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Fluid–Structure Interaction Simulation of Parachute by Eulerian–Lagrangian Penalty Method

Pak Sol Song[1,*], Hyong Gyu Jon[2], Kum Kwon Choe[3], Kwang Ho Kim[4], Jong Dok Ri[5]

Abstract

In general, modeling and simulation of a model consisting of fluid and solid combinations has been considered difficult, and it has become impossible in terms of computer dependencies and accuracy to be analyzed by Fluent or other programs. The parachute evaluation process, which is historically based on a large amount of experimental data, necessitates many falling experiments. These tests can be costly and time-consuming, and they do not always allow for a thorough knowledge of the dynamic behavior of the parachute. The opening load, drag characteristics, swinging angle, and other numerical simulation results agree well with wind tunnel testing. However, many attempts have been made to solve these problems worldwide, and many research groups have developed new programs with considerable effort. If the solid part is very deformable and nonlinear, such as parachutes or fabrics, this dedicated application is the most important tool for analyzing them. At present, the program is widely used for analysis that requires very high accuracy, such as air cushioning and the movement of bullet in air to ensure safe landing of the unmanned aerial vehicle. Several methods to simulate the parachute behavior have been suggested. Generally, it is very difficult to simulate the parachute characteristics because the parachute fabric has strong deformability and non-linearity. From the requirements, this article proposes a method of simulation of the inflation process of Ringsail parachute. The fluid–structure interaction (FSI) numerical simulation of the Ringsail parachute was constructed using the computational fluid dynamics/computation structural dynamics (CFD/CSD) and arbitrary Lagrangian-Eulerian (ALE) coupling techniques; the mathematical modeling of the FSI results of the parachute's collapse during the inflation the procedure was addressed using the computational infrastructure services of nonlinear finite element code LS-DYNA. The visualization of inflation forces that are canopy projected subject matter, and canopy deformation is obtained. Analysis was done on the FSI mechanism of parachute inflating. The results can be used to design of parachute compared with the experimental data. Our team will further study this field and focus on solving the problems presented here.

Keywords: Arbitrary Lagrangian Eulerian, Ringsail parachute, inflation, nonlinearity, fluid–structure interaction (FSI) method

***Author for Correspondence**
Pak Sol Song
E-mail: SS.PAK@star-co.net.kp

[1-5]Faculty of dynamics, Kim Il Sung University, Pyongyang, Democratic People's Republic of Korea

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INTRODUCTION

Generally, the airdrop process of the parachute can be divided into the following steps:

They are the inflation, descent, and landing phases, among which the divergence phase is most complicated. The expansion process is a typical fluid–solid coupling problem, which involves the interaction between elastic deformation and aerodynamic forces of flexible fabrics. Due to the porous and large deformation characteristics of the parachute fabric, the distribution of aerodynamic pressure is relatively complicated, which makes the flow field extremely irregular. By using theoretical methods and traditional experiences, it is difficult to accurately predict the dynamic behaviors of the parachute canopy and surrounding fluid. Recently, the field of parachute research has made extensive use of numerical simulation approaches, mostly because of the rapid advancements in current computational mechanics and computer technology [1–4]. Russia introduced this technique in parachute research in early 1970s and developed a relatively complete mathematical model for the whole operation of the parachute using the discontinuous vortex method and the large particle method [5, 6]. In the past, a method has been developed to model and analyze the fluid–structure interaction (FSI) characteristics of parachutes using LS-DYNA software [7, 8]. Using the new arbitrary Lagrangian-Eulerian (ALE) finite element method within the LS-DYNA software, this paper provides a physical insight into the annular slot parachute in airdrop tests. The simulation results were obtained under constant velocity of the incoming air. This study can be used for the simulation of the drop test. The simulation of the expansion process of the annular slot parachute is very complicated at low speeds. FSI problems can generally be solved by analytical and non-analytical methods, but these two methods have many limitations in solving completely complex problems, such as parachute inflation, so it is much more efficient to use numerical methods.

Interaction of Fluid and Structure

In FSI, fluid and solid mechanics are coupled, with the fluid's motion influencing the structure's deformation and the structure's response changing the flow field. This interaction is crucial when it comes to parachutes since the airflow surrounding the canopy affects the parachute's inflation, deployment, and overall stability. Complex numerical methods capable of precisely modelling both the fluid flow and the structural response are needed to simulate these interactions.

Numerical simulation methods based on the coupling method between fluid and structure can be classified into two groups: segmentation method and single analysis method.

