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Numerical study on the aerodynamic coupling effects of spinning and coning motions for a finned vehicle

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ABSTRACT

A numerical method was used to compute the flow over a four-finned vehicle under supersonic conditions to study the aerodynamic characteristics of a spinning finned vehicle in a coning motion. For each flow condition, the side force and side moment of a combined spinning and coning motion were computed at roll angles of 0°–90°. The results of the non-rolling, coning, and spinning motions were superposed by using a nonlinear aerodynamic model, and the superposed side force and side moment were compared with those of the combined motion. The results indicated significant aerodynamic coupling effects with the combined motion at low Mach numbers and high coning and spin rates. Flow analysis showed that the coupling effects were mainly produced by the shockwaves and expansion waves around fins.

1. Introduction

Inducing a spin on a flying vehicle can simplify the control system and reduce costs. Such a spin can also eliminate the influence of mass eccentricity, thrust misalignment, and aerodynamic asymmetry. Therefore, spinning has been applied to a wide variety of vehicles, such as sounding rockets, projectiles, and tactical missiles. Spinning vehicles have special flight stability characteristics. In contrast to a non-spinning vehicle, the dynamic motion of the spinning vehicle is characterized as a coning motion [1,2]. For instance, the US Nikehawk sounding rocket and Spanish 140 mm rocket experience the coning motion [3,4]. Therefore, the prevention of a diverging coning motion should be considered during vehicle design. A coning motion is mainly induced by out-of-plane forces and moments. Thus, predicting the aerodynamic characteristics is important. Particularly at high angles of attack, the nonlinear aerodynamic coefficients and Magnus effect are significant and strongly influence the motion of a vehicle.

For a spinning vehicle in a coning motion, the spin rate and coning rate are generally different. Thus, the vehicle is in a combined motion. The aerodynamic coefficients of the combined motion are usually obtained by superposing those of the single-degree-of-freedom motions with an aerodynamic model [5]. Typically, the aerodynamic forces and moments of a single-degree-of-freedom motion can be accurately predicted with a wind tunnel test and numerical method. However, the aerodynamic coefficients obtained from the aerodynamic model may differ from those of the combined motion, which indicates the existence of aerodynamic coupling effects. Therefore, the validity of the superposed aerodynamic coefficients should be verified. The aerodynamic coefficients of a vehicle with a combined spinning and coning motion are difficult to predict with a wind tunnel test. In recent decades, computational fluid dynamics (CFD) has been widely applied to predict the aerodynamics of a spinning vehicle. The development of unsteady methods has increased the flow prediction accuracy for a finned vehicle. Furthermore, compared with wind tunnel tests, the CFD method provides more detailed information on the flow structures. Therefore, the CFD method can be used to verify an aerodynamic model and study the coupling effects.

In this study, a numerical method was used to compute the flow over a four-finned vehicle under supersonic conditions. The coning motion was simulated by using the moving reference frame method, and the spinning motion was simulated by using the dynamic mesh method. A nonlinear aerodynamic model was used to obtain the superposed aerodynamic coefficients. Moreover, a method combining the moving reference frame and dynamic mesh was used to simulate the combined spinning and coning motion. The superposed results of the aerodynamic model were compared with the computed aerodynamic coefficients of the combined motion. The results indicated that significant aerodynamic coupling effects were induced by the combined motion at low Mach numbers and high coning and spin rates. Therefore, for a spinning finned vehicle in a coning motion, the predicted aerodynamic coef-

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Nomenclature

X_E, Y_E, Z_E	non-rolling axes	
V_∞	free stream velocity	m/s
X, Y, Z	aerodynamic axes	
σ	resultant angle of attack	°
X, Y_B, Z_B	body-fixed axes	
$\dot{\phi}$	coning rate	rad/s
$\dot{\psi}$	spin rate	rad/s
C_z	side force coefficient	
C_{my}	side moment coefficient	
l	reference length	m
C_m	arbitrary moment coefficient	
ρ	density	kg/m^3
p	static pressure	Pa
u, v, w	velocities relative to the moving reference frame	m/s
x, y, z	coordinates relative to aerodynamic axes	
E	total energy	kJ/kg
H	total rothalpy	kJ/kg
Ω_x, Ω_y	angular velocities of the moving reference frame	rad/s
$\dot{f}, \dot{g}, \dot{h}$	velocities of the grid motion	m/s
d	diameter	m
y^+	dimensionless wall distance	
μ	dynamic viscosity	N s/m^2
u^*	friction velocity	m/s
τ_w	wall shear stress	Pa
T	period	s
Ma	Mach number	
p_{coning}	static pressure of the coning motion	Pa
$p_{spinning}$	static pressure of the spinning motion	Pa
p_{static}	static pressure of the non-rolling motion	Pa
$p_{coupling}$	static pressure of the combined motion	Pa
C_p	pressure coefficient	
p_{ref}	reference pressure	Pa
q_{ref}	reference dynamic pressure	Pa

ficients of the aerodynamic model are valid at high Mach numbers or small coning and spin rates.

