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Aerodynamic characteristics of a spinning projectile with elastic deformation

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ABSTRACT

The elastic deformation of a spinning projectile with a large slenderness ratio influences its flight stability and maneuverability. Unsteady time-accurate simulation based on a dual-time stepping method and the dynamic mesh method were used to solve the unsteady Reynolds-averaged Navier–Stokes (URANS) equations and obtain the aerodynamic characteristics of a spinning projectile given continuously elastic deformation. Archival wind tunnel experimental data were used, and grid resolution and time independence studies were carried out for numerical validation at angles of attack ranging from 2.09° to 10.4°. The aerodynamic coefficients induced by spin and elastic deformation were compared to the effect of movement frequency, deformation component, Mach number and angle of attack using Fourier transform. Numerical simulations indicate that the time-averaged values and the fluctuation amplitudes of the aerodynamic coefficients increase with movement frequency; two aerodynamic components are induced by elastic deformation, one opposite and one perpendicular to the direction of deformation; nose and body deformation have different effects on the aerodynamic characteristics; and the effective angle of attack induced by elastic deformation and rolling movement decreases as the Mach number increases, thus weakening the influence of movement on the aerodynamic forces.

1. Introduction

Many projectiles spin about their longitudinal axes during flight to simplify the control system and eliminate the effect of eccentricity. As the boundary layer is no longer symmetrical to the plane of angle of attack and its maximum thickness position is shifted towards the spin direction, this induces an out-of-plane force, called the Magnus force [1,2]. Although the Magnus force induced by boundary layer distortion is small, usually 1/100 to 1/10 of the normal force, the corresponding Magnus moment has a significant effect on the flight stability and maneuverability of the projectile [3,4]. Moreover, projectiles with large slenderness ratio are generally adopted to increase flight velocity and range. It has been observed in flight tests that the deformation of a spinning projectile can reach the order of magnitude of its radius [5]. Therefore, the aerodynamic characteristics of the projectile can be significantly influenced.

There are a few studies addressing the effect of elastic deformation on the aerodynamic characteristics and flight stability of spinning projectiles. Linear aerodynamic load distribution methods are usually adopted in aerodynamic modeling of projectiles with elastic deformation. Effective angle of attack is used to express spin and elastic movement, and the aerodynamic coefficients of the projectile are obtained by multiplying the effective angle of attack by the aerodynamic coefficient derivatives [6–12]. Our previous study, conducted at a low Reynolds number and small angle of attack, indicated that a non-linear relationship between the movement and the induced aerodynamic coefficients exists, that the shape of the boundary layer changes with time for elastic deformation, and that it is not appropriate to use linear aerodynamic load distribution methods for movements with high frequencies [13].

Conducting studies on the aerodynamic characteristics of spinning projectiles with elastic deformation using wind tunnel experiments are extremely difficult. Therefore, to investigate the influence of the movement frequency, deformation component, Mach number and angle of attack on the aerodynamic characteristics of a spinning projectile with a given elastic deformation through classical beam theory, computational fluid dynamic (CFD) methods are used as an alternative. Section 2 introduces the computational model and grid. Section 3 describes the motion model coupling the spin and elastic movements. The numerical approach is described in detail in Section 4, including the governing equations, turbulence model, boundary conditions, and dynamic mesh technique. Grid resolution and time independence studies testing the

