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Numerical modelling of Mars supersonic disk-gap-band parachute inflation

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Abstract

The transient dynamic behaviour of supersonic disk-gap-band parachutes in a Mars entry environment involving fluid structure interactions is studied. Based on the multi-material Arbitrary Lagrange–Euler method, the coupling dynamic model between a viscous compressible fluid and a flexible large deformation structure of the parachute is solved. The inflation performance of a parachute with a fixed forebody under different flow conditions is analysed. The decelerating parameters of the parachute, including drag area, opening loads, and coefficients, are obtained from the supersonic wind tunnel test data from NASA. Meanwhile, the evolution of the three-dimensional shape of the disk-gap-band parachute during supersonic inflation is presented, and the structural dynamic behaviour of the parachute is predicted. Then, the influence of the presence of the capsule on the flow field of the parachute is investigated, and the wake of unsteady fluid and the distribution of shock wave around the supersonic parachute are presented. Finally, the structural dynamic response of the canopy fabric under high-pressure conditions is comparatively analysed. The results show that the disk-gap-band parachute is well inflated without serious collapse. As the Mach numbers increase from 2.0 to 2.5, the drag coefficients gradually decrease, along with a small decrease in inflation time, which corresponds with test results, and proves the validity of the method proposed in this paper.

Keywords: Mars entry; Supersonic parachute; Fluid-structure interactions; Inflation dynamics; Arbitrary Lagrange Euler; Compressible flow

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1. Introduction

In the frame of planetary exploration, a large number of vehicles carrying landers for surface exploration have been launched to Mars (Reynier, 2014). One of the Entry, Descent and Landing (EDL) systems is the Mars Science Laboratory (MSL), which will enable access to previously unattainable landing sites up to 2 km above the gravitational equipotential reference surface, up to 60° from the equator, and with a precision of 10 km from the designated surface target (Way, 2006). To achieve this landing site capability, the parachute decelerator system is designed as an integral part of the EDL system. The disk-gap-band (DGB) parachute provides aerodynamic drag to decelerate the entry vehicle from supersonic to subsonic speeds during the entry process (Sengupta et al., 2007b). One primary uncertainty related to this issue is the decelerating performance of the DGB parachute inflation in the supersonic environment (Li and Peng, 2011).

The inflation of the parachute is a typical fluid-structure interactions (FSI) problem. Even at low speed, the prediction of the aerodynamic characteristics of the parachute is difficult owing to the nonlinear nature of structure deformation, in particular for parachutes with complex layouts, such as slots or gaps (Gao et al., 2013; Tezduyar et al., 2010). For the supersonic deceleration process, the layout

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of parachute needs to be specifically designed to achieve high aerodynamic performance.. The DGB parachute has been commonly used in supersonic deceleration, which can be dated back to the 1970's, and has been used in most of the NASA planetary entries to date.

Since the early Viking missions to Mars, a series of DGB parachutes, named Viking type, have been designed and systematically tested, in both flight and wind tunnel tests (Steinberg et al., 1974). The influence of Mach numbers, suspension line ratio, and porosity on the drag and stability of the parachute have been modelled and experimentally studied in supersonic and subsonic environments (Johari and Levshin, 2009; Takizawa et al., 2013; Xue et al., 2015). Nearly all the decelerators used in the Mars Polar Lander, Phoenix, and MSL, e.g., for missions, originate from the Viking type parachute (Reynier, 2014; Sengupta et al., 2007b). In addition, the European Space Agency has developed a 12-m-diameter DGB parachute for use in the ExoMars exploration mission, which is an improved design of the DGB parachute used in the Huyens mission (Lingard et al., 2007; Votta et al., 2010).

