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# Research on FSI dynamic characteristics of parafoil trailing edge deflection

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## Abstract

The parafoil is manipulated by pulling the trailing edge to realize maneuvering, turning, and landing etc., which involves the coupling process between the flexible fabric structure and aerodynamics. Based on the transient nonlinear dynamics' method, the FSI dynamic behaviors of trailing edge deflection is numerically simulated and analyzed. The Structured-ALE (SALE) models algorithm as well as the penalty method are both utilized to modeling the coupling fields and interface, by which the computing efficiency is highly improved. The stress distribution and structure strength of canopy is visualized and analyzed, the surrounding flow field is also visualized in 3D, the evolution mechanisms such as flow separation are studied. At last, the influence of deflection angle as well as the turning position on FSI dynamic characteristics are comparatively analyzed. The results validated the efficiency of our method and could be a good support for the design and application of large parafoil.

**Keywords:** Parafoil, Fluid structure interaction, Trailing edge deflection; ALE method; Flow separation

## 1. Introduction

Parafoil is originating from parachute-airfoil, which is a controllable and flexible aerodynamic structure with several cross sections divided by the airfoil type libs distributed between upper and lower ceiling surfaces. The upper surface is mainly bearing the aerodynamic loads, while the lower surface is mainly bearing the opening impacts, thus the local broken of lower surface wouldn't cause the whole damage of parafoil's aerodynamic characteristics[1]. The fabric's permeability of parafoil is extremely low to make the ram air from leading edge of airfoil during the flight, and the internal pressure in cross sections can keep the airfoil shape of parafoil in flight phase. Comparing with the traditional parachute, the biggest advantage of parafoil is manipulating performance. The manipulation of parafoil is performed by controlling the rigging lines to deflect the trailing edge, the aerodynamic configuration of parafoil will change during the maneuvering and flaring phases. The dynamic problems relating to the manipulation and deflection is overly complex[2]. The world have never stopped the research on the parafoil since it born in 1960's, and gradually formed many advance parafoil precision airdrop systems, which have been successfully applied in both the military and civilian fields. The famous case like Joint Precision Airdrop System (JPADS) of United States, JPADS is a precision guided airdrop system that provides rapid, precise, high-altitude delivery capabilities that do not rely on ground transportation[3]. The system is being developed in two weight classes: 2000 pounds and 10000 pounds. X-38 parafoil is another influential recovery system modified from the U.S. Army Guided Precision Air Delivery System (GPADS), which can achieve a repeatable, low dynamics on heading opening of the full-scale ram-air parafoil[4]. The X-38 parafoil is the biggest parafoil project worldwide until now with 700m$^2$ deployment area and 33 cells. And there are other distinguished parafoil systems like Canadian Snow Goose surveillance system and Sherpa precision airdrop system, the European SLG-Sys autonomous gliding airdrop system etc. The working process of parafoil is a typical fluid-structure interaction (FSI) problem involved with interaction between canopy structure and surrounding aerodynamic pressure. The solving of FSI problems have always been a concerned problem in parachute research field.

To build a reasonable FSI dynamic model can effectively predict the deforming behavior of canopy structure as well as the response of aerodynamic configuration, especially can simulate the damage phenomenon beforehand, and could be a good support for the optimal design of flight system. There is still a lack of extensive attention on the FSI dynamic mechanism specifically focus on the parachute system. Tang etc. simulated the structural behaviors during trailing edge deflection of parafoil based on the ICFD flow solver and mechanical solver[5]. Tezduyar group performed the FSI simulation on ram air parafoil system based on DSD/SST FEA method[6]. Fogell etc. carried out the FSI simulation on the canopy shape during parafoil’s steady flight state based on loose coupling method with CFD and CSD techniques[7]. Altmann analyzed the FSI problems of parafoil by potential flow theory as well as the simplified FEA method[8]. Cao etc. analyze the FSI problem of parafoil inflation by Dichlet/Neumann iteration method[9]. Teng etc. realized the FSI simulation for the steady aerodynamic configuration of parafoil based on LS-DYNA software[10]. He etc. simulated the billowing phenomenon of parafoil’s cell by cable-membrane FEA model and CFD technique[11].

For the large scale parafoil system, the dynamic characteristics of interconnected cells are crucial for the whole canopy and parafoil. As the basic element of canopy structure, this paper firstly focuses on the FSI dynamics of single cell during the trailing edge deflection process, to obtain the aerodynamic loads on surface as well as the structural response of fabric.

