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Improvements in Fluid Structure Interaction simulations of parachutes using LS-Dyna®

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The French Ministry of Defence's procurement agency, the Direction Générale de l'Armement (DGA), is in charge of assessing and testing armament systems in order to equip the armed forces and prepare for the future. DGA Aeronautical Systems, the technical centre dedicated to evaluate and test aircraft, combines test and evaluation to clear, among others, parachute systems. The parachute evaluation is historically based on experimental data and so requires numerous flight tests which can prove expensive and time consuming. In order to have a greater understanding of the parachute dynamic behavior and to optimize the parachute systems flight tests, DGA Aeronautical Systems developed a modeling and simulation capability as a support to evaluation. For this purpose, DGA Aeronautical Systems, with the help of ISAE, developed Fluid Structure Interaction (FSI) simulations of parachutes using the LS-Dyna commercial Finite Element Analysis (FEA) tool. This tool is largely used for solving highly nonlinear transient problems and enables doing coupled multi-physics simulations such as FSI simulations. DGA Aeronautical Systems has been using the software since 2003. In the recent years, the parachute simulation has been much improved thanks to the implementation of a porosity algorithm in LS-Dyna at the common request of DGA and parachute industry. The paper presents recent improvements in Arbitrary Lagrangian Eulerian (ALE) techniques used to analyze the canopy inflation and the quasi-steady state descent phases characteristics. Up to now, only infinite mass type simulations were developed by constraining the parachute confluence point and applying a prescribed airflow to the fluid. The applied airflow velocity came from real in-flight measurements of paratrooper or load trajectory determinations. This simulation type is representative to wind tunnel tests. From now on, thanks to considerable computational resources, finite mass type simulations are also possible. It consists in applying the force of gravity to the parachute system. This allows simulating both the inflation phase (from vertical packed parachute geometry) and the quasi-steady state descent. Among others, the static line parachute of the new French Army troop parachute system called EPC (Ensemble de Parachutage du Combattant) was modeled at real scale. Modeling techniques are presented and results of the EPC static line parachute simulation are compared with real in-flight measurements. The benefits of FSI simulations prior to parachute testing are presented. In a near future, incompressible and compressible Navier-Stokes solvers will be available in the next version of LS-Dyna. These code enhancements will be tested to simulate the parachute flight and hopefully will bring the ability to analyze more accurately the aerodynamics of the canopy and the structural behavior of the fabrics. These future capabilities are also discussed.

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I. Introduction

THe Airmobility Division of DGA Aeronautical Systems, formerly known as CAP (Centre AéroPorté) and then CEV-Toulouse (Centre d'Essais en Vol, Toulouse Test Base), is the Direction Génerale de l'Armement (DGA) body in charge of test and evaluation of parachute systems for the French Army.

Historically based on experimental data, the parachute evaluation often requires numerous flight tests, which can prove expensive and time consuming, and which do not always permit to reach a good understanding of the parachute dynamic behavior. As a support to evaluation activity, DGA developed a modeling and simulation capability. Parachute flight simulation is a complex problem since it requires the dynamic behavior analyze, notably the inflation, of a very thin porous deformable fabric membrane coupled with the surrounding fluid flow. For this purpose, some numerical methods exist to analyze either the structural behavior using CSD (Computational Structural Dynamics) method or the fluid flow behavior using CFD (Computational Fluid Dynamics) method. However, the FSI (Fluid Structure Interaction) method is more adapted since it allows analyzing the interaction of a movable and deformable parachute structure with the surrounding air flow.

In the 1990's, the first FSI simulations of parachutes were developed at DGA. The platform used, named SINPA (SImulation Numérique du PArachute) a French abbreviation for numerical simulation of parachutes, allowed coupling two finite element analysis implicit commercial codes, a fluid solver named N3S and a structural solver named SAMCEF, to analyze fluid structure interactions[1-3]. This coupling method, in which the structural and the fluid responses are calculated separately in two codes, is often referred as partitioned approach. This coupling method gave good results, allowing for example to determine the lift-to-drag ratio and the in-flight canopy shape of a ram-air parachute, but was quite complex to use since the method required a stable coupling algorithm. This method was also computational cost consuming due both to data transfer time from code to code and to fluid re-zoning and re-meshing. In 2002, ENSICA, now called ISAE (Institut Supérieur de l'Aéronautique et de l'Espace) since 2007 following the merger between the two engineering schools SUPAERO and ENSICA, helped DGA to develop the capability of simulating parachute systems[4] with the LS-Dyna code[5]. This commercial finite element analysis tool allows solving FSI problems using a coupling code. Taylor, Tutt and their colleagues[6-11] as well as Lingard and his team[12-14] have also applied it to parachutes systems. This second FSI method, in which the structural and the fluid responses are calculated simultaneously in a single code, is often referred as monolithic approach. The different FSI approaches to simulate ADS (Aerodynamic Decelerator Systems) problems were analyzed and compared by Charles and his colleagues[15]. DGA has been using LS-Dyna to conduct FSI simulations of parachutes since 2003, as a support to test and evaluation.

