The Application of a New Material Porosity Algorithm for Parachute Analysis

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Abstract

This paper documents the simulation of parachute performance and the role of LS-DYNA in the design of parachutes at Irvin Aerospace Inc. It has long been known that fabric permeability is an important weapon in the arsenal of a parachute designer. In the careful balance of payload rate of descent and parachute stability, the permeability of the parachute material often plays a vital role. The substitution of an impervious material with a highly permeable fabric can turn a parachute from a wandering sloth into a plummeting stabilizer. An accurate consideration of fabric permeability has long eluded the parachute designer. The implementation of a penalty coupling method to describe the interaction of components defined by Eulerian and Lagrangian formulations permits the effect of fabric permeability to be accounted for within the coupling definition. The majority of this paper discusses the implementation of a new porosity algorithm that allows the effect of fabric permeability to be accurately assessed. Correct consideration of material permeability has existed within LS-DYNA for many years, however, these methods were only accurate for the applications originally conceived, namely the airbag. Although both parachute and airbag analyses investigate fabric structures, they differ in many respects, perhaps most significant is that the parachute designer is as concerned about the air that has passed through the parachute as he is with that remaining inside the parachute. Whereas the air that has passed through the airbag is of minimal concern to the automotive engineer. The influence of the air once it has passed through the structural medium can now be assessed within LS-DYNA. This paper provides a level of validation for the technique when considering parachute applications and discusses the importance of this breakthrough to the parachute designer.

Introduction

Parachute behavior can be described as a complex interaction between a highly deformable structure and the fluid through which it flows. To appropriately simulate, and therefore understand and predict, this behavior requires an accurate method of assessing this complex relationship. Analysis of a parachute or a flow field without its associated partner is excluding the inherent interaction between the two. The author has previously published data that describes the use of Fluid Structure Interaction techniques within LS-DYNA to replicate parachute behavior[1]. That work discusses the benefit of visualizing the flying shape and anticipating the performance of a newly designed tactical mass assault troop parachute, prior to fabrication and testing. The study exposed the inability to consider fabric permeability as an authentic limitation that would restrict the application of the methodology for a number of applications.

This paper discusses the application and validation of a penalty coupling method that enables the affect of fabric permeability to be accounted for within the Arbitrary-Lagrange-Euler (ALE) coupling definition. A more thorough description of the numerical approach and algorithm implementation is provided by Aquelet et al[2].

It should be noted that consideration of material permeability already exists in the penalty coupling method utilized for fluid-structure interaction models within LS-DYNA. Version 970 and earlier includes a load curve look-up flag defining porous flow through the coupling segment within the *CONSTRAINED_LAGRANGE_IN_SOLID keyword card. When this parameter is activated, the mass that needs to be vented is removed from the gas mass and discarded from the simulation. The removed mass is recorded in the dbfsi file. This method was originally conceived for airbag applications within the automotive industry, and is an appropriate simplification for these analyses. In the majority of cases the automotive engineer is wholly concerned with the gas remaining inside the airbag as opposed to that escaping through the enclosing material.

This approach has limited benefit to the parachute engineer. The fluid, generally air, which passes through the parachute, is of critical importance to the design and performance of a parachute.

Fabric Permeability and Parachute Design

Two forms of porosity are considered in parachute design; geometric porosity and fabric permeability. Geometric porosity is defined as the ratio of all open areas or physical gaps to the total canopy area. Fabric air-permeability is defined as the airflow through the canopy cloth in CFM/ft^2 (cubic feet per minute per square foot), at ½ inch water pressure. When considering parachutes consisting of both geometric porosity and fabric permeability, a term referred to as equivalent porosity is often used. The Space Shuttle Orbiter landing-brake parachute, and fighter aircraft spin/stall recovery parachutes, see Figure 1, are examples of parachutes containing high geometric porosity.