## 2. Fluid structure interaction modeling

### 2.1 Structural dynamics

The parafoil structure is mainly composed with the fabric, upon which only the main stress exists under loading. The governing equations of fabric structure can be stated as[12]

$$\rho_s \frac{\partial \boldsymbol{u}}{\partial t} = \boldsymbol{\sigma}_s(\boldsymbol{u}) + \rho_s \cdot \boldsymbol{f}_s \quad \text{on } \Omega^s \tag{1}$$

Where $\rho_s$ is the material density， $\boldsymbol{u}$ is the velocity vector of struture point， $\boldsymbol{\sigma}_s$ is the Coriolis stress tensor， $\boldsymbol{f}_s$ is the ourter force acting on the structure。

Considering the nonlinear characteristics of fabric structure dynmamics, the membrane element is used to simulate the fabric, of which the constitutive equation is

$$\begin{aligned} \varepsilon_1 &= \frac{1}{E_1}(\sigma_1 - \upsilon_1\sigma_2) \\ \varepsilon_2 &= \frac{1}{E_2}(\sigma_2 - \upsilon_2\sigma_1) \end{aligned} \tag{2}$$

Where $\sigma_1$, $\upsilon_1$, $E_1$ are serpeartelly warp stress, poisson’s ratio and elastic module, accordingly, $\sigma_2$, $\upsilon_2$, $E_2$ are serpeartelly weft stress, poisson’s ratio and elastic module.

### 2.2 Fluid dynamics

he flow around the parafoil in this paper is low speed and incompressible, the Euler governing equation of fluid is used as follow[13]

$$\boldsymbol{\rho}_f\left(\frac{\partial \boldsymbol{u}_f}{\partial t} + \boldsymbol{u}_f \cdot \nabla \boldsymbol{u}_f + \boldsymbol{f}_f\right) - \nabla \cdot \boldsymbol{\sigma}_f = 0 \quad \text{on } \Omega^f \tag{3}$$

$$\nabla \cdot \boldsymbol{u}_f = 0 \quad \text{on } \Omega^f \tag{4}$$

Where $\boldsymbol{\rho}_f$ and $\boldsymbol{u}_f$ are density and velocity vectors, $\boldsymbol{f}_f$ and $\boldsymbol{\sigma}_f$ are outer force and stress tensors.

By introducing the Arbitrary Lagangrian and Eulerian formulation, the finite element mesh can move freely, and the fluid governing equation can be rewrited in ALE formulation as

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} - \boldsymbol{w}) \cdot \nabla \boldsymbol{v} - \frac{1}{\rho_f}\boldsymbol{\sigma} = \boldsymbol{g} \tag{5}$$

Where the fluid particle velocity is $\boldsymbol{u}_f=\boldsymbol{v}-\boldsymbol{w}$, $\boldsymbol{v}$ and $\boldsymbol{w}$ are serperatelly the partical and mesh point velocity under reference configuration. The Dirichlet and Neuman's boundary conditions are

$$\begin{aligned} \boldsymbol{v} &= \boldsymbol{g}(t) \quad \text{on } \partial\Omega_1^f \\ \boldsymbol{n}\cdot\boldsymbol{\sigma} &= \boldsymbol{h}(t) \quad \text{on } \partial\Omega_2^f \end{aligned} \tag{6}$$

Where $\Omega_1^f$ represents the velocity boundary of fluid field, and $\Omega_2^f$ represents the coupling boundary between fluid and sturcture.

### 2.3 Penalty method

Another key technique for the FSI problems is the information transfer on coupling interface. The energy conservation should be maintained during the transmission. Normally, it is difficult to realize the total matching between fluid and sturcture mesh in FEA, whild it is possible to perform such technique by ALE penalty method in this paper.

In explicit dynamics integration method, the penetration depth at next time step should be[14]

$$\boldsymbol{d}^{n+1} = \boldsymbol{d}^{n} + \boldsymbol{v}_{rel}{}^{n+1/2}\cdot\Delta t \tag{7}$$

Where $\Delta t$ is the time step, and $\boldsymbol{v}_{rel}$ is the relative velocity between the master and slave points. The master point velocity can be seen as the fluid element point velocity during the motion in ALE formulation, then

$$\boldsymbol{v}_{rel}^{n+1/2} = \boldsymbol{v}_{s}^{n+1/2} - \boldsymbol{v}_{f}^{n+1/2} \tag{8}$$

The penetration occurs only when $\boldsymbol{n}\cdot\boldsymbol{d}^{n} < 0$, and the coupling force is

$$\boldsymbol{f}_c^n = k\cdot\boldsymbol{d}^n \tag{9}$$

Where k is the stiffness coefficient, and the equilibrantcan be loaded as

$$\boldsymbol{f}_s^n = -\boldsymbol{f}_c^n \tag{10}$$

Then tranform the fluid force into the *i* point by the shape function $N_i$

$$\boldsymbol{f}_f^{i,n} = N_i\cdot\boldsymbol{f}_c^n \tag{11}$$

For solid element, $\sum_{i=1}^{8}\boldsymbol{f}_f^{i,n} = \boldsymbol{f}_c^n$ , which satisfy the acting force interaction princple on couping interface.

