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Short communication

Effects of suspension line on flow field around a supersonic parachute

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ABSTRACT

Numerical simulations based on a simple "immersed boundary technique" are performed to investigate the effects of suspension lines on the flow field around a three-dimensional rigid supersonic parachute mode consisting of a capsule and a canopy. The computational results show that the flow field has an unsteady pulsating characteristic. Furthermore, it is shown that the suspension lines prompt the formation of shock waves around them, which subsequently interact with the wake from the capsule and the canopy shock system. A good qualitative agreement is observed between the numerical results and experimental data.

1. Introduction

The effects of the suspension lines on the performance of parachutes have been widely investigated using the experimental studies. Steinberg et al. [24] showed that the suspension line length ratio (i.e., the ratio of the length of the suspension line to the diameter of the canopy) directly affects the drag coefficient of parachute system with Mach number ranging from Mach 0.2 to 2.6. Moorman [12] used ringsail modeling techniques to examine the effects of some design parameters such as the suspension line length ratio, over-inflation control line on the flight characteristics of both single and clustered Orion spacecraft parachutes. Connors et al. [3] and Heinrich [5] showed that for the supersonic parachute system, the suspension lines might interact with the canopy bow shock, and prompt an unsteady flow field as a result. Recently subscale MSL (Mars Science Laboratory) experimental studies have investigated that shock waves were generated in front of the supersonic parachute suspension lines, which may exacerbate the supersonic flow instability and cause the area oscillations of the flexible canopy [17–21].

With advances in computer performance and numerical modeling techniques, direct numerical simulations of the flow fields around supersonic parachute models emerged and the corresponding flow physics can be investigated in detail. However, in almost all the numerical simulations of the parachute problem, no real suspension lines were actually implemented in the numerical models. The effect of suspension lines on the parachute system is mainly considered to set up the force balance conditions at the junctions of the suspension lines and the canopy [7,8,10,11,25,28,29]. The flow structure induced by the presence of the suspension lines and the significance of shock waves generated in front of the parachute suspension lines has never been investigated numerically. Therefore, it sets up the motivation of this numerical study.

Accordingly, as a first step, this paper aims to present a way to apply a simple "immersed boundary technique" (SIBT) [10,11,28,29] to treat the boundaries of the rigid parachute suspension lines in a supersonic parachute system. Miyoshi et al. [10,11] used this technique to simulate the flow fields around two-dimensional (2D) and three-dimensional (3D) flexible canopies at low subsonic Mach numbers (Mach number is 0.06). It was shown that simulation results for the temporal evolution of the canopy inflation were in reasonable agreement with the experimental observations and the time history of computational payload force was in good agreement with the experimental data during the parachute inflation stages. This technique was further applied for the 2D, axisymmetric and 3D flexible parachute systems at supersonic conditions (Mach number is 2.0), where the simulation results agree with the supersonic parachute performances in wind tunnel and flight tests [28,29]. In addition, in these early numerical works, the structural dynamics of the 2D and 3D parachute models was treated via a mass–spring–damper model [2], which has been used to simulate many kinds of fluid–flexible body interaction problems such as the fluid–membrane interaction [6]. This study then proceeds with the numerical simulations of the supersonic flows over a rigid parachute with rigid suspension lines at freestream Mach number of 2. The computational results will be compared with the exper-

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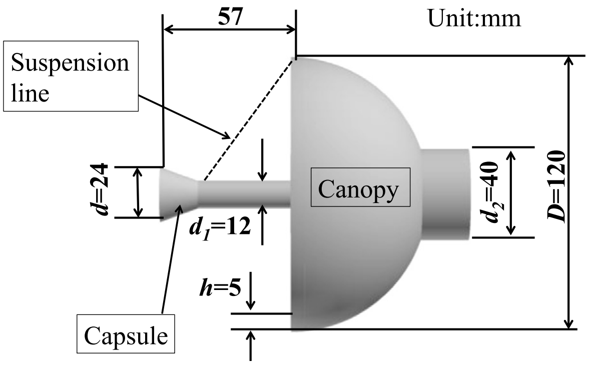

Fig. 1. Parachute model used in the present computation ($X/d = 2.38$, the same as that used in [27]).

Table 1
Specification of suspension lines in the ISAS/JAXA experiment.

Parameter	Value
Number	8
Interval angle	45 deg
Diameter	1.2 [mm]
Length	66 [mm]

Table 2
Freestream flow conditions employed in the present simulations.

M_∞	Re	P_0	P_∞	T_0
2.0	2.04×10^7 [m^{-1}]	166 [kPa]	21.0 [kPa]	298 [K]

imental data measured at the Institute of Space and Astronautical Science (ISAS)/Japan Aerospace Exploration Agency (JAXA).