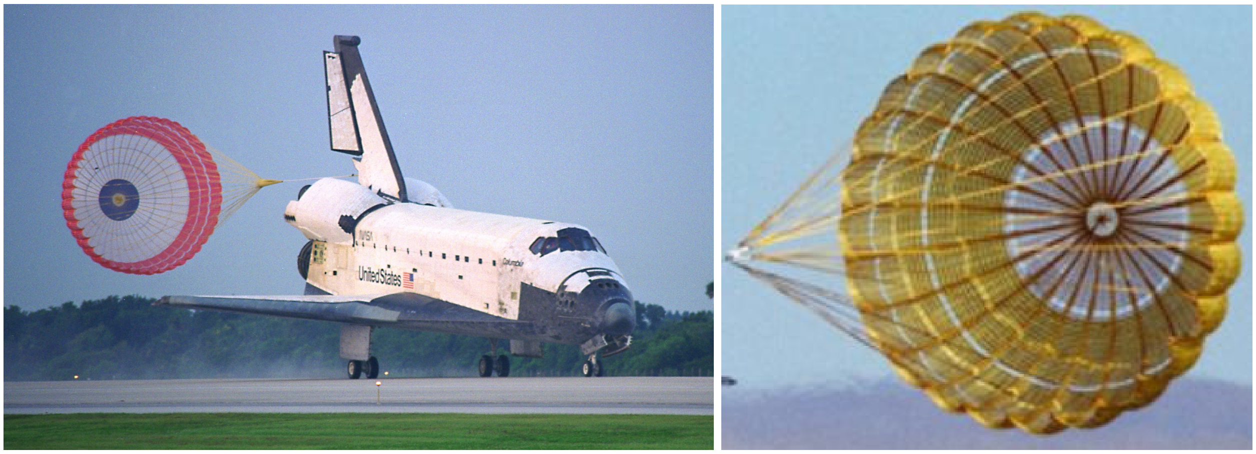


Figure 1: Parachutes Exhibiting High Geometric Porosity

Parachute porosity, whether geometric or permeability based, affects drag performance, stability and opening forces. Parachute drag performance, maximum oscillation angle, and opening forces all reduce with increasing porosity. Further, a parachute that is too porous will not open at all. In the majority of applications, the reduction in stability and opening forces is advantageous but the decrease in drag is not.

Simulation Methodology

It is possible to use LS-DYNA in a number of ways to simulate this highly dynamic fluid, and structural event. The large deformations associated with parachute behavior limit the applicability of the Lagrange formulation for both the parachute and the flow field. The Lagrangian description remains a viable option for the structure. An alternative technique for the fluid domain is the multi-material Eulerian formulation. This formulation permits material flow through a mesh, fixed in space, whose elements are allowed to contain a mixture of different materials. This method completely avoids any mesh distortions for the fluid domain. The incorporation of an Eulerian-Lagrangian penalty coupling algorithm permits the interaction of flow field, Eulerian formulation, and the parachute, Lagrangian definition, within the same simulation.

The Eulerian formulation is not completely free from shortcomings. The user must be aware of the propensity for dissipation and dispersion inaccuracies connected with the fluxing of mass across element boundaries. In addition, the Eulerian mesh is required to span the entire range of activity associated with the Lagrangian structure. In many applications, this can result in a large size mesh and hence a high computing cost. To circumvent these possible drawbacks the following methodology is currently applied for parachute performance predictions at Irvin:

- Model the parachute using a Lagrangian formulation.
- Model the fluid domain using a Navier-Stokes based multi-material Eulerian formulation.
- Perform the analyses using conditions similar to a wind tunnel, i.e. infinite mass; equating the results to the quasi-steady-descent phase of the parachute flight.

The last step reduces the computational cost associated with modeling vast spatial timelines associated with real parachute functions, specifically deployment and inflation. It also permits the reduction in complexity of boundary conditions. The use of a penalty-based coupling algorithm significantly reduces the energy conservation errors connected with alternative constraint-based techniques. Kinetic energy is consumed at interfaces when constraint-based coupling methods are used. This is inappropriate when considering a parachute simulation.

Irvin developed this methodology several years ago and it has yielded excellent results for a number of parachutes. Particularly noteworthy is the replication of an undesirable flight characteristic exhibited by a replacement candidate for the venerable T-10 mass tactical assault parachute. The identification, and subsequent removal, of this flight mode through simulation design iterations demonstrated the powerful potential of such techniques.

