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The Road Ahead: A White Paper on the Development, Testing and Use of Advanced Numerical Modeling for Aerodynamic Decelerator Systems Design and Analysis

By the AIAA-ADS sub-committee on Advanced Modeling Development and Validation

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Abstract

Quantitative engineering analysis of parachutes and inflatables has been part of the routine design process since the days of World War II. But in most cases, the shear complexity in which their flexible structure interact both externally and internally with the surrounding air demands that empirical data be used to either validate or supplement such analysis. Advanced modeling embodied in the techniques of Computational Fluid Dynamics (CFD), Computational Structure Dynamics (CSD) and Fluid-Structure Interactions (FSI) has great potential for diminishing such reliance. But even though its application to aerodynamic decelerator systems (ADS) has been under consideration for the past four decades, progress has been painfully slow and the results rarely integrated into today's engineering design practice. This report aims at discussing why advanced modeling has not reached the level of practical use that has occurred in other aerospace fields. Such lack of progress origins partly from advanced modeling requiring substantial human resources that are not usually associated with parachute programs (expertise in computational methods in particular). Moreover, the extensive experimental database for Verification and Validation needed to support advanced modeling development is missing. This white paper begins with a pedagogical review of the most current implementations of CFD, CSD and/or FSI in the context of ADS applications. This is followed by a discussion of both non-ADS and ADS examples in which advanced modeling has been shown to yield interesting and relevant results. The report also identifies the type of data and measurement techniques that are needed for V&V, as well as the most pressing challenges – both theoretical and empirical - that are impeding progress. The paper ends with a series of recommendations for action items to be considered in the near and long terms.

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I. Introduction

Parachutes, and more recently inflatables such as ballutes and airbags, define a class of aerospace systems known as Aerodynamic Decelerator systems (or ADS) which are used to stabilize, decelerate and/or land air vehicles, people or cargo. They are used in a variety of missions, ranging from humanitarian relief, flight crew safety, mass airborne soldier insertion, autonomously-guided precision airdrop of supplies, and planetary reentry. They are deployed from many types of aircraft and spacecraft, and under different and sometimes extreme environmental conditions and dynamic pressures. In most applications, aerodynamic decelerator systems are crucial to mission success as with the landing parachutes used for spacecraft returning astronauts to Earth. Therefore, continued R&D efforts aimed at improving the reliability and performance of parachutes and inflatables, as well as at reducing their development cost, are crucial. And like in many other engineering fields, such efforts should include continued *computer modeling* R&D for improved analysis and design.

Quantitative engineering analysis of ADS applications has been part of the routine design process since the days of World War II. But the uncertainties and unknowns related to their complex aerodynamics and structural dynamics remain significant and correctable only through direct access to empirical data. Advanced modeling development, herein embodied in the numerical techniques of Computational Fluid Dynamics (CFD), Computational Structure Dynamics (CSD) and Fluid-Structure Interactions (FSI), in which the details of both aerodynamics and structural dynamics become *outputs of the analysis rather than inputs*, has long been recognized as an essential step towards improving the scope, accuracy and relevance of ADS engineering analysis (Maydew, Peterson, 1991; Strickland, Higuchi, 1996). But even though advanced modeling has been under development for the past four decades, progress has been painfully slow and the results rarely integrated into today's engineering design practice.

Pursuing advanced modeling for ADS applications stems from the greater levels of detail made available, for example on instant canopy shapes, canopy and payload motions, and structural forces and fluid pressure distributions (internal and external). As such, advanced modeling has the potential of substantially lowering the design costs by reducing the number of rather expensive experiments and airdrop tests required for system certification. CFD/CSD/FSI simulations can also foster novel experimental approaches by providing detailed fluid flow and structural deformation characteristics of the parachute systems used under various scenarios, including scenarios not experienced by production systems.

This report aims at discussing why advanced modeling has not reached a level of practical use in ADS engineering unlike in so many other aerospace fields. Here it will be argued that such inaction origins partly from a basic misunderstanding of what advanced modeling really is and what it can do, and also from the perception that *all* ADS system applications necessarily demand the simulation of a tightly-coupled fluid-structure system which in itself is nearly unfeasible with current algorithmic and computer technology. And so the first overall goal of this report will consist in clarifying what current implementations of CFD, CSD and/or FSI can do for ADS analysis and engineering. This will be done via 1) a pedagogical review of the capabilities and limitations of current CFD, CSD and FSI algorithms (Sect. II), as well as the current experimental techniques available for validation and verification (V&V; Sect. III); and 2) a discussion of both non-ADS and ADS examples in which advanced modeling has been shown to yield interesting and relevant results (Sects. IV and V). The discussion will continue with the identification of ADS applications (or aerodynamic decelerator components) that can - and should - be studied with advanced modeling, albeit in approximated form, in the short and medium term (Sect.VI).

The second overall goal of this report shall identify many of the challenges that remain for applying and validating, advanced modeling to aerodynamic decelerator systems (Sect. VII). From this analysis, we shall identify and recommend the theoretical and experimental developments that are needed in the short, medium and long terms to improve the power and relevance of advanced ADS systems modeling (Sects.VIII and IX).

This white paper is the result of a large number of discussions and information exchanges among the members of a team formed in early 2010 within the Aerodynamics Decelerator Systems (or ADS) Technical Committee of the American Institute for Aeronautics and Astronautics (AIAA). The names of these team members are listed in Appendix 1. This group was charged with the dual task of firstly exploring the technical challenges, short term and long term, that must be overcome to allow the routine use of advanced modeling in ADS design; and secondly identifying partnerships with other government entities, as well as with corporate members of the parachute industry, that could help accelerate the pace of development of advanced modeling as applied to the problems of interest to the ADS community. From those discussions have emerged a series of documents including a position paper, a funding proposal for a MURI initiative, an extensive bibliographical study, an opinion survey of the ADS community and users, and even a workshop proposal, all aimed at the furtherance of these goals. All these documents, and many others, are – or will be - accessible on the Aerodynamic Technical Committee's web site (www.aerodecelerator.org).

Please note that this paper is a shortened version of a full-length white paper that shall be posted shortly after this conference on www.aerodecelerator.org. The sections that have been omitted or shortened are identified as such in the text. Most of the shortened text is found in Sections IV and V.

II. Conceptualizing a fluid & structure-coupled simulation

To the non-expert in computer simulations, a "typical" FSI simulation represents the numerical representation of the interaction among aerodynamic, elastic, inertial, and thermal forces. Alternatively, the FSI simulation solves the equations for the temporal evolution of a fluid about a flexible structure and the motions of the structure itself as a coupled system. Given the widely known intricacies and nonlinearities of fluid flows (i.e., turbulence, temporal dependence, environmental conditions, etc.) and highly flexible structures (i.e., complex and evolving shape, elasticity, contacts, etc.), such numerical processes can become, depending on the required resolution and fidelity of the simulation, extremely costly in terms of both human and computer resources. Unfortunately, these challenges have led to the perception by many ADS designers and analysts that FSI simulations have a low return on investment, and they are rarely seen as a useful tool for every-day design and engineering.

In an attempt to correct this perception, the discussion below provides a general outline of the steps, questions, and approximations taken to find a FSI solution, or perhaps find cases where just a CFD simulation may be enough. The focus is on how practitioners of advanced modeling use appropriate *approximations* to specific and well-defined *applications*. In this manner, not only advanced modeling embodied as either CFD or full FSI simulations may be used as a practical means for conducting engineering analyses of ADS problems.

A. What is advanced modeling?

A first but obvious concept to clarify from the beginning is that of ***Advanced Modeling***. Herein advanced modeling shall be meant as a numerical process by which the motions of the flows and of an aerodynamic decelerator structural components are explicitly computed (simulated), at *the relevant spatial and temporal resolutions*, via the use of the techniques known today *as Computational Fluid Dynamics* (or *CFD*), *Computational Structure Dynamics* (or CSD) and/or *Fluid-Structure Interaction* (or *FSI*) modeling. As discussed further below and elsewhere (Accorsi, 2007; Charles, 2007a, 2007b and 2007c), these three components may be used separately and sequentially in simulations schemes that are known as "loosely coupled FSI simulations"; or all at once during the same integration time step in "fully coupled FSI simulations".