2. Parachute model

As shown in Fig. 1, the rigid parachute system employed in the numerical simulations consists of a capsule and a canopy, connected by 8 suspension lines. The canopy is assumed to have the form of a hemisphere with a diameter of 120 mm and a thickness of 5 mm. Moreover, the capsule is assumed to have the form of a cone with a frontal surface diameter of 24 mm and a half-cone angle of 20 degrees. In constructing the model, it is assumed that the capsule is connected to the canopy by means of a rigid rod with a diameter of 12 mm. It is noted that the configuration of the parachute model is the same as the physical model used in the JAXA experiment. Notably, in the experiment, the whole rigid parachute system was mounted to the wind tunnel by a supporting rod with a diameter of 40 mm at the top of the canopy. Moreover, the suspension lines were assumed to be fabricated of stainless-steel and to be configured in according to the specification given in Table 1. Furthermore, the lines were assumed to have zero thickness in the geometrical sense and to be rigid. Finally, the SIBT was imposed on the boundaries of the cell intersected by the zero-thickness line, and the effects of flow-induced vibrational motion were ignored.

3. Computational conditions and methods

3.1. Computational conditions

Table 2 shows the freestream conditions used in the present simulation. Note that these conditions are the same as those used in the JAXA experiment.

3.2. Numerical methods

The supersonic flow fields around the parachute model were obtained by solving the 3D compressible Navier–Stokes equations using an in-house parallel structured single-block code. In obtaining the numerical solutions, the inviscid fluxes were solved using the Simple High-resolution Upwind scheme (SHUS) [22], in which the accuracy was improved through the use of the 3rd-order MUSCL scheme [26] with the Van Albada flux limiter [1]. By contrast, the viscous terms were computed using the 2nd-order central differencing scheme. In addition, the coefficient of viscosity was handled in accordance with the Sutherland's law. To ensure the time-accuracy of the unsteady flow field calculations, time advancement was performed using the 3rd-order total variation diminishing Runge–Kutta scheme [23]. Note that the dimensionless time step was set to be 6.0×10^{-6}, in order to maintain the Courant–Friedrichs–Lewy number of about 0.5. In performing the unsteady calculations, in terms of initial conditions, each variable takes its freestream value. As to boundary conditions, at the inflow boundary, all conservative variables were set to the freestream values, given by Table 2. At the outflow boundary, the conservative variables were solved from the solution just inside the computational domain (or "zero gradient condition was applied"). And non-slip and adiabatic conditions were imposed on the body surfaces of the capsule and canopy for the wall boundary conditions.

Finally, the immersed boundary technique developed in Refs. [10,11,28,29] was used to treat the boundary of the three-dimensional suspension lines. This simple immersed boundary technique is full different from the classic immersed boundary methods developed by Peskin [15], which are limited to low Reynolds number and incompressible flow because the forcing is incorporated into the continuous equations and the forcing terms used are generally not well behaved in the rigid limit [9]. The immersed boundary technique employed here was first proposed by Ochi and Nakamura [13] in our group. It can approximately give the velocity vectors of the virtual cells, without introducing the forcing terms to the governing equations. The velocity vectors in the virtual cell, which contains the control nodes of the suspension lines, were obtained from the relationship between the fluid and virtual cell [10,11,28,29], as in Eq. (1):

$$V_v = V_f - 2(V_f \times n_v)n_v + V_b \tag{1}$$

where V_f, V_v, V_b refer to the velocity vector in the fluid cell, virtual cell and velocity of suspension line node, respectively, and n_v is a unit vector normal to the suspension line. By assuming the suspension line is rigid in this work, $V_b = 0$. Notably, the numerical code originally developed by our research group to compute the moving boundary conditions of the flexible canopy surface [10,11,28,29] was adapted to compute the rigid boundary conditions of suspension lines here. Furthermore, the structure consideration of the suspension lines in the SIBT calculations was treated using a mass–spring–damper (MSD) model [2,10,11,28,29]. Specifically, each suspension line was treated as an assembly of mass nodes attached to springs and dampers. Since the suspension lines were assumed to be rigid in the present model, the initial position and velocity of each mass node were provided to the flow calculation by the immersed boundary technique at each calculation step.

It is noted that a turbulence model was not adopted in the present study since (1) most algebraic turbulence models could not perform satisfactorily for most complex separation flows [16], and (2) previous studies using rigid and flexible parachute models demonstrated a satisfactory agreement between the results obtained by the laminar numerical simulations and those obtained in wind tunnel tests [10,11,27–29].

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