The modified version of that parachute system is now undergoing operational testing and is slated to replace the T-10 later in this decade. Figure 2 illustrates a flight test with simulation flow field velocity vectors overlaid.

The fabric shown in Figure 2 is classified as a low-porosity fabric. When assessing the steady state characteristics of this parachute the approximation of an impermeable fabric was valid. Minimal differential pressure is developed across the canopy when a constant rate of descent is achieved.

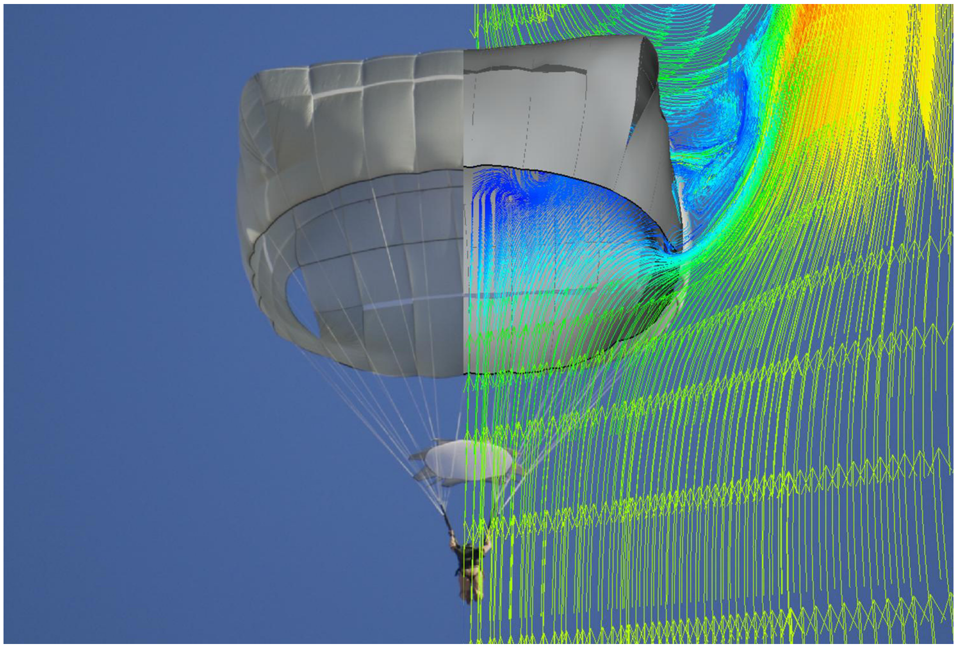


Figure 2: Flight Test and Simulation Comparison

Implementation and Testing of Permeability Algorithm

The method selected to provide accurate permeability assessment was to modify the Euler-Lagrange coupling that facilitates the interaction between the fluid and the structure. An anisotropic Ergun porous flow model was implemented to compute coupling forces.

The Ergun[3] equation is commonly defined:

$$\frac{\Delta P}{L} = \frac{\mu}{K_1} \cdot v_f + \frac{\rho}{K_2} \cdot v_f^2$$

