory basis

2.1. Yaw motion

With the increase of angle of yaw, the flow lies increasingly closer to one side of the projectile surface. Thus, the calculation of the yawing motion of a projectile in a dense medium can be applied for the whole penetration channel.

A functional form for the relationship of overturning moment to instantaneous yaw is derived by Roecker and Ricchiazzi [21] as follows,

$$\frac{d^2\psi}{d_s^{\,2}} = J \cdot \cos\psi \cdot \sin\psi \tag{4}$$