SIMULATION METHOD

The Approach of Eulerian–Lagrangian Penalties

Since the parachute's descent has a comparatively slow rate of divergence, the fluid field can be thought of as an incompressible stream. A computer method for tackling FSI issues that combines the benefits of both Eulerian and Lagrangian descriptions is the Eulerian–Lagrangian penalty method. Considering the complex structural dynamics (SD) and fluid dynamic (FD) characteristics of the parachute, we must first propose some assumptions as follows.

Eulerian Framework

This method solves the governing equations on a stationary grid while representing the fluid in a fixed spatial domain. This works great for capturing the turbulence and intricate fluid flow patterns surrounding the parachute canopy.

Lagrangian Framework

A moving coordinate system that tracks the material points represents the structure, including the suspension lines and parachute canopy. This makes it possible to accurately model material behavior and massive deformations.

Penalty Method

A penalty term is included to guarantee that the fluid and structural domains are compatible. In essence, this term couples the fluid and structural equations by enforcing the no-slip boundary condition at the fluid–structure interface.

1. No prestress exists before expansion becomes axisymmetric.
2. A fluid with low velocity is thought to be incompressible.

A perfect fit between fundamental and fluid meshes is generally unachievable.

The transformation of structural and fluid node information was implemented by the Eulerian–Lagrangian penalty coupling algorithm.

One important method for ensuring the energy conversation in FSI issues is the computation of the coupling interface. In general, complete matching between the structural and fluid meshes cannot be implemented. The Eulerian–Lagrangian penalty coupling algorithm is responsible for implementing the transformations of the structural and fluid nodes information. The solid circles represent the fluid element nodes, while the hollow circles represent the structural membranes element nodes in the network These nodes' locations can be derived from the local reference of ALE fluid elements, allowing for the tracking of the structural joblessness nodes and the application of coupling force.

Using the fluid as a medium with holes, the following equation is gradually updated in the explicit dynamic incremental approach when the time increment reflects the structural nodes' consequence level.

$$t = t^n, \vec{d}^n. \vec{d}^{n+1} = \vec{d}^n + \vec{v}^{n+1/2} \Delta t \tag{1}$$

$\vec{v}_r$ is the reference velocity of acquire and slave nodes, which are the slave node velocity is $\vec{v}_s$, whereas the master node acceleration can be considered as a fluid particle within a fluid component, with the mass and velocity processed from the fluid component nodes using finite element transform functions, thus

$$\vec{v}_r^{\,n+1/2} = \vec{v}_s^{\,n+1/2} - \vec{v}_f^{\,n+1/2} \tag{2}$$

Penalty occurs if

$$\vec{n}_s \vec{d}^n < 0 \tag{3}$$

To achieve force equilibrium on the connection interface, the coupling forces must be applied in a different direction to the slave and master nodes. However, for the master nodes, the connecting force can be dispersed based on shape functions N_i at every node *i*, so

$$F_f^i = N_i F \tag{4}$$

The coupling interface satisfies the action-reaction fundamental terms. We can use the Eulerian–Lagrangian penalty connection technique in the LS-DYNA program to solve such aerodynamics finite element representations of parachute expansion when they are developing. The Lagrangian algorithm should be chosen by the structure elements, the Eulerian algorithm by the fluid elements, and the penalty approach can guarantee the transmission of FSI information on the coupling interface.

Fluid and Parachute Models

In many applications utilizing FSI modeling, accurate comparisons require a constant starting condition. Establishing conditions are particularly crucial while examining the unstable characteristics. Several methods for constructing FSI initial conditions are documented in references [8, 9]. The main goal of these methods is to gently begin the FSI computations. Making the starting circumstances consistent and matching what was seen during NASA (National Aeronautics and Space Administration) drop experiments is the main goal of further enhancing the starting condition with the approaches shown here. PC (Parachute) clusters are used in a parallel processing environment for all computations disclosed in this research. To improve the computations' parallel performance, the meshes are divided. The METIS [3] algorithm is the foundation for mesh partitioning. The canopy structure mesh and the fluid mechanics interface mesh for a parachute as shown in Figure 1. There are 18900 two-node cable elements, 54332 four-node quadrilateral membrane elements, and 82305 nodes in the structure [10, 11].