B. The many faces of Advanced Modeling

Although easy to define, conceptualizing the implementation of CFD/CSD/FSI for ADS applications turns out to be a complicated task. Comprised of cloth and lines, parachutes and inflatables are far easier to build than aircraft. But their texture and elasticity yield structural and fluid motions that are quite complicated, much more so in fact than that of aircraft. Unlike aircraft which are solid structures that deflect air around them and are only minimally deformed by the air, parachutes not only deflect the surrounding air but also adopt complex and evolving shapes that are dictated by the very airflow and pressures that they generate. Such a feedback is complicated further by the fact that both shape and flows may be not only unsteady but also occur over a wide range of length and temporal scales.

Fortunately, such complexity also presents itself with a myriad of manifestations which themselves can be approximated. During steady descent for example, the fluid-structure feedback is still very much present but the canopy structural deformations generally small and evolving at rates that are much smaller than those of the surrounding flows. This in turns allow for significant algorithm simplifications, such as assuming linear stress-strain responses of the structure, a significant reduction of the number of structural degrees of freedom in comparison to the number of fluid degrees of freedom, and significant reduction of required structural motion updates, again in comparison to the relevant fluid time scales. Thus advanced modeling in ADS engineering inevitably involves approximating one or many of the elements involved in the CFD, CSD or FSI portions of the calculations. And so, the term “advanced modeling” usually does not refer to a single algorithm or method of solution, but rather to a large ensemble of approaches tackling approximations of the same or different aspects of fluid motions, structural motions and, when coupled, of fluid-structure interactions.

C. The six basic elements of an FSI simulation

Conceptualizing a FSI simulation involves the numerical representation of the six basic elements shown in figures 2.1 – 2.5 namely 1) the fluid, 2) the structure, 3) the specific interactions between fluid and structure, 4) the mapping of the fluid-structure interface, 5) the meshing of both fluid and structure, and 6) the temporal evolution of the mesh. (The reader interested in further details is invited to consult the material distributed during the 2007 ADS Seminar on FSI Techniques [FSI workshop talks by Charles & Accorsi] and the references cited therein). The need for the correct representation of the fluid and structural motions, as well as the meshing needed to support both fluid and

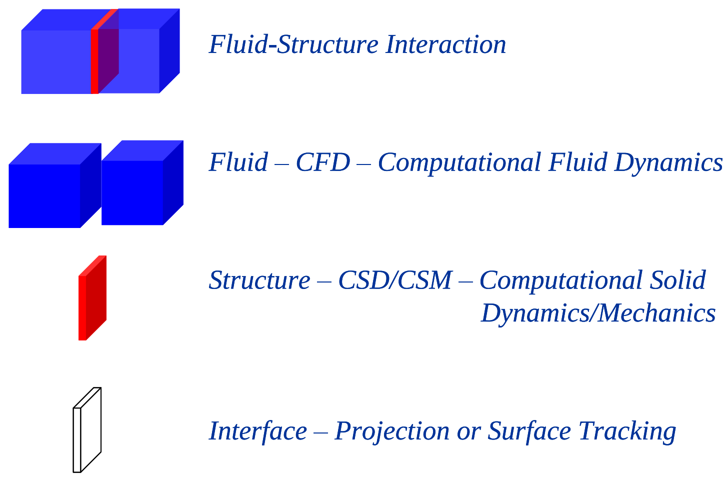


Figure 2.1 Four of the six basic elements of a FSI simulation.

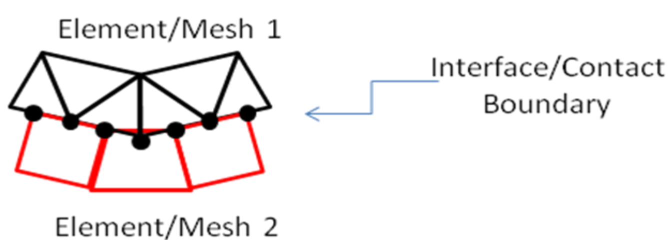


Figure 2.2 Conceptual *interface* between different physical elements and meshes of a fluid in contact with a structure.

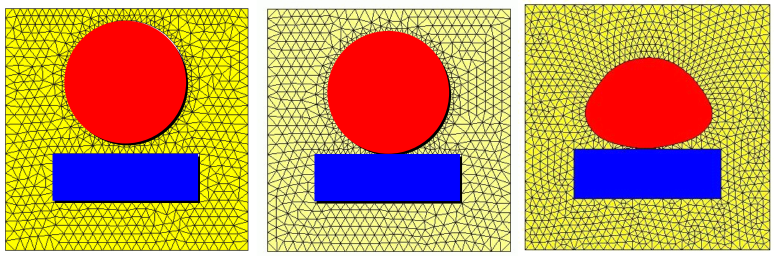


Figure 2.3 Fluid mesh evolution about a pressurized bag impacting a hard object.

structural element coordinates, are often implemented by the use of well-known solvers for the fluid equations of motion (aka CFD solvers) and structural element equation of motions (aka CSD solvers). Less known, however, are the intricacies related to the mapping of the fluid-structure interface (figure 2.2) and the evolution of the fluid mesh over time (figure 2.3). The former problem naturally arises from the fact that neither fluid nor structure is truly continuous and that neither has compatible meshes along the fluid-structure interface. On the other hand, mesh evolution follows from the motions of the structure through time which imposes a redefinition of the mesh used to solve the fluid equation of motion. As shown below, such re-meshing over time involves the use of several approximations that may not be always valid from one ADS application to another, or worse, from one size scale (of a given application) to another.

Thus specific decisions must be made to represent and implement each of the six elements. Inevitably, and for the sake of practicality, such decisions lead to schemes that approximate a problem (application) rather than try to resolve it. For that reason, a given fluid-structure system, such as a descending parachute of specific shape, porosity and mission may require several FSI simulation methods rather than just one. In the following, a series of important concepts and definitions are reviewed for the benefit of the non-expert, with their common name printed in bold for ease of reference.

D. *Direct* vs. *partitioned* solution of an FSI problem; "strong" vs. "weak" fluid-structure coupling

Of the many methods of conducting FSI simulations, there are two common mesh-based approaches: *direct* and *partitioned*. For the **direct solution** method the fluid and structure equations are solved simultaneously. However, while the direct procedure is well suited for highly nonlinear FSI problems and/or problems with **strong interactions between the fluid and the structure**, the method is often impractical. With strong interactions, the influence of one component (i.e., either fluid or structure) on the other would occur in such a fashion that a change in one component would elicit an immediate response in the other. For example, with problems involving incompressible, viscous fluids, the solution of a large system of coupled nonlinear algebraic equations is required, and this operation can be computationally quite expensive. Additionally, the coefficient matrix associated with the direct method grows very rapidly as the method is applied to increasingly complex and highly spatially resolved systems. Finally, the coefficient matrix is often ill-conditioned in the sense that it magnifies small errors. Commonly referred to as "**fully coupled**," the direct method is also referred to as either "**monolithic**" or "**fully implicit**".

Where interaction between the fluid and structural components are relatively **weak**, i.e., as occurring when changing one component would not elicit an immediate response of the other, a **partitioned** (or **segregated**) procedure has proven to be very efficient. For these methods the fluid and structural fields are solved separately and forces (pressures), velocities, and displacements are passed through an interface. Therefore, a very appealing feature of this approach is the ability to use standalone, optimized solvers for each of the fluid and structural components. Figure 2.1 portrays the conceptual decomposition of the partitioned FSI problem emphasizing the introduction of the interface component to the problem.

As will be shown in the FSI examples below, *all* simulations performed so far on parachutes and inflatables have used the partitioned approach, mostly in the hopes of producing solutions in a reasonable amount of time with limited computer resources. This approach is, of course, acceptable as long as these FSI simulations are subjected to rigorous Validation and Verification as discussed in Sect. III. But given that there will be cases where the physics simply prohibits the use of partitioned FSI, there is a need right now for a quantitative definition of what is meant by *weak* and *strong* fluid-structure coupling in the context of ADS applications.