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Nomenclature

a	diffusion parameter
a_{jk}	Fourier coefficient
c_{f1}	normal force coefficient distribution along x axis
c_{f2}	moment coefficient distribution along x axis
c_{fM}	Magnus force distribution along x axis
C_p	pressure coefficient, P/P_∞
C_x	axial force coefficient, drag force/qS_{ref}
C_y	normal force coefficient, normal force/qS_{ref}
C_z	Magnus (lateral) force coefficient, Magnus force/qS_{ref}
C_{mx}	rolling moment coefficient, rolling moment/$qS_{ref}L_{ref}$
C_{my}	Magnus (yawing) moment coefficient, Magnus moment/$qS_{ref}L_{ref}$
C_{mz}	pitching moment coefficient, pitching moment/qS_{ref}
C_k^M	coefficient in motion equation
d	projectile base diameter .... m
g_1	$\rho V_\infty^2 S_{ref}/2$ .... N
i	imaginary unit
L	total length of the projectile .... m
L_{ref}	L .... m
Ma	Mach number
P	static pressure .... pa
q	dynamic pressure, $\rho V_\infty^2/2$
Re_L	Reynolds number based on the projectile length
S_{ref}	projectile cross-sectional area .... m^2
t	physical time .... s
T	static temperature
u_m	mesh displacement velocity
V_∞	freestream velocity .... m/s
$\mathbf{V}_e$	elastic deformation rate .... m/s
x	coordinate in longitudinal direction .... m
$\bar{x}$	normalized x coordinate, x/d
$y+$	normal viscous sublayer spacing
$z_{\pm k}$	aerodynamic characteristics in y and z directions
α	angle of attack .... deg
β	sideslip angle .... deg
γ	diffusion coefficient
Γ	incidence angle induced by deformation
$\delta_e(x,t)$	elastic deformation .... m
$\hat{\delta}(t)$	deformation in yz plane .... m
Δ	the relative variation of a_1 at different movement frequencies
Δh	height of the first layer mesh .... m
Δt	time step .... s
η, λ	deformation constants
θ_k	phase .... rad
ξ	$\beta + i\alpha$
ξ'	$d\xi/dt$
$\xi_{local}(x,t)$	local angle of attack .... deg
ρ	density .... kg/m^3
φ	coordinate in circumferential direction
$\Phi(x)$	deformation mode
ω_x	spin rate .... rad/s
$\overline{\omega}_x$	non-dimensional spin rate, $\omega_x d/V_\infty$
∇	Laplace operator

Subscripts and Superscripts

b	body
e	elastic
M	movement
ref	reference
V	control volume
x	x axis
∞	freestream condition

accuracy of the unsteady CFD results are described in Section 5. Section 6 presents the frequency analysis of the aerodynamic coefficients and an analysis of the effect of each individual factor on the aerodynamic characteristics of a spinning projectile with elastic deformation.

2. Computational model and mesh

A secant-ogive-cylinder (SOC) spinning projectile with a slenderness ratio of six is adopted to investigate the aerodynamic characteristics induced by elastic deformation under different conditions. A schematic of the model and grid are shown in Fig. 1a. The projectile base diameter $d = 0.08$ m. The total length of the projectile is $6d$ and the length of the body is $3d$. The computational domain is divided into an inner zone and an outer zone by the interface, which is indicated in bold in Fig. 1a. Fig. 1b illustrates the grid details at the projectile nose.

The projectile spins clockwise from the view of the projectile nose; the coordinate system is demonstrated in Fig. 1a. The incoming flow includes components in the x and y directions, and the sideslip angle is zero. The direction of the forces and moments are parallel to the coordinate axes. The reference area and reference length are $S_{ref} = 0.005027$ m^2 and $L_{ref} = 0.48$ m, respectively. All the forces are normalized by qS_{ref}, and moments are normalized by $qS_{ref}L_{ref}$.

As demonstrated in Fig. 1, a full three-dimensional structured hexahedral grid is generated for the numerical simulation. The mesh is refined around the nose, the projectile base, the boundary layer and the connection between the ogive nose and body where the curvature changes abruptly. To eliminate the influence of the grid on the numerical results, three types of mesh are generated for grid resolution study. The specific grid parameters are shown in Table 1. Grid points in the axial direction consist of points on the ogive nose and the body, and the off-body points are symmetrical in both fore and aft directions, which extend about one projectile length upstream and downstream from the nose and the base. Accurately capturing the boundary layer distortion is critical for Magnus effect. The height of the first layer grid is set as 1×10^{-6} m, which ensures $y^+ \leq 1.0$. Generally, this can meet the requirement for adequately resolving the boundary layer. The mesh stretching ratio is also kept within 1.1 to ensure that there are enough points in the viscous sublayer.

Table 1
Computational grid characteristics.

	Axial	Radial	Circumferential	Total (Mil.)	Δh (m)
Coarse	$100 + 50$	50	96	1.25	5×10^{-6}
Medium	$120 + 60$	70	116	2.33	1×10^{-6}
Fine	$200 + 100$	100	192	6.39	1×10^{-6}

3. Elastic deformation model

The elastic deformation of a projectile with large slenderness ratio may affect the aerodynamic characteristics significantly. Determining the specific patterns of variation for the aerodynamic characteristics is of great importance. Here, we assume that the projectile is experiencing three-dimensional bending motion.