The canopy contains 29,200 nodes. There are 4180 three-node triangle elements and 2140 nodes in the fluid mechanics interface mesh. First, we construct the initial state of this one parachute. Starting with a parachute shape that was produced using the symmetric FSI computation described in reference [12], we proceed. We perform an additional symmetric FSI computation with a horizontal inflow velocity of 285.0 feet per second (ft/s) [13–16]. Next, we create two meshes for quadrilateral dynamics of fluids. Using the semi-discrete formulation provided in reference [17], we first do a fluid mechanics calculation with the cluster mesh while maintaining the parachute forms and placements fixed. There is a 285.0 ft/s inflow. With a time-step size of 0.174 s and seven nonlinear iterations per time step, we calculate 400-time steps. After that, we perform another fluid mechanics simulation with the same input velocity while maintaining the fixed forms and placements of the parachute. The Eulerian fluid is described using the equation of state and material attributes. Using a coupling technique centered around the penalty method, the ALE method provided in LS-DYNA is used to model the fluid structure interaction. The coupling approach also incorporates an Ergun law-based permeability mechanism. To prevent excessive computation time, the hydraulic system and their suspension lines/rises are not linked.

There are 54332 three-node triangle membrane components, 18900 two-node cable elements, and 82305 nodes in the structure [18]. The canopy contains 29200 nodes. The flexible fabric for the parachute is shown in Figure 2.

There are 24980 four-node quadrilateral components and 6280 nodes in the fluid dynamics interface mesh. All the parameters with their values are mentioned in Table 1.

RESULTS AND DISCUSSION

The fluid is entering at a speed of 80 m/s. In this paper, we considered the complete inflation process. From the simulation results of the expansion process, after the complete inflation of the parachute, the air flows into the parachute at about 3.3 s as shown in Figure 3, no re-swelling occurs, and only elastic deformations occur [19]. This is due to holes drilled in the parachute. As can be seen from the results, as the parachute expands, the velocity of the air leaving the breathing cavity increases gradually. Fluid Particles around the groove influence the resistance of the flow rate of air [20, 21]. The velocity of the upper air globules is higher than below, so the pressure is lower. This pressure difference has a positive effect on the divergence of the parachute. Velocity vector and stress distribution simulation at 0.7 s is shown in Figure 4. Velocity vector and stress distribution simulation at 3.3 s is shown in Figure 5.

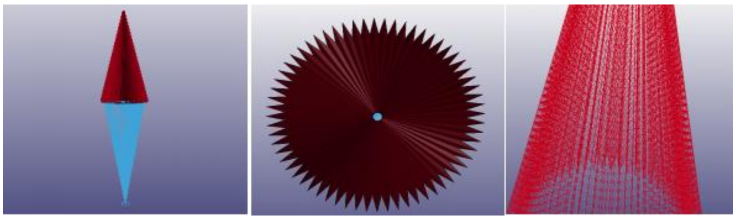

Figure 1. Canopy structure mesh for a parachute.

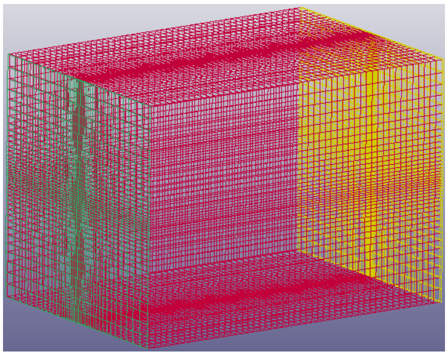

Figure 2 Flexible fabric for a parachute.

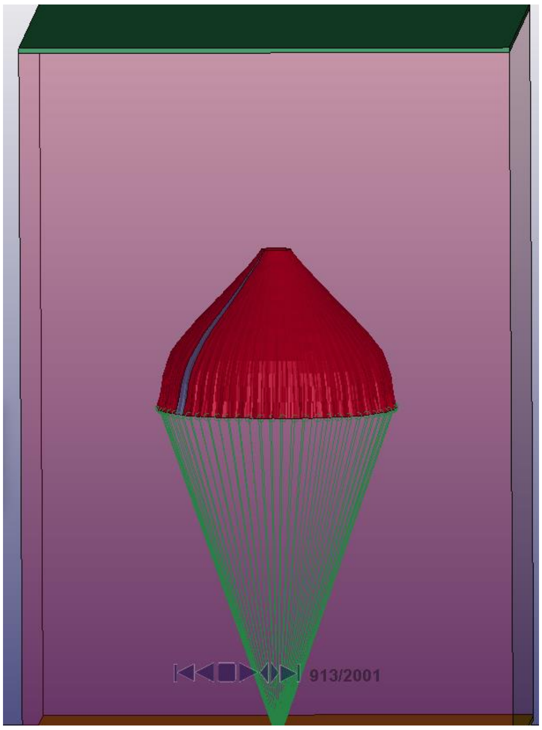

Figure 3. Shape of a parachute after complete inflation (3.3 s).