E. CSS cycle in a partitioned solution; "tight" vs. "loose" coupling

A common scheme for implementing a partitioned solution is the **C**onventional **S**erial, **S**taggered cycle (**CSS**) depicted in Figures 2.4 and 2.5. Starting at the structural

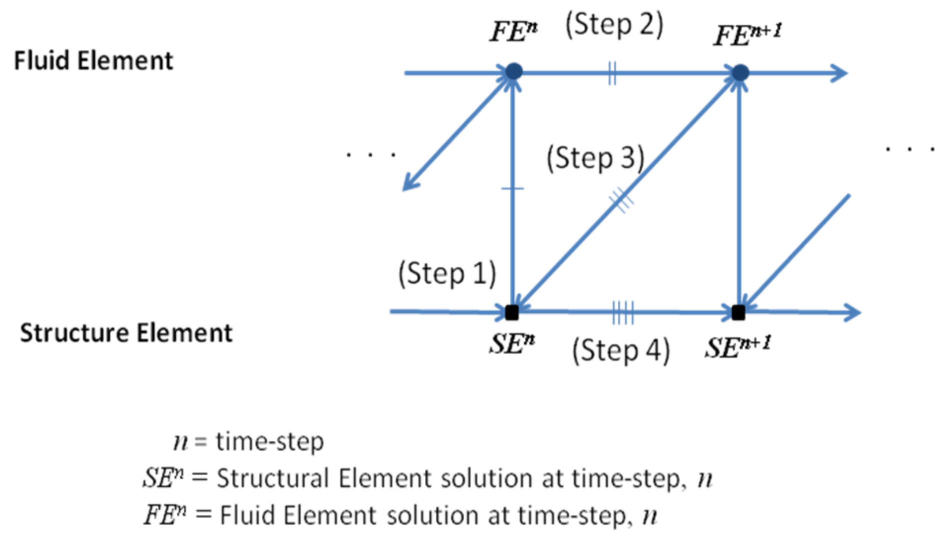


Figure 2.4 CSS cycle for a partitioned FSI procedure.

element solution computed at the n^th^ time-step, SE^n:

Step 1: $(SE^n \rightarrow FE^n)$ Transfer the velocities and displacements of the structure to the fluid boundary and update the fluid mesh,

Step 2: $(FE^n \rightarrow FE^{n+1})$ Solve the fluid subsystem problem with new boundary information for the next time-step,

Step 3: $(FE^{n+1} \rightarrow SE^n)$ Extract the relevant portion of the fluid field solutions and convert it to new load data to transfer to structure boundary,

Step 4: $(SE^n \rightarrow SE^{n+1})$ Compute structure subsystem response and evolve the structural solution to the next time-step.

Figure 2.5 illustrates the process in the physical domain by "showing" the interface (Sect. II.C). The structure field displacements, **d**, at time t^{n+1} over selected points at the interface, is "predicted" and used to determine new fluid mesh positions = $\boldsymbol{r}_i^{n+1}$, grid velocity = $\boldsymbol{u}_i^{G,n+1}$, and fluid velocity at the interface, i.e., to determine the fluid solver boundary condition = $\boldsymbol{u}_{\Gamma,i}^{n+1}$. The G superscript indicates velocity of the fluid grid nodes which must be computed for the ALE formulation of the problem and is discussed below (Sect. II F.). The Γ subscript is to indicate the fluid velocity along the boundary of the interface. It should be noted that one of several different predictors may be chosen for this portion of the algorithm, and as with many of the other algorithmic features discussed in this paper, the specifics of the algorithm may not always be known to the user of commercial software, and therefore, rigorous *Verification and Validation* becomes ever more important (Sect. III), especially when porting an FSI scheme validated for one application to another.

With the **loosely coupled** algorithm, the fluid and structure equations are solved once, (i.e., sequentially traversing the CSS cycle from Step 1 to Step 4) or at most a few times (for example, repeating

Steps 1, 2, and 3 within each structural element time step). Since the time-scales for the fluid and structural elements typically differ, following this scheme implies no exact energy balance is imposed on the solution. **While computationally efficient, the algorithm is only 1st-order accurate in time**.

However, if the algorithm includes convergence criteria for the element solvers, then the problem is referenced as being "**tightly**" or "**strongly coupled**."(Farhat et al., 2006). Convergence is enforced by implementing sub-iterations that are performed between each pair of consecutive time-stations (i.e., repeating Steps 1, 2, and 3 until a convergence stop criteria is met). There are various implementations of the sub-iteration schemes which result in a **2nd-order time accurate solution**. Appendix 2 contains a more detailed example of how to implement a strongly coupled algorithm.

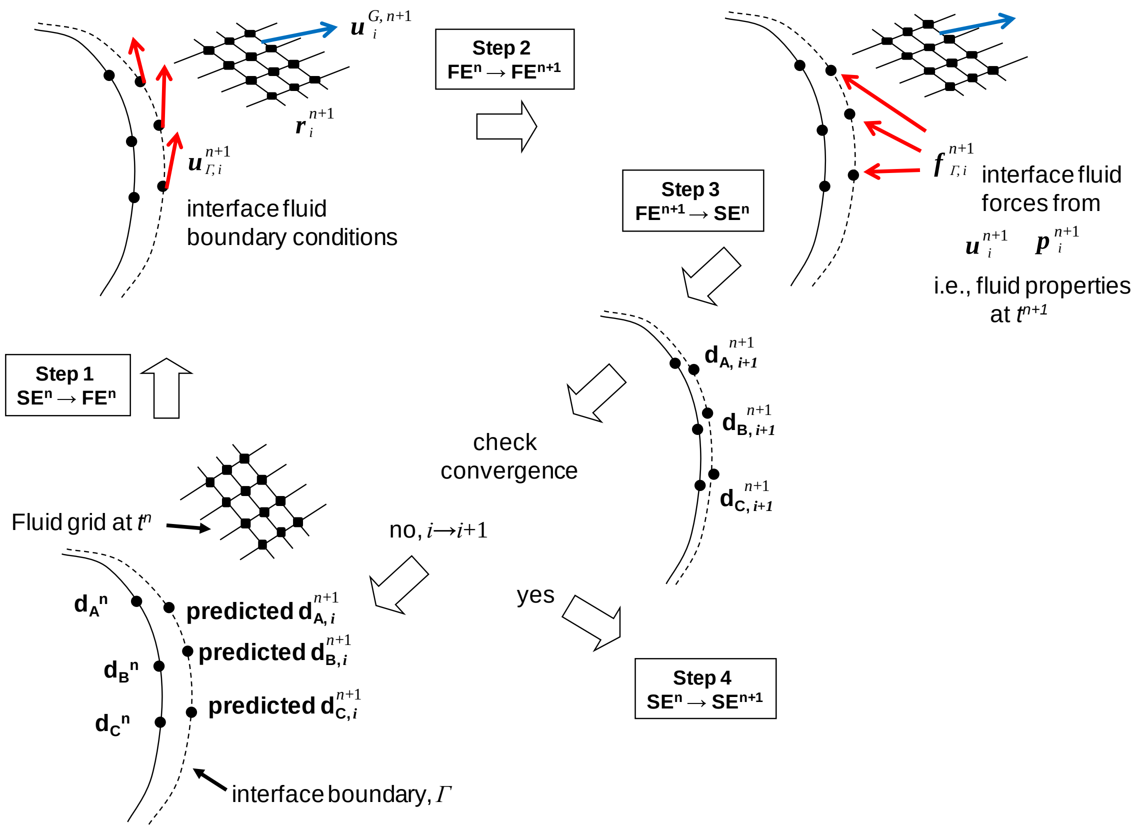


Figure 2.5 Schematic representation of the role of the *Interface* in a FSI updating sequence.

In most ADS FSI schemes used nowadays, steps 1 and 4 of the cycle explicitly account for the meshes, which are the basis for the numerical techniques presented. These meshes are the discretized representations of the component domains and their construction and quality are intrinsically tied to the quality of the simulation. Indeed, the meshes for the fluid and structure components need not be of similar morphology as illustrated in Figure 2.2, and they can even be different when the interface is between two like elements as in two separate structures in contact with one another. In such a case, the interface is often referred to as a contact surface or boundary. This distinction would be appropriate, for example, in an ADS simulation of canopy deployment where fabric would be in contact with fabric (risers) and interface. Note that this problem of dissimilar fluid and structure meshes can be avoided to a certain extent, as discussed for example by Tutt et al. (2010) and Gilmanov et al. (2009).

In general, finer meshes are required for the fluid element than are needed for the structural element, and there is a strong dependency between the fluid solution accuracy and the quality/characteristics of the mesh. This linkage becomes more important when considering unsteady flow problems which dominate

ADS FSI applications and for which the solution depends on appropriately sized and oriented meshes in the boundary layers and separated flow regions of the problem.