The simulations presented in this paper were conducted using version 971 of the LS-Dyna solver. The workstation used was a PC with four 64-bit bi-core processors and 24Go of RAM. The simulations were run using only 6 cores with MPP (Massively Parallel Processor) computing form. The pre processing and post processing activities were conducted using LS-Prepost version 2.4 or 3.0.

II. Modeling techniques

The parachute structure, created from the parachute constructed profile geometry, is modeled using a Lagrangian formulation. The parachute fabric is composed of four-nodes membrane elements which are simplified shell elements with only in-plane admissible loads (no resistance to bending for example). As shown in Fig. 1, the ribbons, suspension lines and risers are composed of seatbelt elements which are simplified cables/beams with no flexion stiffness. The fabric material is an elastic and orthotropic material which allows using different Young modulus in fill and warp directions. If necessary, a dummy simulating a paratrooper is used and the risers of the parachute are attached to the dummy shoulders in two points. The dummy is modeled as a rigid body. In this way, no strain/stress is computed in the dummy.

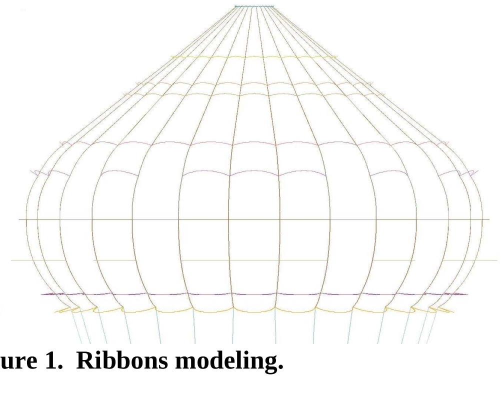

Figure 1. Ribbons modeling.

The fluid flow is modeled using an Eulerian formulation and is composed of ALE (Arbitrary Lagrangian Eulerian) solid elements. This formulation, compared to the Lagrangian formulation, allows the detachment of the material movement from the mesh movement. During a simulation time step, after the common motion of the material and the mesh, the mesh is put back to its original or user-defined position and the material data follow an advection process. Thus, no mesh distortions of the fluid volume occur, avoiding to lead to wrong results or to increase the computational run time.

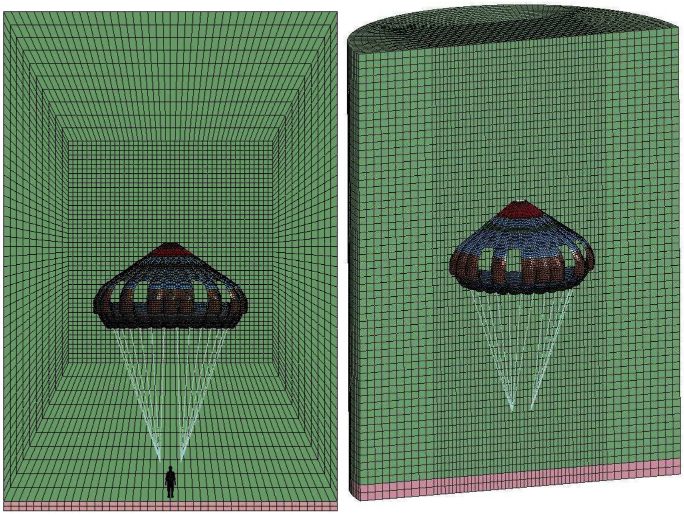
a) b)

Figure 2. Parallelepiped (a) and cylindrical (b) fluid volume modeling.