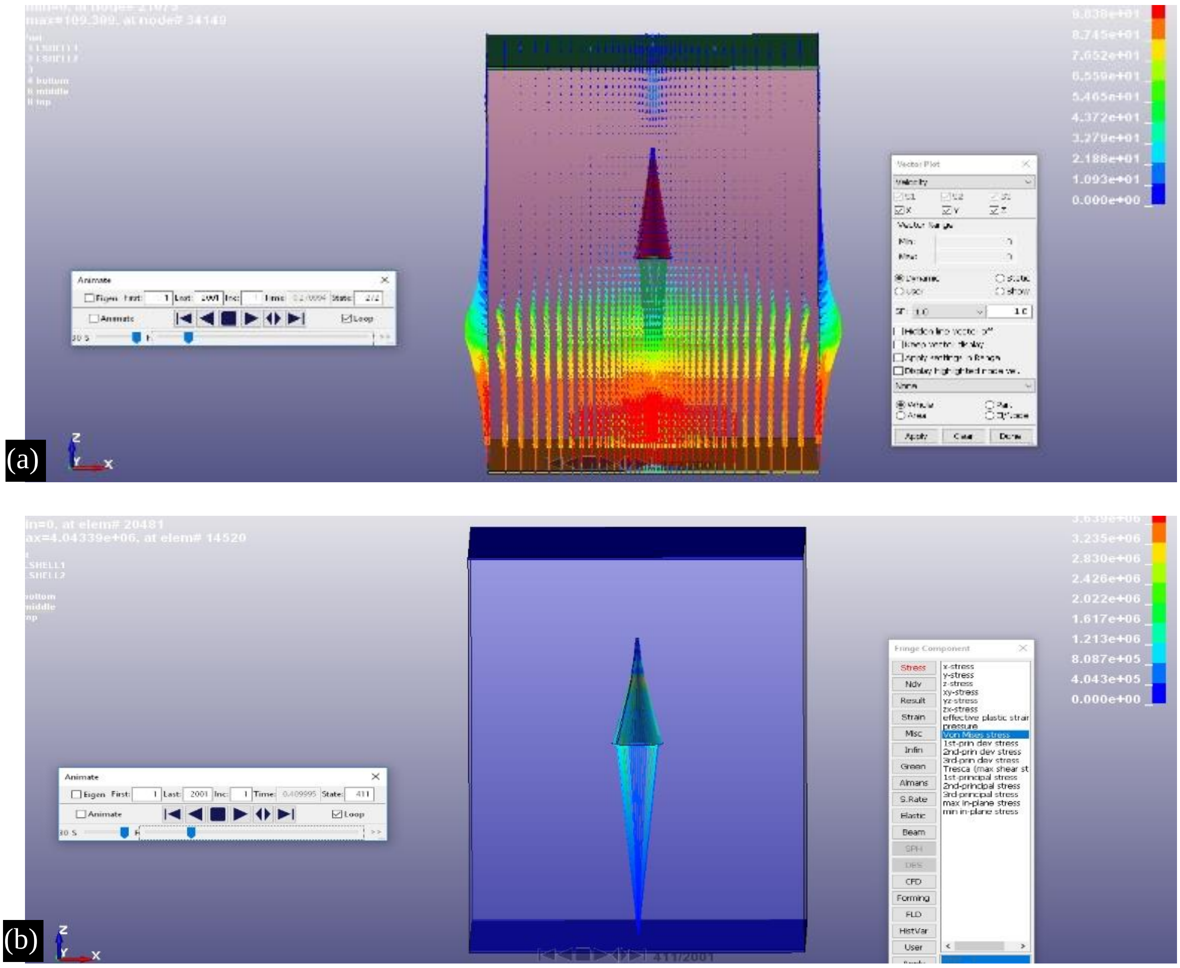

Figure 4. (a) Velocity vector (0.7 s) and (b) stress distribution (0.7 s).