F. Arbitrary Lagrangian-Euler (ALE) in a partitioned solution

It is important to discuss the choices that are made for the kinematical description of the fluid and structural elements as they are related to the associated meshes. For structural dynamics solutions, a **Lagrangian** algorithm is used such that each node of the computational mesh is associated with a material particle, i.e., particles of the structure are tracked as they move. This perspective is changed into the so-called **Eulerian** perspective, in which the dynamics of each fluid element is tracked with respect to a fixed grid. This Eulerian reference frame allows for large distortions in the fluid field. A step in the computation must then be used to reconcile these two descriptions. This step is usually carried carry out by the **Arbitrary Lagrangian-Euler** (ALE) description, which introduces the ability to move or fix computational mesh nodes to meet the requirements of the physical process—fluid dynamics or structural dynamics (Donea et al. 2004).

Historically, there have been several different ALE implementations and the details of each implementation are usually specific to the particular software package or in house-developed code. Such details differ in which changes in either component are transferred to the other. For example, one approach consists in allowing the fluid mesh to distort for a specified number of steps and reconciled back to the original configuration with a flux correction and mesh velocity, which in effect brings up a correction for the fluid momentum created by the structural surface motion generated during the update (i.e., Step #4, in Sect. II.E). Other ALE implementations include the so-called *Volume of Fluid* approach (Nichols and Hirt, 1975; Hirt, Nichols, 1981) and the *Immersed Boundary Method* (Peskin, 2002). Thus ALE adds another set of approximations to those already incurred by the use of the partitioned approach. And again, because the specifics of ALE approximation aren't always known (or understood) by users of commercial software, rigorous *Verification and Validation* (Sect. III) must again be called upon to properly establish the legitimacy of a given FSI scheme to a given application.

G. Artificial added mass effects instability

Another important issue surrounding the use of a partitioned solution concerns the sensitivity of the partitioned method on the relative mass densities of the fluid and structural elements. Many of the methods and techniques associated with FSI simulations of ADS applications have been adapted from work completed for aircraft aeroelastic applications. These aircraft problems have relatively stiff structures, such as aircraft wings, and therefore, the coupling with the fluid is weak. As a result, a loosely coupled algorithm has been shown to produce accurate simulations of wing flutter. However, one of the distinguishing factors associated with ADS FSI simulations is that the densities of the fluid and structure have similar magnitudes. With loosely coupled algorithms, the equivalence of element densities was shown to lead to an ***"artificial added mass effect"*** **instability** (Causin et al. 2005). This reference to *added mass* is not to be confused with the added (virtual) mass added to a fluid dynamics system to account for the acceleration a body through the fluid. Instead, the *artificial added mass* is associated with the dependence of the fluid forces on the predicted, as opposed to actual, displacement of the structural boundary as with the CSS cycle depicted in Figures 2.4 and 2.5. Further investigation of the artificial added mass effect by Förster et al (2007), has shown that in fact, for the incompressible flow FSI problem using a serial staggered cycle no method is unconditionally stable with respect to the mass ratio, ρ^F/ρ^S . This restriction does not necessarily prevent the use of serial staggered cycles for ADS FSI applications, but rather serves as a check for computational engineers to consider when conducting such simulations. From a more global, problem-solving perspective, this admonition is part of an application of good engineering principles requiring a clear assessment of the goals to be obtained and the tools available to address a given problem of interest.

H. Assessing the relevant fluid dynamics

Assessing the fluid dynamics most relevant to the application at hand is an important step in simulation planning, as it usually leads to a specific form or approximations of flow simulation that will yield significant savings in computer resources. This assessment includes enquiring about the roles of compressibility, buoyancy and thermal energy transfer within the fluid in applications taking place in the transonic and supersonic regimes; or the role of viscosity and turbulence (and boundary layer modeling) in wake formation; and of the role of viscosity in modeling the effects of the flows through permeable fabric. This assessment is also made necessary by the fact that aerodynamics decelerator systems are used in a wide variety of atmospheric conditions, including non-terrestrial domains, and flow conditions, in which velocities can easily range from less than tens of feet-per-second to supersonic. Thus, this diversity in conditions has a large effect on the equations governing the motion of the fluid - and resulting approximations - and thus on the numerical methods and codes used to approximate the equations. Many of these methods are listed in Tables 2.1 and 2.2.

It should be noted that simulating inflatables for atmospheric re-entry at hypersonic speeds demand solvers (or groups of solvers) that can handle the very wide range of flow regimes, including from rarified gas, through slip flow to low density continuum. Currently, no single solver covers this whole range adequately. And as if this wasn't enough, this type of ADS applications may also involve strong reactive shocks, where the chemistry of the structure influences the pressure.

I. Assessing the important structural dynamics

The traditional approach to structure simulations is based on **Finite Element Analysis (FEA)** (Accorsi 2007). Using FEA for ADS applications is in general challenging for three main reasons, namely (Pruett et al., 2009a and 2009b): 1) parachutes and inflatables are flexible structures that can undergo large displacements and rotations which can no longer be analyzed by standard linear stress-strain theory, but rather by the more challenging **Geometrically Nonlinear analysis** (GNL); 2) parachute materials can not only carry loads in tension but also "wrinkle" in compression. Accurate simulation of wrinkling is also challenging but crucial in load distribution analysis of decelerator surfaces supporting both tensed and wrinkled fabric material components (such as with reefed ribbon-type designs); and 3) not only are the relevant mechanical properties of fabric materials anisotropic, but the degree of anisotropy can change with the motions of the structure.

Approximations are possible, nevertheless, for example in the case of structures that feature all elements in tension and deform at small amplitude and at rates that are smaller than the fluid's. Such cases are the least computationally demanding as they involve linear stress-strain material properties that are more straightforward to solve via **Linear Transient Analysis (LTA)** techniques (Accorsi, 2007), such as the **Hilber, Hughes, and Taylor** (**HHT**) method. Obviously, LTA involves the least radical structural mesh redefinition over time. Moreover, given that linear stress-strain properties of parachute materials have been well studied in the laboratory, the simulation input parameters that are required are known with a certain degree of certainty.

J. Simulating fabric permeability effects

Parachute fabric permeability is a key parameter of parachute design as it influences drag, stability, and opening forces (Knacke 1992). Indeed, parachute drag, maximum oscillation angle, and opening force all reduce with increasing permeability; and 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. Moreover, the woven nature of parachute cloth means that many of its basic properties are dependent on the very forces that are being applied to it. In the case of permeability, greater pressure differentials applied across a piece of fabric may increase the size of the interstices between the

Table 2.1 Catalog of CFD formulations and equations

Steady vs. unsteady aerodynamics

Incompressible vs. compressible aerodynamics

Viscous simplifications:
Reynolds-averaged Navier-Stokes (RANS), incl. turbulence modeling for Closure of RANS;
Thin-Layer Navier-Stokes;
Parabolized Navier-Stokes; Boundary layer equations; Vortex methods

Inviscid Simplifications:
Euler equations; Full Potential equations;
Transonic small-disturbance equation; Prandlt-Glauert equation;
Laplace's Equation

Potential Flow and Panel Methods; Prandtl's Lifting-Line Theory;
Vortex Lattice

Table 2.2 Algorithm catalog

Finite Difference, Finite Element/Pseudo-Spectral, Finite Volume

Grids: Structured Grid, Unstructured Mesh(Complex geometry)—cell types tetrahedral, prism, pyramid, hexahedron, Grid properties affecting solution: cell height and growth (capture BL), outer boundary size--supersonic vs subsonic (5 up/down, front; 10 rear), grid sensitivity study-convergence, adaptive mesh refinement

Turbulence Modeling: DNS, RANS, LES, Hybrid (RANS/LES)

Unsteady validation: coupling of time-step with grid size, linking to known unsteady flow characteristics, e.g., Strouhal Number

yarns at places along the piece, to allow more fluid to pass through the fabric with less resistance and in non-uniform fashion. Obviously, this can be an important effect when considering parachute inflation analysis, given that a parachute is likely to experience maximum load during that time. Given that many of the parachutes in use today have measurable permeability, advanced modeling *must* allow for the inclusion of permeability effects.