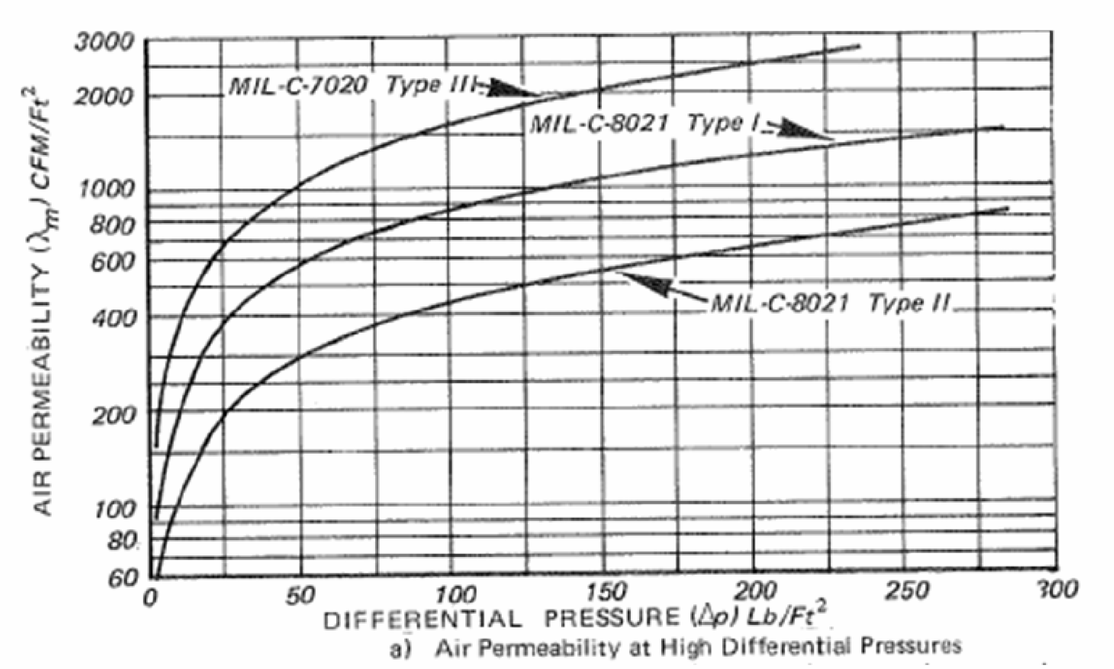
where:

$$K_1 = \frac{\varepsilon^3 \cdot D^2}{150 \cdot (1-\varepsilon)^2}$$

$$K_2 = \frac{\varepsilon^3 \cdot D}{1.75 \cdot (1-\varepsilon)}$$

K_1 and K_2 are referred to as the viscous and inertial factors, respectively. D is defined as the characteristic length, ε is the porosity and is equal to the ratio of the void and total volume. v_f, μ, and ρ are fluid velocity, viscosity, and density, respectively.

The Ergun equation describes the magnitude of porous flow velocity at a given differential pressure based upon two coefficients. These coefficients assume a constant porosity, not to be confused with a constant permeability. Porosity is a characteristic of the fabric, whereas permeability is a description of the flow velocity at a given condition. Many materials can be highly porous without being permeable. It should also be noted that the porosity of some fabrics can change significantly with applied load. Figure 3 displays historical permeability data[4] of a common parachute cloth fabric, of particular interest is the widely used MIL-C-7020 Type III.



a) Air Permeability at High Differential Pressures

Figure 3: Parachute Fabric Permeability Data

The data shown in Figure 3 was obtained at constant porosity, fluid viscosity and density. By amalgamating these constants the Ergun equation can be expressed:

$$\frac{dP}{e} = a \cdot v_f + b \cdot v_f^2$$

Where e= computational shell thickness. The viscous and inertial coefficients (*a* and *b*) can then be obtained from the experimental data shown in Figure 3.

A simple model was constructed to validate this method of coefficient selection and evaluate the interpretation of the Ergun equation. Figure 4 illustrates a model containing two fluid elements with a fabric interface. A constant pressure was maintained in each solid element producing a constant differential pressure across the fabric boundary. The data presented in Figure 3 was then compared with the flow velocity predicted in the model.

