Fluid-structure Interactions on Steerable Cruciform Parachute Inflation Dynamics

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Abstract. To develop the decelerating and rigging potential performances of cruciform parachute during to its relatively large stand-off with lower cost production in precision aerial delivery operations, the fluid structure interaction behaviours of steerable cruciform parachute is studied. The concept of suspension lines control of cruciform parachute is firstly proposed. Based on the multi-material Arbitrary Lagrange-Euler method, the coupling dynamic model between a viscous incompressible fluid and a flexible large deformation structure of the cruciform parachute is solved. The inflation performance of a cruciform parachute under different steerable conditions is analysed. The decelerating parameters of the parachute, including drag area, and opening loads are obtained from FSI simulation. Meanwhile, the evolution of the three-dimensional shape of the cruciform parachute inflation is predicted.

1. Introduction
As the huge demands in military and humanitarian resupply, the precision aerial delivery systems experience a significant development during the last 20 years. Accordingly, the steerable ability of parachute during the decelerating process become mature and make great efforts to the precision aerial delivery operations. The ram air parafoil is most familiar and know to all for its accurate steerability, while the control mechanism of parafoil is relatively complex and even require some intelligence of payload to keep system stable in some extreme environments\cite{1, 2}. Nowadays, people are still making efforts to seek a low-cost, minimally complex, and accurate precision delivery system\cite{3, 4}.

As an alternative to ram-air parafoils, round parachute control technology has been extensively developed by U.S. Army Natick Soldier Research Development and Engineering Center (NSRDEC)\cite{5-7}, such famous accurate delivery system of round parachute is the Affordable Guided Airdrop System (AGAS)\cite{8}. Based on the extensively studied in the past from the standpoint of structural integrity\cite{9} and aerodynamic effects of canopy geometry\cite{10}, including intentionally introduced asymmetry\cite{11}, as well as the evaluation of control line reefing techniques for high controllability of parachute with minimal actuator power requirements\cite{12}. Yakimenko and Fields et al. are seeking the feasibility of steerable ability of cruciform by implementing the actuator on the
suspension lines[13, 14]. The construction of cruciform parachute is simple and economical, of which the canopies are composed by two identical fabric rectangles, crossed and joined to each other at the square intersection to form a flat surface having four equal arms[13]. Fagley et. al. examined the bleed air spoiler (BAS) control technique on cruciform parachute canopy by computational study method[15], Potvin et. al. performed an extensive field testing regimen to explore the potential gliding capabilities of cruciform and hybrid cruciform canopies[16]. Herrington et. al. presents an experimental approach for testing a steerable cruciform parachute system using a vertical wind tunnel[17].

To develop the dynamic response performance of a cruciform parachute during inflation stages at line-reefing steering conditions, the ALE code in LS-DYNA software is utilized in this study to perform the FSI simulation of parachute. The steerable parachute concept is firstly designed, then the finite element model of parachute and fluid domain are built and the penalty coupling method is applied for FSI simulation.

2. Problem Statement and concept design

The concept of steerable cruciform parachute origin from the low-cost demands in precision airdrop, delivery and recovery tasks. The cruciform parachute addressed in this paper is a 16 suspension lines cross parachute consisting of a cruciform canopy, which can be steered by adjusting the length of a dynamic line through the single actuator on it during flight, and one static line can be shortened beforehand with a constant length during flight. Thus the asymmetry of initial cruciform parachute can be broken and the spin control can be achieved by intentionally introducing a difference between the steerable and static lines, $\Delta l = \delta_s - \delta_d$, and $L=2.8 \text{m}$ is the arm length, $W=0.72 \text{m}$ is the arm width and $l=2.82 \text{m}$ is the suspension length of cruciform parachute (Figure 1).