One current approach for accounting for such effects in FSI is to find out how much fluid pass through the fabric (structure) and remove this air mass from the calculation. This can be done by utilizing test data, or (independent) modeling data, to describe the flow velocity through the fabric as a function of differential pressure. The fluid solver, as well as the fluid and structure interface calculation, reference this curve or look-up table in order to decide how much flow to let through the interface (Aquelet et al., 2006) Obviously, the approach is physically-well grounded only in such cases where the pressure differentials along the porous structure are spatially and temporally distributed in manners that are similar to those generated in the tests (or models) used to define the lookup table. This will not be the case in applications involving high-enough rates and gradients of pressure-differentials across the fabric. As mentioned previously, pressure gradients varying over small-enough scales may yield increased permeabilities that are not only non-uniform spatially, but also substantially different from those of the lookup table, not to mention those stated in U.S. fabric specifications.

Several commercial FSI packages have begun to include options for permeability calculations. But all use permeability models and/or data which the user will be well-served to know and understand.

K. Assessing the overall simulation goals

Assessing the overall simulation goals should be the very first step in a project. Such goals would in turn determine: type of information needed from the simulation in terms of accuracy/fidelity, resolution, and validation; available computer resources; and level of algorithmic and numerical complexity that is required. Naturally, these three considerations are interrelated. For example, simulation accuracy and resolution are frequently constrained by the availability of computing memory. In addition, increases in accuracy can lead to more complex algorithms and/or more time steps, which in turn lead to increased CPU requirements. Depending on the motions of the fluid and the structure, as well as the time interval to be simulated, errors may increase and propagate more quickly than desired. Often these errors may be resolved by using a smaller time-step, however, this is again at the cost of more computer processing time. The list can quickly overwhelm even the "intelligent user" of computational methods, but as with most engineering decisions, prudent choices can lead to results more economically than, or which could not be obtained from, other means.

Finally, in considering the wide variety of environments within which ADS operate, a natural approach to scoping a problem is to separate the stages of the problem into areas which lend themselves to dominant flow and structure characteristics. For example, an airdrop application may be decomposed into extraction, deployment, and gliding stages each of which involves the dominant influence of different fluid and material properties. While a rigid material approximation could be appropriate after opening, such an estimate has little utility for deployment simulations. In addition, separating a simulation into stages or parts also offers the possibility of distributing each part to different teams of code designers, thus "parallelizing" and accelerating the pace of the overall simulation development. The key is to carefully map the problem dynamics to the constraints of the employed tools/methods. Later sections will include several FSI examples applying this principle and illustrate more detailed and specific types of problems currently under investigation.

III. Experimental techniques for validation and verification

The processes for the verification and validation of advanced computational simulations involve two distinct steps. The AIAA has published definitions of these two terms (AIAA 1998):

"Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model."

"Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model."

In other words, the verification process is answering the question "Are the mathematical equations being solved correctly?" and validation is answering the question "Is the physics being implemented correctly?" Both processes are required to ensure the simulation provides accurate solutions to the problem.

Typically, the verification process employs analytical and benchmark numerical methods to ensure convergence of the simulation solution. These methods will discover syntax errors in the coding and other issues in the code which are not directly related to the physics of the problem, whereas the validation process is a comparison with analytical and/or experimental data to ensure that the simulation is providing solutions which accurately reflect the physics of the problem. Given the complexity of the typical systems being modeled in the simulations, experimental data are the primary source for validation.

Experiments have been used traditionally for various purposes, such as gaining a fundamental understanding of the physics of a problem or system, to develop/improve mathematical models of physical phenomena, or to assess the performance of specific system (Oberkamp et al. 2006). The criteria for the data collected for these types of experiments are substantially different than data required for validation purposes. As stated by Oberkampf and Roy (Oberkamp et al. 2006), a validation experiment is an experiment that is designed and executed to quantitatively estimate a mathematical model's ability to simulate a physical system or process. Additionally, the data are intended for the computational model developer or code user, not the parachute system developer. In order to conduct a validation experiment, the computational modeler has to be able to mimic the real world experiment with well defined initial and boundary conditions. For example, if a validation experiment was designed to evaluate the forces and moments on an airfoil in a wind tunnel, then the computational model of that system should also model the wind tunnel walls with properly defined inlet conditions. This requires the experimentalist to carefully measure the geometry of the wind tunnel and all the mounting hardware for the airfoil. The experimentalist must also carefully measure and monitor the inlet velocity, pressure, temperature, turbulence intensity, and any other parameters that could affect the performance of the airfoil. The AIAA standard for verification and validation has defined a set of requirements for experimental data which are summarized as follows: (AIAA 1998)

1) A validation experiment should be jointly designed by experimentalists and CFD code developers or users working closely together throughout the program, from inception to documentation, with complete candor as the strengths and weaknesses of each approach.
2) A validation experiment should be designed to capture the essential flow physics, including all relevant physical modeling data and initial and boundary conditions required by the code.
3) A validation experiment should strive to emphasize inherent synergism between computational and experimental approaches.
4) Although the experimental design should be developed cooperatively, independence must be maintained in obtaining both the computational and experimental results.
5) A hierarchy of experimental measurements of increasing difficulty and specificity should be made, for example, from globally integrated quantities to local flow measurements.
6) An uncertainty analysis procedure should be employed that delineates and quantifies systematic and random error sources by type.

Based on these criteria, the experimentalist must follow rigorous and strict guidelines when developing and executing a validation experimental program.

To completely validate a computational simulation, it should be able to provide stable, reliable solutions over a wide range of scales from the laboratory models to full-scale prototypes. Scale plays a critical role in the design of the validation experiment and will determine the type and fidelity of data which may be measured. Validation experiments can be classified into three types: small, medium, and large-scale. Large-scale experiments employ models that are at or near full-scale systems, but may only provide globally integrated quantities such as forces and descent rates. On the opposite end of the scale, laboratory-scale models provide substantial amount of high-fidelity data over a relatively limited range of parameters. Medium-scale experiments fall in between these two limits.

Experimental techniques for validation purposes may be grouped into three broad categories of (a) techniques for globally integrated quantities, (b) point-wise measurement techniques, and (c) field measurement techniques. Category (a) methods which typically consist of canopy force and system descent rate measurements are applicable to all scales ranging from full-scale drops to laboratory experiments. These techniques are fairly common and well established for all three scales noted here. Strain gage-based load cells or force transducers along with data acquisition systems are commercially available for a wide range of loads.

Point-wise techniques are capable of collecting a time series of values for a particular parameter at a specific location. Measurement of the velocity, pressure, or strain rate at a single point in the flow field or on a point on the canopy is an example in this category. The point-wise methods are primarily applicable to laboratory and medium scale cases at the present time. Measurements of velocity components are typically performed by pressure-based probes such as pitot tubes, hot-wire anemometry, and laser-Doppler Velocimetry (LDV). The latter techniques are only applicable to laboratory scale experiments.

Field measurement techniques permit the measurement of a desired quantity simultaneously over a large number of locations on a plane or in a volume. The velocity field surrounding a canopy and the deformation of a flexible surface are two examples of field measurements relevant to the ADS applications. Moreover, field measurements are able to supply data at spatial resolutions comparable to those in numerical simulations, and as such are valuable methods for the validation of FSI simulations. Some established field measurement techniques appropriate to ADS applications are those that measure the flow field and canopy surface deformations.

Optical techniques used for flow field measurements consist of Doppler Global Velocimetry (DGV), Particle Image Velocimetry (PIV), and Particle Tracking Velocimetry (PTV). Even though there are other high resolution velocity field measurement techniques, the ones listed here are well-established and have been applied to a variety of situations. DGV is an extension of the LDV method, and was originally developed for high speed flows. With proper adjustments, this technique may be applied to a plane of 1.5 meter scale and velocities on the order of 1 m/s (Jenkins et al. 2010). PIV is a technique that has been in use for the last 20 years in various laboratories (Adrian et al. 2010), and commercially available systems may be acquired to interrogate a plane of a few feet in extent (Raffel et al., 2007). This technique has been applied to a small scale flat, circular canopy model in a water tunnel (Johari and Desabrais, 2005). The PTV technique is similar to the PIV technique except that individual particles in a flow field are tracked in time to extract the Lagrangian velocity of that particle. The ensemble of particle velocities is then mapped out to a Cartesian grid. An initial assessment of a PTV method for flow field measurements in a 3.6 m × 3.6 m × 3.0 m volume around a medium-scale parachute was recently conducted (Feng et al., 2007).