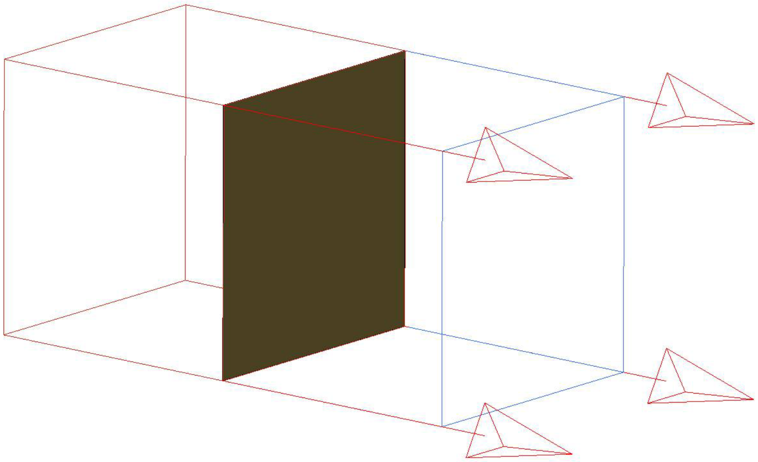


Figure 4: Permeability Coefficient Validation Model

The range of differential pressures over which the coefficients are effective was also assessed. Table 1 presents a comparison of experimental and simulation porous flow velocity over a range of differential pressures, 25-225 lb/ft^2.

Differential Pressure (lb/ft^2)	Experimental Velocity (ft/s)	Numerical Velocity (ft/s)	Relative Error (%)
25	660	685	3.6
50	1050	1080	2.8
75	1400	1385	1.1
100	1650	1645	0.3
125	1850	1875	1.3
150	2050	2085	1.7
175	2250	2280	1.3
200	2450	2460	0.4
225	2650	2630	0.8

Table 1: Comparison of Experimental and Numerical Porous Flow Velocity

The relative errors are within acceptable limits, and can be classified as non-existent when compared with the variation of the permeability defined in the MIL-C-7020 Type III specification.

It should be noted that similar validation methods were performed for various fabrics over a variety of differential pressures, all with similar success. Experimental data pertaining to MIL-C-7020 Type III was the most extensive and reliable and for these reasons has been included in this paper.

Incorporation of Fabric Permeability into Parachute Simulation

A pertinent example of a parachute design that could not accurately be assessed using previous versions of LS-DYNA is the TP8 low altitude troop parachute. The TP8 is an aeroconical class of parachute. Aeroconical parachutes are commonly used for aircrew ejection systems.

The TP8, shown in Figure 5, is fabricated from two base cloths of different permeability. The crown of the canopy, shown in blue, is constructed from cloth exhibiting a permeability of ~10 CFM/ft^2, and the dark yellow cloth is rated at ~80 CFM/ft^2, both at ½ inch water pressure.

Figure 5: TP8 Flight Test

Drag coefficient, C_d, is widely used as a measure of parachute performance and is defined:

$$C_d = \frac{F}{s \cdot q}$$

Where:
F = drag force
s = canopy surface area
q = dynamic pressure

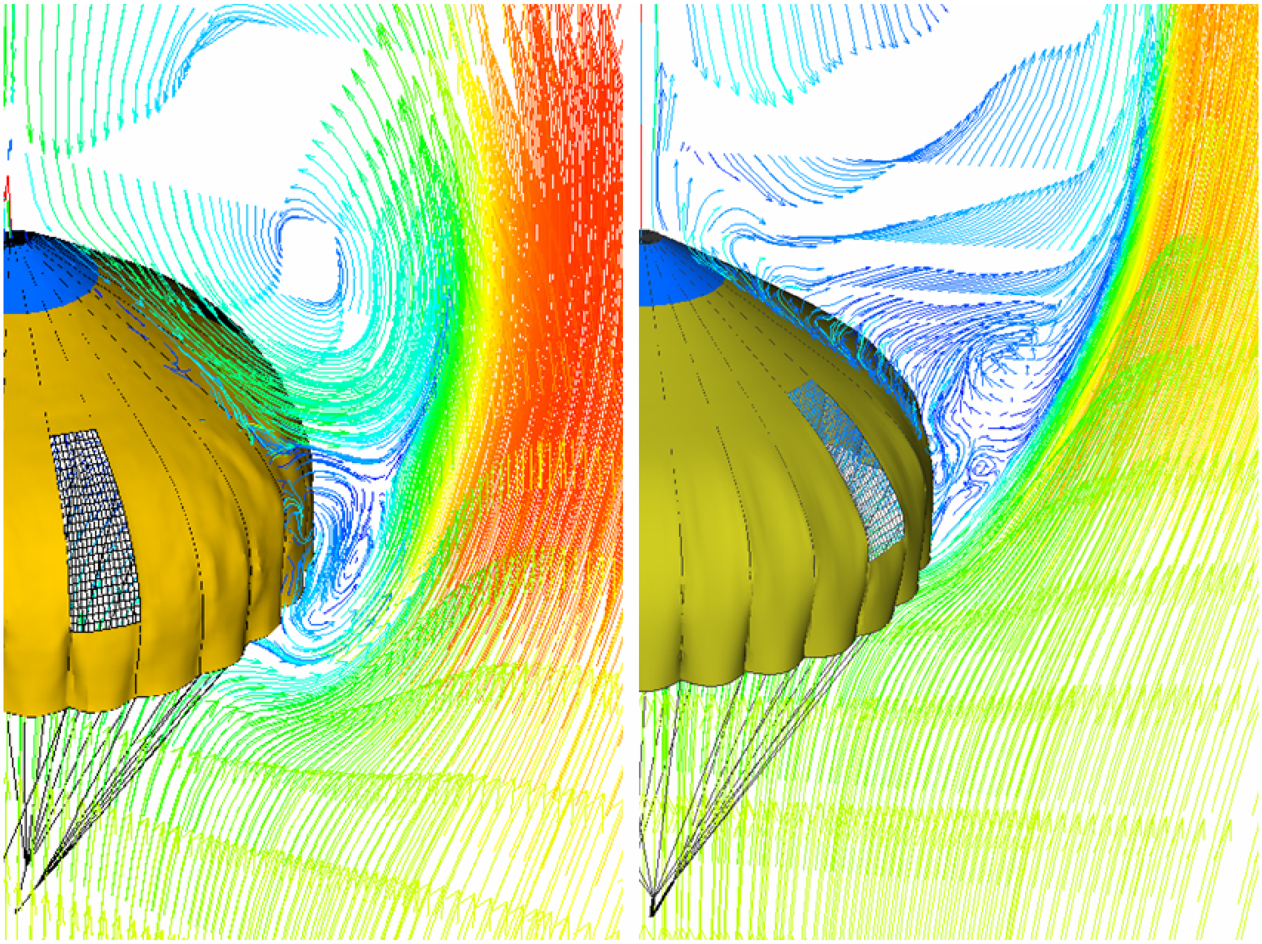
Test data indicates that the TP8 exhibits a drag coefficient of approximately 0.6.

LS-DYNA has been used to apply a constant flow rate to the parachute in a wind tunnel type simulation. This flow rate equates to the steady rate of descent in an actual flight test.

Interrogation of the *dbfsi* file provides parachute force time history data. This file is used to ensure the simulation has reached steady state and to compute the drag coefficient. Suspension line force data in either *sbtout* or *elout* files are used for cross-reference purposes.

LS-DYNA models created prior to the incorporation of the permeability coupling predicted a drag coefficient of 0.75. Clearly, this prediction was in conflict with the observed value of 0.6, a value derived from a significant and reliable test series. The assumption of an impervious canopy cloth was the obvious factor in the difference between test and simulation results..

Following the implementation and validation of the permeability coupling, the same model was modified to incorporate both viscous and inertial coefficients of the Ergun equation. Figure 6 illustrates a cross-section of flow velocity for the TP8 simulation with and without accounting for fabric permeability.



WITHOUT PERMEABILITY *WITH PERMEABILITY*

Figure 6: Visualization of Permeability Affect

Figure 6 presents an excellent illustration of the influence of fabric permeability in parachute design. The porous flow through the canopy cloth has completely changed the nature of the parachute wake. The large recirculation of air behind the parachute remains very close to the canopy on the left and has a significant affect on parachute stability. By permitting air to flow through the canopy, the recirculating air has been pushed further downstream where it has considerably less influence on the stability of the parachute.

Figure 6 presents a qualitative assessment of the permeability affect. Of more importance is whether this results in a discernible difference in drag coefficient. Figure 7 provides time history data of the drag force produced by the canopy when subjected to a flow velocity of 18 ft/s. The figure presents a comparison of the same simulation with and without permeability. The data clearly depicts the reduction in drag associated with the incorporation of permeability. Also noticeable is the reduction in numerical noise, this is associated with a more benign parachute inflation, a characteristic of porous canopies.