![Figure 1. Layout of steerable cruciform parachute](image_url)

3. Fluid Structure Interaction Model

3.1. Structure and fluid dynamics

Parachute components are flexible and continuous media. The governing equation of structure system is

$$\rho_s \frac{\partial u}{\partial t} = \sigma_s(u) + \rho_s f_s \quad \text{on} \quad \Omega^s$$  \hspace{1cm} (1)

where $\rho_s$ is material density, $u$ is the velocity vector of structure media, $\sigma_s$ is Cauchy stress tensor, and $f_s$ is the external body forces acting on structure. For canopy structure formulation, a special membrane element like traditional airbag fabric constitutive material model is better suited to it. For the thin fabrics, buckling (wrinkling) can occur with the associated inability of the structure to support compressive stresses. The membrane is a two-dimensional (2D) shell suited for a 3- or 4-node element.
Besides on, air permeability of parachute fabric is one of the important properties must be considered, here it’s determined by the Ergun equation.

\[
\frac{dP}{dr} = a(\mu, \beta) \cdot v_m + b(\mu, \beta) \cdot v_r^2
\]  

(2)

The fluid field during parachute inflation is time-variant spatial domains, let $\Omega'$ be the spatial domain, the N-S equations for incompressible flows are [18]

\[
\rho_f \left( \frac{\partial u_f}{\partial t} + u_f \cdot \nabla u_f + f_f \right) - \nabla \cdot \sigma_f = 0 \quad \text{on } \Omega' \\
\nabla \cdot u_f = 0 \quad \text{on } \Omega' 
\]  

(3)  

(4)

$\rho_f$, $u_f$, $f_f$ and $\sigma_f$ are the density, velocity vector, external body force and stress tensor respectively. By introducing the ALE formulation, the finite mesh can be freely moved. The fluid particle coordinates are $X_i(t)$, $(i = x, y, z)$, where $t \in (0, T)$.

3.2. Coupling method

We use the ALE penalty-coupling algorithm implemented in the LS-DYNA nonlinear dynamic software to solve the FSI equations for steerable cruciform parachute inflation process. Both the fluid and structure models can be independently meshed, and the time step of explicit dynamic integral method in ALE algorithm is in proportion to the mesh size. Besides on, the negative volume and an hourglass effect should also be avoided by introducing the scale factor of time step. At each time step, the velocity and pressure should be decoupled by a penalty method, and the fluid and structure equations would be associated, solved, and iterated once.

4. Numerical Simulation

In this study, the infinite mass inflation is simulated, the cruciform the parachute is attached to a fixed point in space and flow can pass through the simulation domain, like a wind tunnel configuration, as shown in figure 2. The parachute’s folding and deployment process are also not considered in this paper, and we focus on the fabric inflation behaviours during steerable process, thus the initial state of cruciform parachute model is simplified as illustrated in figure 2. The fabric was meshed by 2D tetrahedral shell and the line was meshed by 1D discrete beam elements. The fluid domain was meshed by 3D solid elements.

Figure 2. Finite element model of cruciform parachute and fluid domain for FSI simulation
5. Results and Discussions
The inflation process of cruciform parachute without steering by line control are presented in figure 3, the canopy is asymmetrically inflated, and the steady shape is hemisphere. Figure 4 illustrates the FSI phenomenon between canopy structure and surrounding flow, the cruciform parachute begins to swing and rotate after the canopy inflated. It is clearly to know that the numerical simulation of FSI has captured parachute’s opening process.

Figure 3. Inflation geometry of cruciform parachute

Figure 4. FSI phenomenon of cruciform parachute inflation
Figure 5 shows the drag area of parachute’s projection under 3 cases. It is shown that the canopies reach to a maximum area at about 1.1s for all 3 cases after a slight shrinkage occur. After the canopies are fully inflated, the drag area keeps at a steady value in case 1. On the contrary, the canopies regularly fluctuate after fully inflated both for the other two steering cases, which indicate that the aerodynamic shape of canopy can be controlled and steered by the suspension lines retraction control.

Figure 6 predicts the opening forces evolution of canopy for all 3 cases, it can be seen from the figure 5 and 6 that the peak forces appear at the shrinkage of canopy at about 0.4s before the fully inflate state. The peak force values are same, and the evolution rules are similar for all 3 cases.

6. Conclusions
This paper addressed the steering concept and FSI simulation of cruciform parachute under infinite mass inflation. The steering conditions were designed and the numerical models for different steering conditions were built and solved, and curves from different work conditions of the numerical models were also compared and investigated. The results show that the aerodynamic shape and decelerating performance can be regulated and steered by the line retraction control, the method used in this paper can also provide a simplified approach for FSI dynamics estimation of steering parachute inflation, as well as the indication of fluid and structure dynamics. Future study should consider much more steering conditions and comparing with the airdrop and wind tunnel experimental results.

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