Canopy surface measurements can be carried out using several methods including laser scanning (Lee and Li, 2007), traditional photogrammetry with specific marked targets (Jones et al. 2007; Shortis et al., 2009), or the Image Correlation Photogrammetry (ICP) method where the deformations of a stochastic pattern of markers is tracked (Schmidth et al., 2003; Ghaem-Maghami et al., 2007). All these techniques have been successfully applied to parachute canopies in laboratory and sub-scale models.

IV. Sample FSI simulations from non-ADS applications (Short version)

Advanced modeling has become part of the investigative toolkit of many fields of science and engineering. Most interesting is the fact that many of the computational and algorithmic challenges encountered in ADS applications are, or have been, faced in many of these fields. Most have been solved via either the use of relevant approximations, taking advantage of existing structural stiffness (relative to the fluid's), and/or of structural motions being known from detailed experimental investigations.

Editorial note: The following examples below, which are merely listed in order of appearance, are further discussed in the "long" version of this white paper posted on www.aerodecelerator.org.

A. FSI in aircraft mechanics and aerodynamics

B. Turbomachinery example

C. CFD simulations for suction feeding by fish

D. FSI simulation of a robot avian model

V. Current modeling capabilities for ADS applications (Short version)

Efforts aimed at simulating aerodynamic decelerators with FSI have taken place since the 1990s. These have covered the gamut of ADS applications from landing parachutes, to drogues, to airbags, and to inflatables used for atmospheric re-entry. Interestingly, the recent usage of FSI, CSD and CFD tools has involved the use of commercial solvers rather than codes developed in-house. This section aims at providing a short, *and by necessity incomplete*, survey of the kind of results that can be obtained with today's advanced modeling capabilities, including CFD and CSD as stand-alone tools of investigation. A full bibliography of *all* advanced modeling studies of aerodynamic decelerators published in the past four decades can be found on www.aerodecelerator.org.

Editorial note: The following examples below, which are again listed in order of appearance, are further discussed in the "long" version of this white paper posted on www.aerodecelerator.org.

A. Historical perspective

B. CFD simulation examples

B1. Aerodynamics of a rigid ringslot parachute model
B.2 CPAS test platform aerodynamic coefficients for low-DOF modeling

C. CSD simulation examples

D. FSI simulation examples

D.1 Tension cone simulation for the NASA MSL program
D.2 DGB parachute in the wake of a re-entry capsule
D.3 Simulation of the US Army T-11 paratrooper parachute
D.4 Orion Airbag Landing System Example
D.5 Cruciform parachute model in a wind tunnel

VI. Short term goals for aerodynamic decelerator systems modeling

A. Introduction

The examples reviewed in section V clearly show where CFD, CSD and FSI can be most useful for ADS applications in the near future. Although many versions of these simulations tools have been developed in-house by several governmental and academic institutions, current commercially-available software packages are reliable enough for simulating flows about complicated fixed shapes. Most of these packages also have implemented loosely-coupled partitioned schemes that should also be reliable enough in problems where the fluid-structure interaction is weak (Section II.D).

Thus in the short term at least, it is realistic to imagine CFD and FSI as tools for ADS design in a variety of problems in which the structural deformations are small and slow. This should apply particularly well for decelerators used in steady speeds at low rates of oscillation, which is quite crucial as ADS design invariably begins with drag performance characterization during descent. Moreover, and particularly with landing chutes, the motion dynamics of the payload is characterized by small acceleration *modulii*, or in other words by flow dynamics that isn't quite unsteady and thus easier to tackle numerically**.**

Even though these simulations tools (and required computing power) are immediately available for basic drag characterization, not much simulation effort has so far been dedicated for the actual productions - and publication in the public domain - of numerical data relevant to ADS design. The reason for this state of affairs will be discussed in a later section. But for now, attention will be paid here to identifying the most important types of ADS problems that could be tackled by current (and well-developed) CFD/CSD/FSI techniques.

B. CFD studies of well-defined rigid shapes

Even though parachutes and inflatables are inherently soft structures, the payload that they carry usually are not. Moreover, and in a first approximation, parachute sub-components such as suspension lines and canopy fabric under tension may be considered as "rigid" enough to allow the use of CFD simulations in the study of several problems of importance to ADS applications, a sampling of which is listed in Table 6.1. In many of these cases, the resulting CFD data could be used in low-DOF models that otherwise would require empirical data as, for example, with the payload aerodynamic coefficients used in NASA's *Decelerator System Simulation Application* (DSSA) (Cuthbert and Desabrais, 2003; Potvin, Charles and Desabrais, 2007).

The main computational challenges inherent in these CFD-only studies reside mostly in 1) a good solid shape reproduction of the payload or canopy component involved in deflecting the flow; 2) a good boundary layer resolution, which by necessity will require a very large number of grid points; and 3) a well-chosen turbulence model if RANS is used. But we note that these challenges have already been met with current desk-top and workstation computer technology, as exemplified by recent CFD studies (McQuilling et al., 2011; Mohammadi and Johari, 2010).

Table 6.1 Proposed CFD studies of important ADS problems

Application	Remarks
Payload aerodynamic coefficients versus angle of attack (w/r) to relative wind and free stream velocity	Results to be implemented in low-DOF models of canopy-payload oscillations during descent
Suspension line drag versus angle of attack (w/r) to relative wind and free stream velocity	Important contribution to the overall drag of hemispherical parachutes (near-sonic and supersonic applications) and parafoils
Discharge coefficient of vents and gaps	Important input in the computation of a parachute's total porosity
Drag efficiency of rigid cup clusters versus angle relative to relative wind; calculation of the tangential force	Important input for the dynamic modeling of the descent of a parachute cluster system

C. "First Order" CFD studies of inflated canopies

As demonstrated at length in one of the most used parachute design manuals (Knacke, 1992) the prediction of the averaged drag performance of aerodynamic systems in the post-inflation descent stage is based on knowing the scaling properties of the drag coefficient C_D in terms of the following design considerations:

1) Nominal (D_0), constructed (D_c) or projected diameter (D_p)
2) Mach number
3) Reynolds number
4) Suspension line length
5) Total canopy porosity
6) Fabric and tape stress-strain characteristics
7) Payload-canopy separation distance

Additionally, these properties depend on whether the canopy is reefed or not, and used singly or in a cluster.

Given the large number of different parachute designs being used currently, a systematic investigation of all such designs in terms of these seven parameters would be quite time-consuming both in terms man-hour and computer hour. An alternate - and workable - short-term research program could be based instead on the study of the test cases shown in Table 6.2 [M. Gionfriddo/H. Johari; private communication], which were inspired from Knacke's design guide (Knacke, 1992). These cases could be created by first generating an 'inflated' model of the canopy using a presumed pressure distribution for structural simulation (CSD), and then by subsequent flow analysis of the rigid inflated canopy using CFD. More sophisticated FSI simulations involving time dependent response of the system would be considered as a follow-up level of sophistication. All the cases listed in that table involve full-scale canopies at realistic descent velocities; many are featured in the form of graphs the design manual (Knacke, 1992). Providing numerical data over the documented range of parameters as well as extrapolation to new design points would not only boost confidence in the computational capabilities, but also extend the range of applicability of these design plots.

D. "First Order" FSI studies of inflated canopies

FSI techniques *should* be considered as the next and ultimate level of sophistication in the study of the problems listed in Tables 6.1 and 6.2. Moreover, all should be feasible using the loosely coupled partitioned approach. Additional problems to consider could include payload wake effects on parachute deformation (particularly in near-sonic and supersonic realms) as already investigated by Lingard et al. (2007) as well as the topics listed in Table 6.3.