The steady-state drag force from Figure 7 can be used to calculate a modified drag coefficient; the simulation now predicts a C_d of 0.59.

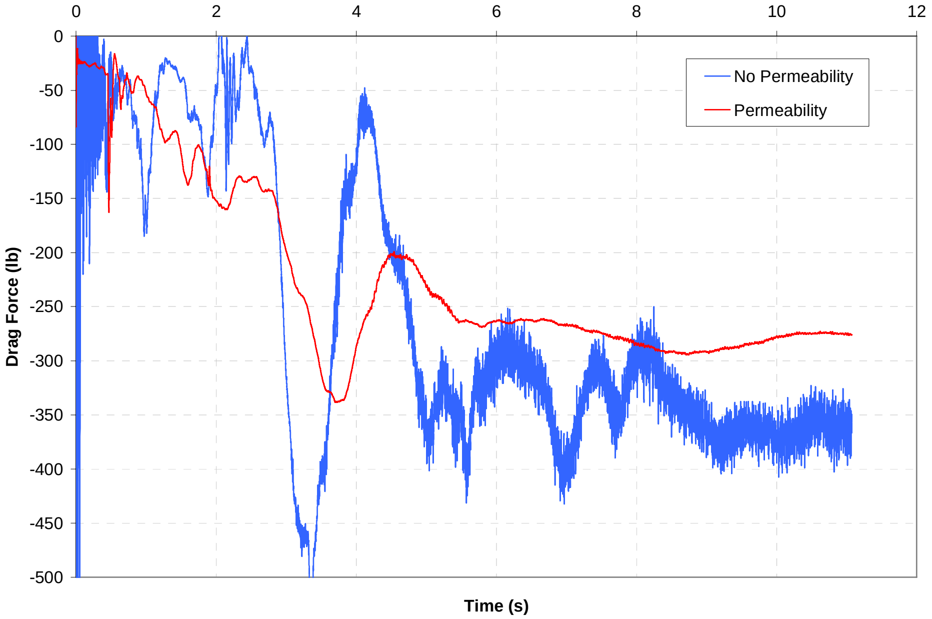


Figure 7: Drag Force Time History Data

Conclusions

The combination of bluff body aerodynamics and a highly deformable structure, fabricated from a porous media, creates a truly unique and multifaceted environment. To appropriately simulate, and therefore understand and predict, this behavior requires an accurate method of assessing this complex relationship. This paper has provided a description of the implementation and validation of a fabric permeability algorithm within the Euler-Lagrange coupling definition for the LS-DYNA transient dynamic finite element analysis software. It has also discussed the importance of such a development to the parachute engineer and the future of parachute design.

Numerical results have been shown to provide excellent correlation with actual test data, providing an authentic capability to model parachutes fabricated from permeable fabrics.

It is the contention of the author that this addition to the LS-DYNA software will present benefits to a number of applications. Automotive airbags, pressure vessels and airbags designed for aircraft and spacecraft impact attenuation could all benefit from this enhancement.

The prospective goals of this ongoing research are to incorporate the affect of fluid viscosity and particularly density changes during parachute flight. This will enable extremely high altitude and interplanetary aerodynamic decelerators to be evaluated over a range of conditions. Also of interest is the influence of fabric loading on porosity and the subsequent change in permeability.

Acknowledgements

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References

[1] Tutt, B., “The use of LS-DYNA to Assess the Performance of Airborne Systems North America Candidate ATPS Main Parachutes”, AIAA Aerodynamic Decelerator Systems Conference, 2005.

[2] Aquelet, N., Wang, J., Tutt, B., Do, I., and Chen, H., “Euler-Lagrange Coupling with Deformable Porous Shells”, ASME Pressure Vessels and Piping Division Conference, 2006.

[3] Ergun, S., “Fluid Flow Through Packed” Chem. Eng. Prog., 48(2), 89-94 (1952).

[4] Knacke, T., “Parachute Recovery Systems Design Manual” Para-Publishing, CA, 1992.