When considering infinite mass type simulation, ambient elements with constant pressure inflow are placed at the bottom of the fluid volume as shown in pink color in Fig. 2. This method will be explained afterwards in the paper. The fluid volume surrounding the parachute structure is a cylinder or a parallelepiped meshed using butterfly blocks options of the LS-Prepost mesher. The fluid is finely meshed in the center, so close to the parachute fabrics where the precise analysis of the fluid structure coupling behavior is desired, and coarser close to the fluid volume boundaries where the fluid is not perturbed by the parachute, as shown in Fig. 2. Material properties and equation of state are defined to characterize the Eulerian fluid. In the model presented in part b) of Fig. 2, the fluid volume is coarsely meshed and the cylinder is around 25m high and 10m in diameter.

To simulate the fluid structure interaction, the ALE method included in LS-Dyna is used with the coupling algorithm based on the penalty method. A permeability algorithm based on Ergun law is also implemented in the coupling method[16,17]. The suspension lines/risers and the fluid are not coupled in order to avoid high computational time consumption.

III. Infinite mass type simulations

Infinite mass type simulations were developed by constraining the parachute confluence point (or the dummy) and by applying a prescribed airflow to the fluid. This simulation type is representative of wind tunnel tests.

A. Steady-state descent phase analysis

If only the steady state descent phase analyze is required, the constructed profile model is placed in the fluid flow at a desired velocity. Once the steady state phase is reached, the parachute drag force is obtained and can be compared to in-flight measurements.

The first analyses of parachutes in flight were conducted on cross parachutes used as extraction parachutes. This kind of parachutes has a very simple constructed profile; it consists in sewing together two fabric strips as shown in Fig. 3. Moreover, the inflated profile being highly different from the constructed profile, the fluid structure coupling feasibility was easily demonstrated.

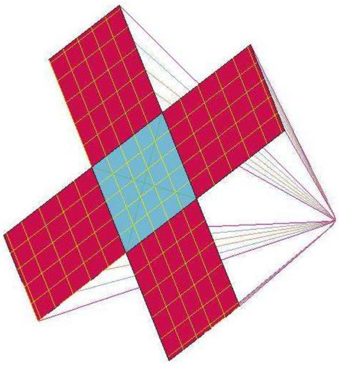
Figure 3. Constructed profile of a cross parachute.

In this simulation case, the applied fluid velocity is the aircraft speed with the hypothesis of a constant laminar flow behind the aircraft. This simple technique does allow analyzing the quasi-steady state descent parameters as for example the inflated profile or the resulting drag. The difference between a porous fabric and a non-porous fabric on the inflated profile can be easily compared as shown in Fig. 4. Thanks to the addition of the porosity algorithm in LS-Dyna, the accuracy and quality of the simulations were significantly improved during the last years. The resulting drag force with the non-porous fabric was 20% higher than the theoretical drag force. Adding the porous fabric modeling, the resulting drag force is 2370daN for a measured drag force of 2400daN.

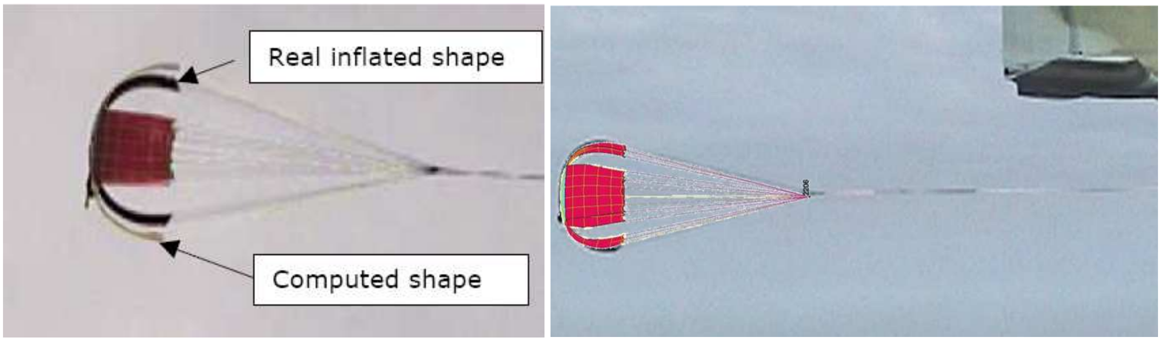

Figure 4. Superimposition of the in-flight inflated profile with the computed one for a non-porous fabric on the left and the correct porous fabric on the right.

After having demonstrated the feasibility on simple problems, the technique was applied to personnel parachutes. The new French Army static line parachute called EPC (Ensemble de Parachutage du Combattant) was modeled. When using infinite mass type simulation for personnel parachutes, the dummy is constrained and the prescribed airflow velocity is the rate of fall determined by in-flight measurements. Figure 5 shows the computed and in-flight inflated profiles of the EPC parachute.