## 3. Numerical model

The numerical model for parafoil's cell FSI simulation is illustrated in Fig.1, of which the cell is inflated in billowing state, and meshed by the FEA elements. And the meshes of fluid field are built and formed by the simplifed ALE (SALE) technique during the simulation process. The SALE method only need the spacing and bunching laws on the edges of fluid field beforhand, and the structure mesh would automatically generated during the integration steps, which greatly decrease the solution time and improve the simulation efficiency for such complex explicit dynamics integration problems.

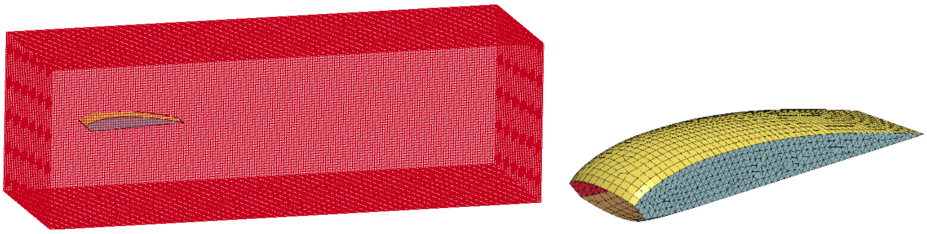
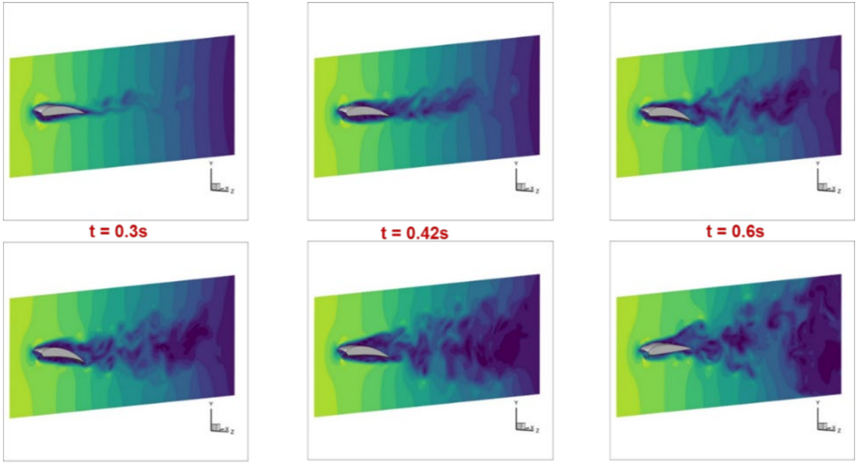


Figure 1 –FSI model of cell in billowing state.

## 4. Simulation results

## 4.1 Fluid field results

The simulation results including the velocity contours of fluid field is illustrated in Fig.2, from which you can see the evolution details of flow surrouding the structure during the trailing edge deflection process. The vorteies burn from the upper surface and gradually transits to the trailing edge, most of them are broken during the evolution process. The flow seperation phenomenon can also be seen from the figures, which is casued by the obvious low speed region on the upper of trailing edge when the deflection angle increases.



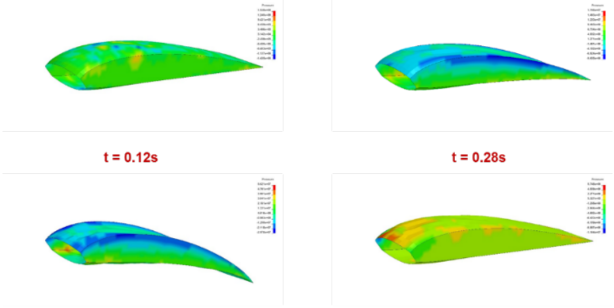
t = 0.3s t = 0.42s t = 0.6s

t = 0.66s t = 0.8s t = 1.2s

Figure 1 –Velocity contours of fluid field during trailling edge deflection process at time 0~1.2s