Table 6.2 List of the test cases shown in Knacke (1992) that could be further informed by CFD simulations (and later FSI simulations)

Canopy	Independent parameter	Dependent variable	Fig. #	Comment
Flat circular; hemispherical; extended skirt; flat ribbon	Line length (L/D_o)	Drag coefficient (C_{Do})	5-20	Effect of suspension line length from free fall and wind tunnel studies
Apollo drogue chute behind CM, PTV, ICTV	Forebody-canopy separation distance ($L_s/D_{forebody}$), forebody diameter ($D_p/D_{forebody}$)	Drag coefficient (C_{Do})	5-21	Fairly large separations when at full-scale, may be scaled down in the simulations
Flat circular; flat square; guide surface; flat ribbon	Rate of descent, or more appropriately Reynolds number, Re_o	Drag coefficient (C_{Do})	5-18	Solid flat canopies are unstable and would require FSI to get the proper drag coefficient
Flat circular; solid 15, 30, 45-deg conical; ¼-spherical	Rate of descent, or Reynolds number, Re_o	Drag coefficient (C_{Do})	5-16	Small canopy diameter of D_o = 3.8 ft; no mention of stability
Solid conical	Cone angle and rate of descent	Drag coefficient (C_{Do})	5-17	28-ft solid fabric conical canopy data with smoothed curves
Extended skirt with several diameters	Rate of descent, or Reynolds number, Re_o	Drag coefficient (C_{Do})	5-25	Reasonably stable descent observed
Cross chutes of different sizes	Rate of descent, or Reynolds #, Re_o	Drag coefficient (C_{Do})	5-27	Potential rotation; some wind tunnel data on small scale models

Table 6.3. FSI simulations of interest in constant-speed flow

Application	Remarks
The venetian blind effect on square of crisscrossing ribbons as seen on ribbon-type parachutes [Knacke, 1992, figure 6-24].	Crucial information for the understanding of dynacally-induced changes of the (total) porosity at high freestream velocities
Vent and gap enlargement at high dynamic pressure	Crucial information for the understanding of dynamically-induced changes of the (total) porosity at high freestream velocities

VII. Challenges for the FSI modeling of ADS applications

The previous two sections have shown that already there are several aspects and types of aerodynamic decelerator systems that can be modeled with affordable computer resources and with either standalone CFD and/or CSD, or the (simpler) partitioned types of FSI algorithms. That is the good news. However, a large number of challenges remain before advanced modeling can be considered as a routine design tool for *all* ADS problems. These challenges are explained here, followed in the next two sections by recommendations that suggest ways to meet them.

Challenge 1 – Creating, testing and using fully-coupled FSI simulations for ADS problems

The last section made the case for the use of advanced modeling in several types of ADS applications, most of them dealing with the quasi-steady-state regime where structural deformations are small and/or take place at small rates, thereby allowing the use of (relatively) fast partitioned FSI simulations (either loosely-coupled or tightly-coupled). Such schemes, however, have proven to be inadequate in fast and large structural deformation cases, as for the simulation of deployment and inflation at very high (deployment) speeds. Here fully coupled fluid and structure simulations (Section II.D) may be the only meaningful approach to the problem.

There are several major impediments which currently prevent the use of fully-coupled FSI modeling in ADS applications. First, this approach requires solving a large set of highly nonlinear (and coupled) Partial Differential Equations (PDEs) for fluid dynamics, structural mechanics, and mesh motions (Appendix 2). Such solutions are particularly difficult to obtain when the structure undergoes large deformations as a result of the aerodynamic forces at play. This often causes the FSI simulations to break down because of the convergence issues of nonlinear and linear iterative solvers and large mesh stretching/distortions.

Challenge 2 – Dealing with the nonlinear mechanics of complex constitutive materials, and with their coupling

This challenge concerns mainly fully-coupled FSI simulations where the non-linear character and the vastly-differing time and spatial scales of many fluid and structural properties become important, and at the same time, difficult to implement into practical and fast-converging algorithms. These include:

- Elastic response of parachute material under static and dynamics loading; permanent deformation or failure of the supporting structures (stitching, tapes, etc) under certain conditions; permeability of woven fabric, which may feature variable porosity at different flow speeds;
- Fluids internal or external to the structure, which may display turbulent properties; compressible effects for high speed applications, etc.

- Material-fluid coupling, which usually assume quasi-equilibrium at exchange of information between domains (as discussed in Sect. II.G), an assumption that is not necessarily correct as with examples such as these: snap-through, over-expansion of skirt diameter, canopy collapse and flutter – all examples where material stress waves, structural deformation, system component motion, and fluid evolution may be out of sync.

Challenge 3 – Widely varying flow regime and structural dimension range

For many terrestrial ADS applications, the flow regimes vary from moderate to high subsonic aircraft speeds at deployment to low and very low speeds after inflation, thus often involving speed-decreases by as much as two orders of magnitude from packed size to fully-inflated. Moreover, decelerator systems also undergo radical dimensional changes over the entire course of a mission, from a packed state to an unfolded and inflated state. And so, structural deformation will be characterized by large amplitude-motions that can also span several orders of magnitude.

As meeting this challenge with a single, fully-coupled approach over the entire dimensional and speed ranges is impractical in the short and medium terms, an alternate approach may be to specialize the modeling to specific mission stages (for example, deployment vs. inflation vs. steady descent) in which these dynamic ranges are reduced. Nevertheless, several challenges will remain even within this approach as speed ranges encountered are still significant. Moreover, where boundary layer, total porosity and other effects involving turbulence are important, dealing with high resolution grids at the higher speeds may present serious challenges from the point of view of computer resources.

Challenge 4 – Full system models with broad range of fidelity for components

Even though the relevant equations of motion of all the simulated components (i.e., fluid and structure) are well-known, no empirical data exist to characterize all of them at the same level of detail (accuracy). For example, the payload of many military airdrop canopy calculations (i.e., cargo or paratrooper) are not modeled at all; or in super/hypersonic applications where shock and wake interactions between payload and canopy are known to be very significant, the support lines of the system are frequently not modeled explicitly in the fluid domain (if taken into account at all); finally, variable winds (inlet flow conditions) are very seldom accounted for, thus eliminating the possibility of modeling wind gusts or such things as long-lived vortices produced by the passage of aircraft.

Challenge 5 – Knowing the applicability range of the numerical schemes

Being aware of the applicability range of a particular FSI scheme, either fully coupled or partitioned, is crucial when used in applications that are different from the original application for which a particular scheme was developed. For example, given that decelerator systems of various sizes use (typically) the same fabric, tape and chord components, the effect of changing structural inertia relative to that of the fluid usually becomes a litmus test for using the same code across canopy sizes (Sect. II.G). Anecdotal evidence exists that general loosely-coupled FSI approaches don't produce stable calculation strategies for all ADS applications, as they are particularly poor when the ADS material is very flexible compared to the fluid or encompasses large masses of fluid. At this time there is insufficient "best-practice" guidance on how to model "delicately-balanced" ADS FSI applications. This issue must be explicitly explored and addressed by the technical community.

Challenge 6 – FSI research overhead

Preparations required to get started with fully-coupled FSI systems or even partitioned systems are very tedious, time consuming, and difficult to port across applications. Moreover, FSI modeling requires in-depth understanding of a large body of knowledge and technicalities. Such technicalities include:

- Numerical methods/techniques: Grid generation and quality, FEM/FVM/CSD, convergence, singularity of linearized matrix systems, numerical dissipation vs. physical dissipations, numerical stability, preconditioning, Generalized Minimal Residual Method (GMRES); other smart linear solver, etc.;

- High performance computing issues: highly parallel computing, load balancing, compiler flags, graphics processing unit (GPU) based supercomputers, cloud computing, FSI on laptop, etc;
- So-called "coupling" issues like: FEM/FVM-Mesh-CSD coupling, time-sub-temping, brute-force search algorithms, multi-physics/strong coupling, etc.;
- Issues related to the dynamics of systems: airdrop terminal velocity, parachute inflation, breathing of parachutes and skirt vibrations, physical instabilities, etc.

This required body of knowledge is bound to severely impact the ADS FSI workforce as the heavy focus on interdisciplinary expertise requirement will discourage student interest in such topics for research thesis. In many ways, it shouldn't be surprising to find the bulk of the ADS FSI workforce as being composed mainly of experienced engineers and scientists with doctoral degrees. **In our view the need for a very specialized workforce trumps the need for computer resources, as the latter are made increasingly affordable and/or available through alliances with government agencies**.

Challenge 7 – Constructing an experimental database for meaningful FSI V&V

As Section V shows, the number of FSI studied of ADS applications has quickly outgrown the relevant experimental database currently available for V&V. This is critical since, even though FSI brings a much-improved theoretical description of reality in comparison to the low-DOF modeling of the past, the accuracy of the many approximations used in FSI cannot be confirmed *without* explicit comparison with experimental data. As discussed in Section II, such approximations include those used in the *Interface* (in connection with ALE and permeability effects, for example) approximations that really cannot be validated by means other than experimental.