Figure 5. Real and simulated inflated profiles of the EPC.

Numerous simulations with applied rates of fall corresponding to the paratrooper mass range were conducted in order to obtain the corresponding drag forces. The flow velocities field and pressures field were analyzed and gave expected global results.

In order to save computational run time, after a first simulation with an important fluid volume, this volume can be simply adjusted according to the fluid flow perturbations around the parachute. Moreover, after having validated the numerical methods on a full-size parachute, simulations on a ¼ symmetry model, illustrated in Fig. 6, were conducted in order to optimize simulation time. Full-size model results and ¼ symmetry model results were compared on a few chosen parameters which gave entire satisfaction. This time saving allows increasing the elements number in order to assess the quality and accuracy gain while having a reasonable simulation time.

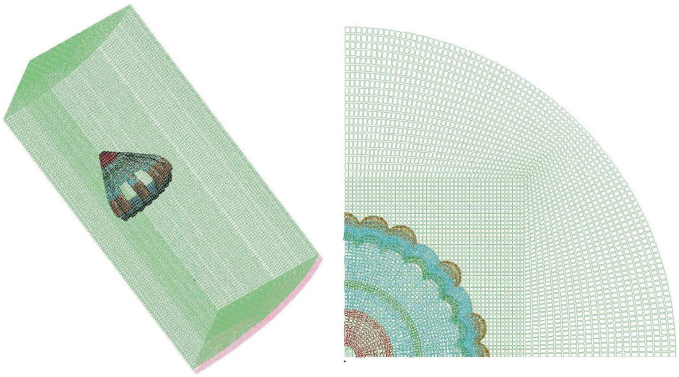

Figure 6. A ¼ symmetry model of the EPC parachute.

For first steady state descent analysis, the dummy was coupled with the fluid in order to evaluate its influence on parachute behavior. The fluid perturbations due to the dummy had no influence on the parachute and consequently the coupling between the fluid and the dummy was omitted in other simulations.

Figure 7 and Figure 8 show the fluid velocity vectors, on different sections, colored according to the velocity magnitude and pointed according to the flow direction. In Fig. 7, the fluid flow passing through the vents can be visualized and shows an increase in fluid velocity at these locations.

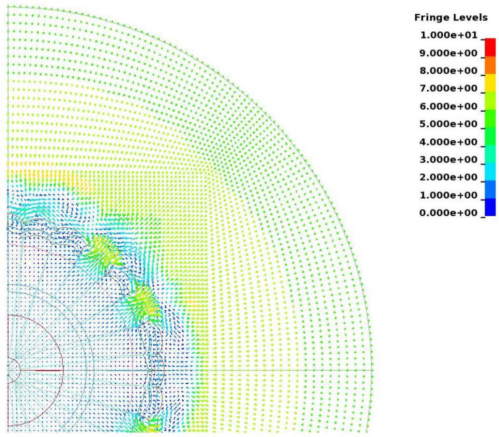

Figure 7. Fluid velocity vectors on a horizontal section through vents.

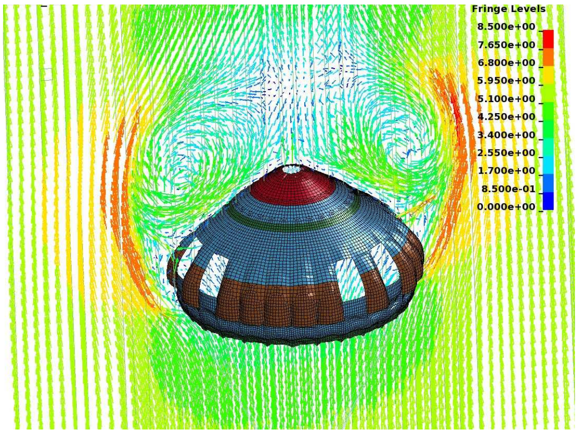

Figure 8. Fluid velocity vectors on a vertical section.

B. Inflation phase analysis

To simulate the inflation phase, the parachute initial geometry is not the constructed profile but a straight line vertically folded profile which corresponds to the parachute shape just after it leaves the deployment bag. The first state of the inflation simulation is much simplified compared to the folded and packed parachute geometry which was not modeled during the study. Nevertheless, the numerical technique to fold a fabric exists and can be conducted using LS-Dyna. For example, the capability of folding airbags[18] has been demonstrated for many years and is now commonly used by automobile industry. However, the difference of size between an airbag and a parachute and the relative complexity of folding and packing a parachute make it difficult to simulate, particularly due to computer resources limitations.