In addition, numerical simulation techniques are efficient tools to assess the deceleration performance of the parachute, in particular for the FSI phenomenon. A loose coupling FSI model of a cross parachute was built in the early stages (Stein et al., 2001). Based on the Arbitrary Lagrangian–Euler (ALE) method, a fully coupled FSI model for a supersonic parachute was built and solved. The FSI behaviour of the flexible fabric and the drag performance of the parachute under the influence of the forebody were studied (Lingard and Darley, 2005). A further detached eddy simulation methodology was developed to predict the FSI characteristics of the MSL parachute during wind tunnel tests. The rigid and flexible canopy models, unsteady flow field, and turbulent flow were carefully simulated, but the structural deformation of the parachute was not considered in detail (Gidzak et al., 2009b). Parachute dynamics, drag performance, and suspension line interaction behaviours were predicted and analysed, and the supersonic inflation of a subscale parachute was presented in the experiments (Sengupta et al., 2009). Large-scale FSI simulations of compressible flow over the inflated flexible supersonic DGB parachutes were performed and compared with the experimental results of NASA at matching flow conditions and structural properties. A number of significant dynamic behaviours were discovered, such as the canopy area oscillation depending on the resolution of the simulation (Karagiozis et al., 2011). The Computational Fluid Dynamics (CFD) tool was utilised to investigate the effects of compressibility, and the deformation of the flexible canopy was calculated with a mass-spring-damper model. These two calculations are coupled by the immersed boundary method. The unsteady characteristics of the flow field and the canopy oscillations were investigated (Kim and Peskin, 2006; Xue and Nakamura, 2011). In particular, the coupling behaviour of the capsule wake and canopy bow-shock were parametrically studied by varying the trailing distance (Hiroyuki et al., 2015; Xue, 2015). Based on the deforming spatial domain/stabilized space–time (DSD/SST) technique, which was applied to three-dimensional (3D) computations soon after its development (Tezduyar et al., 1993, 1994), FSI modelling of several kinds of parachutes was carried out, including ram-air parachutes (Kalro and Tezduyar, 2000), and solid round parachutes (Stein et al., 2000), Large-scale parachute designs were validated by this technique in the subsonic range.

However, most of the FSI modelling in the current stage focuses on the aerodynamics of the parachute with the inflated canopy as an initial condition. The folded state of parachute is ignored, as this would introduce a larger canopy deformation and unsteady flow into the inflation simulation. Thus, the parachute's opening process, initiating from the folded type of pre-inflated model to the fully inflated state, should be predicted and analysed.

To match the set-up of the parachute system in both the airdrop and wind tunnel tests, the opening process can be theoretically sorted into infinite mass and finite mass conditions. When the parachute's unit area bears a considerably heavy load, the deceleration of the parachute and the fluid during the opening process can be ignored, and the inflow velocity is maintained at a constant value. This is called infinite mass inflation. In contrast, the finite mass condition implies that the personnel parachute dropped from an airplane has a finite load. Thus, the primary difference between the infinite and finite mass conditions is that, under the infinite mass condition, the velocity of the parachute system does not decay during the opening process; whereas, under the finite mass condition, the velocity of the parachute system decreases substantially. During the wind tunnel tests, the translation of the parachute system is fully constrained with a constant inflow velocity, which corresponds to the infinite mass inflation problem, while during the airdrop tests, the payload hanging below the parachute is freely moved in accordance with the finite mass inflation. Tutt and Taylor et al. have specifically conducted the infinite and finite mass inflation of a parachute by means of the LS-DYNA tool at low speed (Tutt et al., 2011; Tutt and Taylor, 2005). However, there are limited simulations to evaluate the supersonic capacity of FSI techniques for parachute inflation.

We focus on the numerical prediction of the infinite mass inflation of a Mars supersonic parachute system in the wind tunnel tests. By utilising a novel multi-material ALE algorithm in the LS-DYNA transient dynamic analysing code, this study has provided a physical insight into the FSI characteristics of a sub-scale model of the MSL DGB parachute which is used for the Mars MSL mission. This data is compared to that from supersonic wind tunnel tests. Steps were taken to develop a parametric modelling and design methodology of an initially folded parachute and capsule system. Represented by the cable and membrane elements, the parachute's structural dynamics solver is governed by the Lagrangian description of motion,