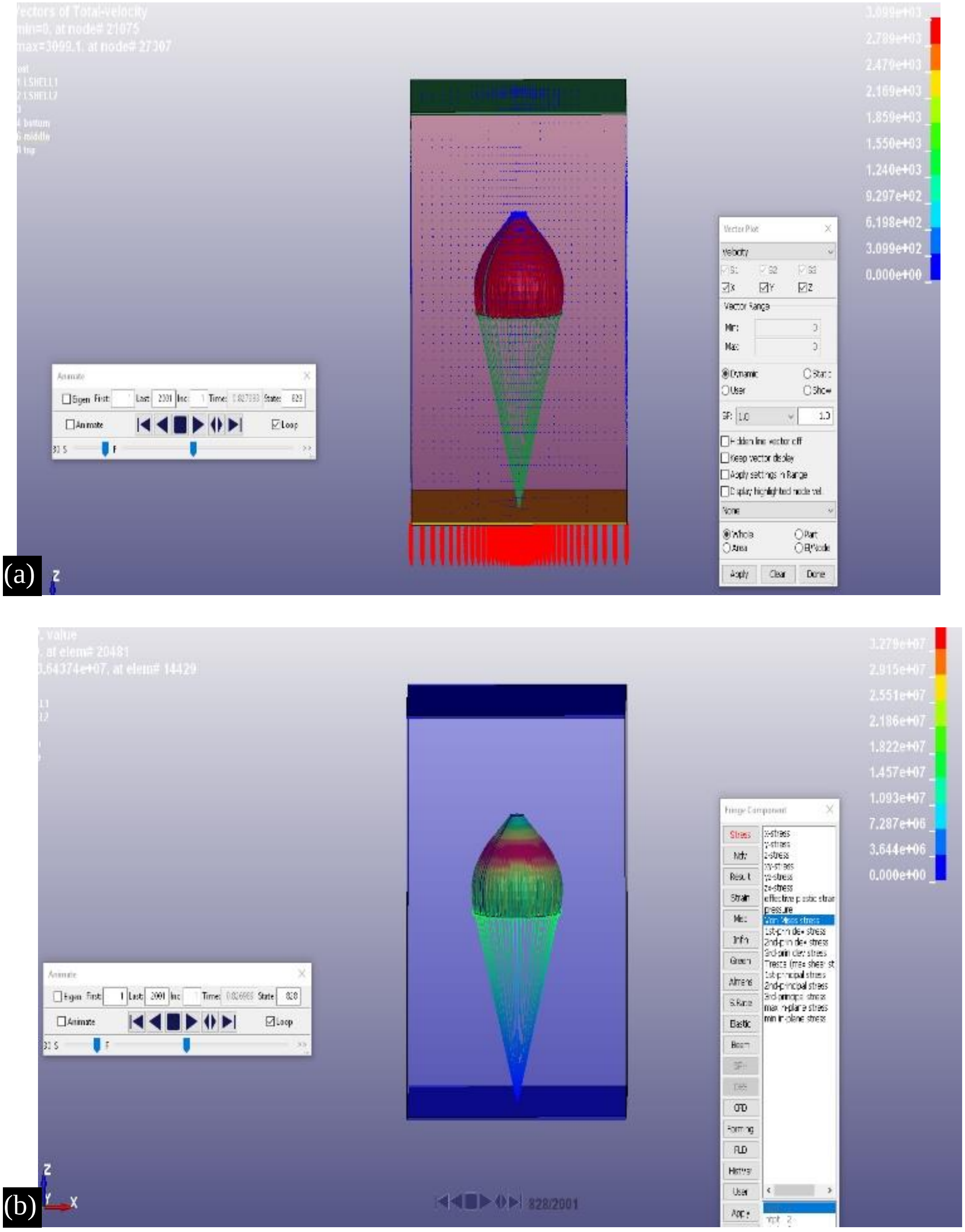

Figure 5. (a) Velocity vector (3.3 s) and (b) stress distribution (3.3 s).

Table1. Parameters of parachute.

Parameter	Value	Unit
Load mass	450	kg
Acceleration due to gravity	9.81	m/s^2
Air density	1.225	kg/m^3
Falling speed	6.00	m/s
Coefficient	0.8	
Nominal diameter	18.81	m
Manufactured diameter	16.93	m
Area of canopy	450	m^2
Number of lines	63	
Length of line	21.64	m

From the simulation results, the parachute can still maintain a reliable asset capacity, which is due to the large circulating resistance in the groove made on the cloth.

CONCLUSION

- In this paper, the expansion process of ring slot parachute is studied.
- The parachute inflation dynamics were studied by modeling techniques of the FSI finite element model and the ALE coupling algorithm.
- Both the structure of the parachute and the numerical simulation models of the surrounding fluid were developed by computational mechanics method and the results of three-dimensional shape deformation and expansion process of the parachute were obtained using the ALE finite element method.
- The divergence problem caused by the narrow groove of the parachute fabric was also solved.
- The numerical simulation methodology and techniques used in this paper can be generalized in the field of parachute simulation and can be used to study dynamic problems for other types of parachutes.

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