To get the initial geometry prior to inflation, a parachute forming phase is conducted without using fluid. The technique consists in applying a dynamic traction on the parachute apex until reaching the expected geometry and then verifying that there is strain neither in the fabric nor in the suspension lines/risers. Other techniques were also conducted as for example applying the gravity to the structure and constraining the apex. The main problem to take into account during this phase is the contact control since the resulting folded geometry highly influences the quality of the numerical inflation phase following. In order to have a neatly done geometry and to simplify contact control problems, small mass were added to some nodes located on the leading edge. These numerical mass were only added during the parachute forming phase and were removed before the inflation phase.

Figure 9. Drop of a small hemispherical parachute.

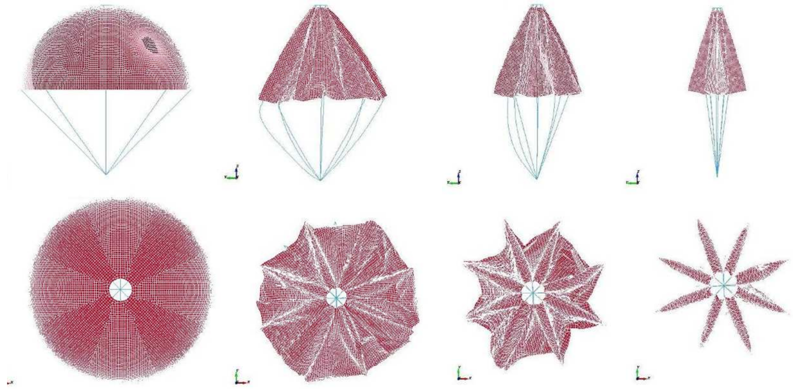

Figure 10. Parachute forming process using added mass.

In Fig. 10, different steps of this parachute forming process are shown on a small home made hemispherical parachute. This 4.2m² hemispherical parachute was designed in order to conduct a series of drop tests from the tower represented in Fig. 9. The payload was highly instrumented in order to evaluate strain sensors for parachute fabric and to compare flight test with simulation.

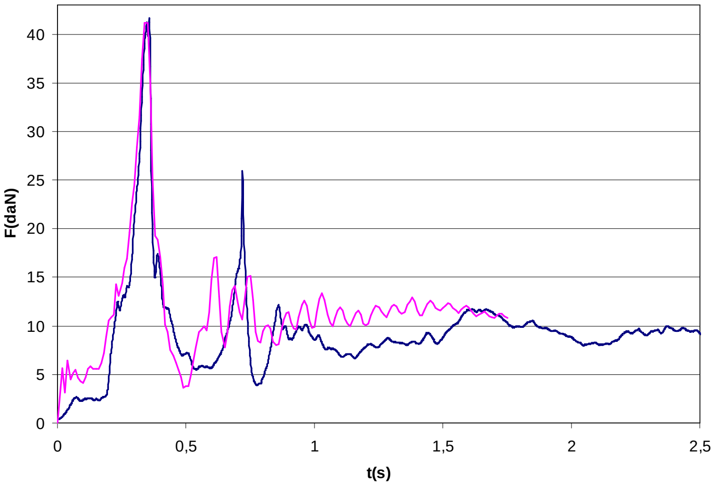

Figure 11. Drag force at the confluence point versus time. Simulation (in pink) and flight test (in blue).

Figure 12. The folded geometry.

The vertically folded geometry shown in Fig. 10 was used to inflate the parachute. The simulated inflation results were compared with high speed camera images and measurements from the acquisition system which was synchronized with the camera. The maximum drag force and the inflation time were validated as shown in Fig. 11. The second drag force peak corresponding to the parachute breathing was higher than <predicted. Figure 13 illustrates the fabric stress mapping in fill and warp directions at the opening shock time. Unfortunately, at the time of this writing, the strain comparison between tests and simulation is not yet conducted.