## 4.2 Structural field results

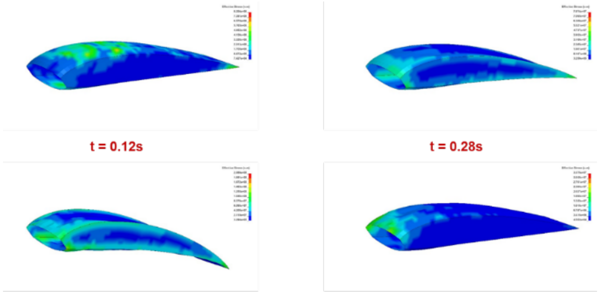
The structure field of cell's canopy under the aerodynamic pressures can also be obtained during the FSI simulation. As the Fig. 3 and Fig. 4 shows, the stress and pressure distributions on the canopy are nonuniform significantly during the deflection process. And the high stress region mostly concentrate upon the central forepart of upper surface, which would easily cause the stress concentration phenomenon on this area.



t = 0.12s t = 0.28s

t = 0.64s t = 1.2s

Figure 2–Structural stress distribution contours on cell's canopy during trailling edge deflection process at time 0~1.2s



t = 0.12s t = 0.28s

t = 0.64s t = 1.2s

Figure 3–Pressure distribution contours on cell's canopy during trailling edge deflection process at time 0~1.2s

## 5. Conclusion

The FSI dynamics problem for inflated parafoil cell during trailing edge deflection process is analyzed in this paper. The simulation results show: the SALE technique as well as the penalty method are effective for the FSI simulation of such large translation combined with the structure deformation behaviors, both the fluid and structure evolution details could be visualized to predict the dynamic behaviors of parafoil trailing edge delfection. All in all, the achievments in this paper could be a significant tool and support for the design of large parafoil precision airdrop system.

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## 7. Copyright Statement

## References

[1] J. Xiong, *Research on parafoil system dynamics and homing progress,* in, National University of Defense Technology, Changsha, 2005, pp. 167.

[2] Y. Han, C. Yang, H. Xiao, X. Xu, X. Yang, M. Cheng, *Review on Key Technology and Development of Parafoil Precise Airdrop Systems*, Ordnance Industry Automation, 31 (2012) 1-7.

[3] B. Richard, H. Mike, L. Kristen, M. Andrew, *DOD NEW JPADS PROGRAMS & NATO ACTIVITIES*, in: 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, AIAA, Seattle, Washington, 2009.

[4] R. Fox, J. Smith, T. Bennett, *Development of the NASA X-38 parafoil landing system*, in: 15th Aerodynamic Decelerator Systems Technology Conference, AIAA, Toulouse,France, 1999.

[5] W. Tang, *Deformation of a Ram-Air Canopy due to Control Line Retraction*, in, California State University, Northridge, Northridge, 2018.

[6] K.T. A, T.E.T. B, T.T. A, *Ram-air parachute structural and fluid mechanics computations with the Space–Time Isogeometric Analysis (ST-IGA)*, Computers & Fluids, 141 (2016) 191-200.

[7] N.A. Fogell, L. Iannucci, K. Bergeron, *Fluid-Structure Interaction Simulations of the Inflated Shape and Associated Flowfield of the MC4/5 Parafoil During Steady Gliding Flight*, in: 24th AiAA Aerodynamic Decelerator Systems Technology Conference, AIAA, Denver, Colorado, 2017.

[8] H. Altmann, *Fluid-Structure Interaction Analysis of an Isolated Ram-Air Parafoil Cell*, in: AIAA Aviation 2019 Forum, AIAA, Dallas, Texas, 2019.

[9] S. Nie, Y. Cao, *A Drichlet/Neumann Strongly Coupled Iterative Method for Fluid Structure Interaction of Parafoil Inflation Process*, in: Aiaa Aerospace Sciences Meeting, AIAA, Grapevine, Texas, 2017.

[10] W. XU, H. TENG, *A Simulation Research on Parametric Modeling of 3D-Parafoil Based on LS-DYNA*, Spacecraft Recovery & Remote Sensing, 3 (2015) 11-19.

[11] L. WANG, W. HE, *Parafoil aerodynamic deformation simulation based on cable-membrane finite element model*, Journal of Beijing University of Aeronautics and Astronautics, 43 (2017) 47-52.

[12] X. Gao, Q. Tang, Q. Zhang, J. Li, *Numerical Study on Fluid-structure interaction of Slot-parachute's inflation Process*, Acta Aeronautica et Astronautica Sinica, 34 (2013) 2265-2276.

[13] X. GAO, Q. ZHANG, Q. GAO, Q. TANG, T. YANG, *Numerical simulation on finite mass inflation dynamics of parachute*, Journal of National University of Defense Technology, 38 (2016) 185-190.

[14] X. Gao, *Research on multibody dynamics and fluid-structure interaction of parachute-body system*, in, National University of Defense Technology, Changsha, 2016, pp. 157.