2. Theoretical basis

2.1. Coordinate systems

In general, three axis systems are used to define the combined spinning and coning motion of a finned vehicle [6]. In this study, the gyroscopic coordinate system described by Schiff and Tobak [7] was used. Fig. 1 defines the coordinate systems and motion of the vehicle. X_E, Y_E, Z_E are the non-rolling axes, which are non-rolling with respect to the inertial space. The free stream V_∞ is parallel to the X_E axis. X, Y, Z are the aerodynamic axes. The X axis is fixed to the longitudinal axis of the vehicle. The Y, Z plane is coincident with the crossflow plane. The resultant angle of attack σ is defined by the X axis and free stream V_∞. $\dot{\phi}$ is the coning rate. The axes X, Y_B, Z_B are fixed to the vehicle, and the Y_B, Z_B axes are parallel to the spanwise direction. $\dot{\psi}$ is the spin rate. In this study, the X, Y, Z axes were used to define the direction of the forces and moments. C_z is the side force coefficient, and C_{my} is the side moment coefficient.

If the coning rate $\dot{\phi}$ is zero and the spin rate $\dot{\psi}$ is nonzero, the vehicle is in a normal spinning motion. In such a case, σ is the angle of attack, and the side force and side moment are the Magnus force and moment, respectively. If both the coning rate $\dot{\phi}$ and spin rate $\dot{\psi}$ are nonzero and σ varies with time, the vehicle is in a converging or diverging combined motion. However, this case was not considered in this study. Fig. 1 also shows that the angular velocity vector of the coning motion is parallel to the free stream; thus, the coning motion can be simulated by using the moving reference frame method.

Furthermore, in this paper, the CFD coordinate system was based on the aerodynamic axes. With this definition, the combined spinning and coning motion was simplified to a pure rotation along the X axis relative to the computational coordinate system. Therefore, rigid dynamic mesh could be used to define the unsteady motion. The aforementioned treatment reduced the computational complexity of the vehicle motion, and simplified the data processing of aerodynamic coefficients.

2.2. Aerodynamic model

Simplified linear aerodynamic models are typically used to describe the aerodynamic characteristics of spinning vehicles. Only the time-averaged forces and moments are considered. In this study, the nonlinear unsteady aerodynamic model described by Schiff [6] was used to examine the transient effects, and the side forces and side moments of single-degree-of-freedom motions were superposed.

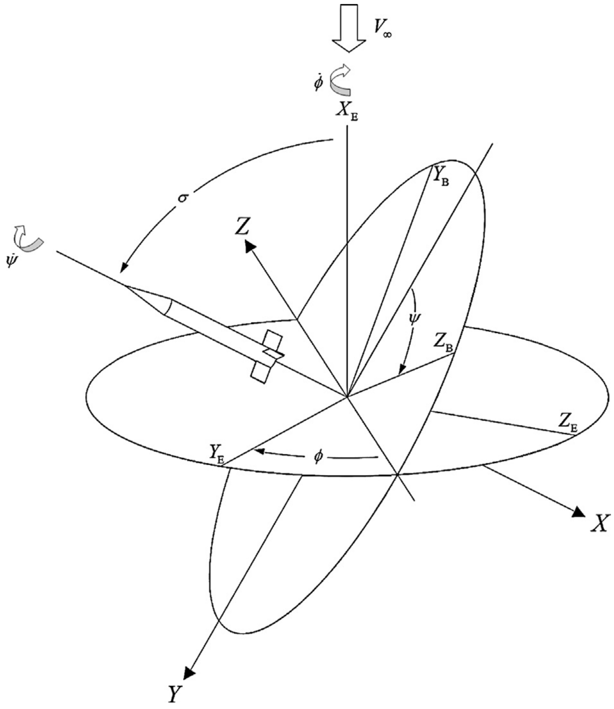

Fig. 1. Definition of the coordinate systems.

For a finned vehicle with a combined spinning and coning motion, if the flight speed is constant and the mass center traverses with no lateral plunging, the side moment coefficient or pitch moment coefficient can be described as follows:

$$C_m(t) = C_m(\infty; \delta, \psi) + \frac{\dot{\sigma} l}{V_\infty} C_{m\dot{\sigma}}(\delta, \psi) + \frac{\dot{\psi} l}{V_\infty} C_{m\dot{\psi}}(\delta, \psi) + \frac{\dot{\phi} l}{V_\infty} C_{m\dot{\phi}}(\infty; \delta, \psi), \tag{1}$$