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Parachute dynamics and perturbation analysis of precision airdrop system

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Abstract To analyze the parachute dynamics and stability characteristics of precision airdrop system, the fluid–structure interaction (FSI) dynamics coupling with the flight trajectory of a parachute–payload system is comprehensively predicted by numerical methods. The inflation behavior of a disk-gap-band parachute is specifically investigated using the arbitrary Lagrangian–Euler (ALE) penalty coupling method. With the available aerodynamic data obtained from the FSI simulation, a nine-degree-of-freedom (9DOF) dynamic model of a parachute–payload system is built and solved to simulate the descent trajectory of the multi-body dynamic system. Finally, a linear five-degree-of-freedom (5DOF) dynamic model is developed, the perturbation characteristics and the motion laws of the parachute and payload under a wind gust are analyzed by the linearization method and verified by a comparison with flight test data. The results of airdrop test demonstrate that our method can be further applied to the guidance and control of precision airdrop systems.

1. Introduction

Parachutes are widely used in modern smart airdrop systems to decelerate and stabilize the payload.[1–4] For the past few decades, applications of smart technology in decelerator systems were still at the exploration stage and were mainly developed for the aerial delivery and airdrop missions. Since the 1990s, the U.S. Army has developed several precision airdrop systems by implementing a guidance, navigation & control (GN&C) system and smart actuator in the parachute and parafoil.[5–7] Research is still under way on methods and materials used in parachutes and airdrop systems to guide and control parachute flight in order to achieve optimum performance to meet the mission requirements.[8] Based on the specific requirements of different missions, several types of parachute–payload systems have been designed and tested,[9] among which the rotating parachute–payload system stands out as a common configurations for smart submunitions that are required to perform a target maneuver operation. However, our airdrop test results show that the stability of the parachute airdrop system often has difficulty in target identification.

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The stability of the parachute system has proven to be one of the most difficult aspects of modeling parachutes because of different stability modes. A two-dimensional (2D) parachute model has been developed to compute various characteristics pertaining to the steady descent of a parachute system by investigating the effects of wind on parachute oscillation using measured wind profiles. On the basis of a typical five-rotational-degree-of-freedom model of the parachute system, the dynamic stability problem has been theoretically and experimentally investigated.[10] The results revealed that during static tests a parachute with less stability vibrated with high frequency and considerable amplitudes when kept at constant angles of attack. Thus it became a significant issue to determine the influence of the parachute's dynamic stability, like the canopy–payload coupling, with added fluid mass components and geometrical porosity, among others.[11,12] The relationship of aerodynamic and inertial parameters with the lateral stability characteristics of a gliding parachute has been analyzed.[13] The multi-body dynamics methodology has remarkably promoted the development of trajectory planning and stability modeling of parachute systems, although the accuracy of these problems still mainly depends on the profound insights of the aerodynamic characteristics around the parachute and payload, in both the static and dynamic states.[14,15]

For mission design, however, good estimates of the aerodynamics of the parachute systems are not easy goals to achieve. In the past, static and dynamic experimental measurements were employed to help the designers obtain optimal solutions.[16–18] In the recent years, computational simulations of parachute systems have gradually played a predominant role in the prediction of dynamic behaviors, and various approaches and numerical methods have been developed to model and perform the simulation of parachute aerodynamics and fluid–structure interaction (FSI) behavior. During both the inflation and steady descent stages, the parachute dynamics are governed by a coupling between the structural dynamics of the parachute and the surrounding fluid flow. As such, the system must be treated as coupled to gain a proper representation of a holistic dynamic system.

Ongoing research has yielded software that improves the accuracy of computational fluid dynamics (CFD) and computational structure dynamics (CSD), and the aerodynamic characteristics as well as the response of the structure can be comparatively studied, which is beneficial for the trajectory and stability computation of parachute coupling systems. On the basis of the deforming spatial domain/stabilized space–time (DSD/SST) technique,[19,20] which was applied to three-dimensional (3D) computations soon after its development,[21,22] FSI modeling of several kinds of parachutes was carried out, including ram-air parachutes,[23] solid round parachutes,[24] and complex solid parachute designs.[25] With the new generation of DSD/SST formulations and space–time FSI techniques,[26] many additional 3D computations presented by parachute FSI were addressed,[27,28] including ringsail parachutes and reefed ringsail parachutes,[29] and the evaluation of the stability characteristics of a parachute based on aerodynamic-moment calculations.[30] The explicit finite element method is also an efficient tool to replicate the FSI dynamics of parachute systems. With the algorithmic enhancements of the arbitrary Lagrangian–Euler (ALE) penalty coupling method in LS-DYNA, considerable efforts were made in the investigation of parachute related recovery problems and in assessing the performance of parachute inflation.[31–37] In addition, the simplified ALE FSI method is also used to simulate the inflation process of a folded parachute.[38,39] Compared with the space–time FSI technique, a semi-implicit method for pressure-linked equations (SIMPLE) algorithm was proposed to analyze the FSI and flow field characteristics of a parachute.[39]

This paper first presents the analysis of aerodynamic characteristics and an FSI coupling mechanism of a parachute–payload system during a precision airdrop operation. The 3D dynamics behavior of parachute systems during inflation and steady descent state is specifically analyzed using the ALE penalty coupling method within LS-DYNA nonlinear dynamics code. Then, a nine-degree-of-freedom (9DOF) dynamic model of the parachute–payload system is developed, which can be used for the prediction of the trajectory and the stability behavior of the parachute–payload system. Good agreement between the simulation and the airdrop test data provides the necessary verification and validation. Finally, on the assumption that the aerodynamic velocity is constant and perturbations are sufficiently minimal, a linear five-degree-of-freedom (5DOF) dynamic model is developed in the steady state. The simulation program has been developed and used to remove the influence of wind gusts, and the equations of the steady states can be applied to analyzing the descent and stability characteristics of a parachute airdrop system. The comparison results proved the efficiency of our method in the guide design of precision airdrop systems.

2. Problem formulation

The spatial motion of a precision airdrop system is chaotic and complicated. Upon payload ejection, the canopy will quickly inflate into a hemisphere shape. Under the effect of the aerodynamic pressure on the surface of canopy, the system is decelerated and guided into a steady state with the payload spinning at a constant rate for target identification. This paper mainly focuses on the forming phase from the opening of the canopy to the steady scanning of the payload. The parachute is a scaled disk-gap band (DGB) parachute (as shown in Fig. 1); the construct diameter of the parachute $D_c = 7.5$ m, the vent diameter $D_v = 0.0738D_c$, the width of gap $H_g = 0.0424D_c$, the width of band $H_B = 0.1209D_c$, the width of band on gore $B = 0.02$ m, the length of suspension lines $L = 1.713D_c$, and the number of gores $N = 24$. The payload is constructed by a conical head, cylindrical body and six wrap-around fins.

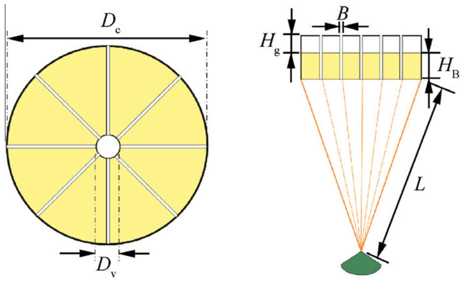

Fig. 1 Schematic of disk-gap band parachute.