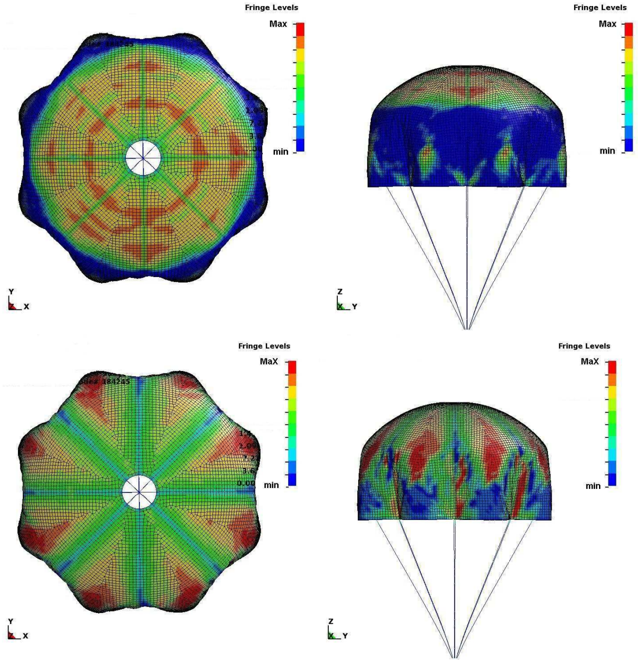

Figure 13. Stress mapping, in fill and warp directions, at the opening shock time.

Inflation analysis was also performed on the EPC parachute. The vertically folded geometry prior to inflation is shown in Fig. 12. The maximum diameter of the numerically folded geometry is 1,6m. The inflation simulation was validated thanks to flight tests conducted on the EPC parachute from a balloon. The parachute speed at the deployment phase end was obtained by analyzing both in-flight video and flight path measurement. This velocity was applied as initial condition to the vertically folded geometry prior to inflation.

Figure 14 compares the computed profile with the in-flight real profile at different times during the inflation. The fluid flow circulation through vents during inflation has been analyzed. The comparison results obtained are very encouraging.

Figure 14. Real and computed profiles compared at different times during the opening.

IV. Finite mass type simulations

After having increased the parachute geometry complexity, the modeling technique was also improved. Finite mass type simulations were developed, modeling the parachute drop. The method consists in applying the gravity to the parachute system and the dummy. For a given paratrooper mass, the inflation and steady state descent can be analyzed. Compared to the infinite mass type simulation, no prescribed velocity is required during the simulation time. Only the initial velocity has to be provided.

As explained previously, the ALE formulation allows the detachment of the material movement from the mesh movement. For infinite mass type simulations, the fluid mesh is fixed in space whereas, for finite mass type simulations, the fluid mesh is mobile. In other words, during a time step, the fluid Eulerian mesh moves with the fluid material and then is put back to a position depending on the Lagrangian mesh position. Different methods to control the Eulerian mesh relaxation exist in LS-Dyna. In this study, the fluid mesh is controlled by the dummy motion. Tutt and his colleagues shew a first application of this technique on scaled models[11].

Finite mass simulations were first conducted on the small hemispherical parachute and then on the EPC parachute, from the constructed profile and from the vertically folded profile. Figure 15 illustrates the inflation simulation of the EPC parachute from the folded configuration illustrated in Fig. 12.

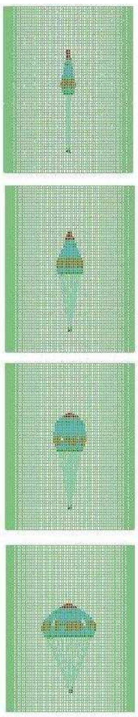

Figure 15. Finite mass simulation of the EPC parachute.

V. Ongoing work

Finite mass type simulations are being developed for classic static line parachutes airdrop applications by simulating the parachute drop from a curved folded geometry. In-flight damaged parachutes performance is also going to be studied by simulating cases with suspension lines breakages or gore tears.

Currently, incompressible and compressible Navier-Stokes solvers are being developed in LS-Dyna and should be available in the next version. These CFD solvers will allow to conduct FSI simulations and will hopefully bring the ability to analyze more accurately the fluid flow and as a consequence the structural dynamic behavior. However, these new capabilities should require more computer resources than the ALE technique does and a porosity algorithm implemented in these new coupling algorithms would be necessary for parachute systems application.

VI. Conclusion

FSI simulations of parachutes with the commercial finite element analysis tool LS-Dyna give encouraging results in predicting in-flight measurements and analyzing parameters hard to measure as fluid flow.

Currently, the main limitations are due to computational run time. In particular, the use of the porosity model highly increases the run time. However, with the fast development of high-performance computing and parallel computing, new parachute systems simulations should be demonstrated in the next years.

Acknowledgments

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