Unfortunately, expanding the V&V database will be a difficult process given the highly coupled and unsteady nature of the flow around a parachute canopy or inflatable. Not only will it be difficult to obtain experimentally field-like fluid and structure data of relevance (like pressure and velocity distributions), but also data that can be reproduced in repeated experiments (or data collection events). The complexity of this problem is further exasperated by the scale of most parachute systems, which typically are in excess of the high fidelity measurement system capabilities. These challenges have severely limited the number of parachute experiments which could be considered for use in validation. Most experiments in the past have been conducted to assist in the development of parachute systems or to solve a particular airdrop requirement with little regard for validation of numerical simulations. There are a few examples which may contain adequate data for use in validation or were specifically designed for validation purposes; but those are very few.

VIII. The way ahead – FSI R&D

There are two broad categories of recommendations for the ADS community to consider, namely recommendations for theoretical work and recommendations for experimental work. The former is discussed first here and the latter presented in Sect. IX.

Recommendation 1 – Assessing quantitatively what is meant by weak versus strong fluid-structure coupling in the context of ADS applications

Deciding whether to a use partitioned approach or a direct solution for a given aerodynamic decelerator problem can always be based on the availability of experimental data. But an equally important strategy is to make that decision from the examination of criteria that are quantitatively based on the physics at play. This ought to be obvious because designers of FSI simulations are expected to have a good quantitative sense of what is relevant physically. For the user, such quantitative measures could help choosing the correct approach from the very start of the simulation-planning process.

Figuring out such a criterion (or criteria) should begin with a basic examination of relevant dimensionless ratios. In the light of the qualitative definition in Section II.D of *weak*-versus-*strong*-coupling based on mutual reaction times, one such ratio could include that of a structural component acceleration modulus δ defined in terms of the length (L_{struct}) and density (ρ_{struct}) scales characterizing the component, fluid velocity (V_{fluid}) nearby and fluid pressure difference (ΔP_{struct}; after subtraction orthogonal fabric tension component supported by the structure), namely as $\delta \equiv L_{struct} a_{struc}/V_{fluid}^{2}$ =

$L_{struct}F_{struct}^{tot}/m_{struc}V_{fluid}^{2} \sim t_{fluid}^{2}\ (\Delta P_{struct}/\rho_{struct}L_{struct}^{2})$. The use of such ratios could be further motivated, over time, by comparisons with simulations and experiments performed on *benchmark problems*, as further discussed in *Recommendation 4* below, and in the end, by the experience (and wisdom) gained by years of use of FSI by the ADS community.

Recommendation 2 - Indentifying the most important aspects of parachute and inflatable design that could be informed by advanced modeling in the short, medium and long term

A sure way towards meaningful progress is to identify which aspects, feature and property (or properties) of aerodynamic decelerators that are ripe for advanced modeling solutions in the short term, which ones could be achieved in the medium term and which ones could see a solution only in the long term. As shown in Section VI, chief among those short term problems are those related to the most basic properties related to the drag performance during steady descent.

But other, less obvious aspects need to be indentified and further defined as problems to be tackled in the medium term. Many would concern events that are more dynamical in nature, such as oscillation-generated canopy deformations during descent. Obviously, other highly dynamical problems such as deployment and inflation would represent a distant goal for fully-coupled FSI treatment, although partial solutions could be entertained in the short term with specific systems operating in dynamical regimes where approximations are possible.

Recommendation 3 – Identifying the algorithmic approaches/approximations that are to yield results in the short and medium term, and at an agreed-upon level of accuracy

Given the many faces of advanced modeling discussed above, it turns out that the solution of many aerodynamic decelerator problems are possible without resorting to a highly-coupled FSI approach. Partitioned schemes, either loosely or tightly coupled, should be good tools for investigating structures that deform slowly and periodically, and with small amplitudes. Simpler modeling approaches in general would be especially relevant in many design problems.

Recommendation 4 - Continued development of FSI capabilities for ADS applications via the study of benchmarks problems or systems

Given the complexity of the flow and structure physics of decelerator systems, there will always be a need for benchmark studies, to be used to clarify a large number of technical issues, *particularly with respect to the approximations used in the fluid and structure solvers, as well as in the specific implementation of the fluid structure coupling*. Very importantly, benchmarks could be used also in accuracy studies of integrated outputs (such as drag) in relation to the accuracy of spatial/temporal outputs (such as fluid velocities and pressures).

By definition, benchmark systems would not necessarily be identical to actual parachute and inflatable systems, but similar and non-trivial enough to include many of the complex features used in any advanced modeling scheme. **Most importantly, such benchmarks should be defined in manners that make them amenable to experimental investigation in a laboratory setting that uses all available measurement protocols – current and future (Sect. III and Sect. IX).** Much work remains to be done before suitable benchmark systems can be built and studied. Candidate benchmarks could be patterned after the following examples:

<u>For CSD:</u> Material Response to simple static loading: Parachute materials with previously characterized material properties can be loaded in a series of simple conditions – a cylinder, a lozenge-shaped pillow, and an inverted parachute shape filled with water - and the response of the material measured experimentally. The same loading situations can be replicated computationally using several different CSD simulation codes and the experimental and computational results were compared (Pruett et al., 2009).

<u>For CFD:</u> Several bluff body shapes have been identified as relevant starting points to approximate the fluid dynamics characteristic around parachute canopies. A circular disk, a smooth cup, and a cup with fluting similar to the crenulations in a parachute, all with their axis of symmetry inline to the oncoming flow, have been characterized recently experimentally (McLaughlin et al., 2011) and computationally

(Noetscher and Charles, 2011). Various fluid dynamic parameters were measured and the differences and similarities among the various shapes and between the experimental and computational efforts were identified.

For FSI: Efforts are currently underway to formulate and conduct a series of complementary experimental and computational investigations of a simple flexible flap responding to and interacting with an incident flow.

IX. The way ahead – FSI V&V

The fourth and last recommendation is perhaps the most important, as it establishes the very foundations from which the viability of FSI simulations for engineering and design will be assessed.

A. Introduction

The validation of FSI numerical simulation should follow the guidelines discussed in Section III, and take advantage of the experimental techniques outlined therein. It is proposed that the validation of ADS FSI simulations should be performed against a hierarchy of data sets each with higher resolution and more specific information. For example, FSI simulations of decelerator systems are used routinely for the computation of drag forces on canopies. The drag force is a globally integrated parameter that can be easily compared against experimentally measured values. However, close correspondence between the computed and measured drag force values may not necessarily validate a FSI simulation tool as a large number of parameters influence the canopy drag. Other parameters such as the geometry of the canopy, the time averaged velocity profiles in the near wake, turbulent velocities and stresses, and the underlying spectral content of the flow field provide a much richer base for the validation effort.

It is clear that many or all of these parameters may not be available from testing of large scale models in the field. It is suggested that specific experiments, at the laboratory or larger scale, be designed for the validation of FSI computational simulation tools. As noted in Section III, the validation efforts require close collaboration between the experimentalists and the numerical analysts to ensure that the numerical models are as close as possible to the physical experiments.

B. Templates for future work

There are a few examples of experiments which may contain adequate data for use in validation or were specifically designed for validation purposes. McBride et al., (1999) measured the pressure on the surface of a rigid parachute model which mimicked the geometry of a ribbon parachute in order to collect data for the validation of a numerical simulation tool (Peterson et al., 1997; Behr et al., 1999) being developed at Sandia National Laboratory. The rigid model was towed through a water tow tank and measurements of the surface pressure were collected through small pressure tap holes located on the interior and exterior of the model surface. The experiments were conducted by accelerating the model up to a velocity of 4 ft/s, then maintained that speed for 6 seconds before being decelerated to a stop. The data were collected for multiple configurations which included three different angles of attack and five roll angles and each configuration was repeated 10 times which resulted in over 300 unique data sets. Recently McQuilling et al. (2011) conducted a CFD analysis of the experimental setup and achieved comparable results. This experiment would constitute a small-scale laboratory experiment.

Bergeron et al. (2009 and 2011), have documented the drag over various types and configurations of suspension lines in a low-speed wind tunnel. Hotwire anemometry was used to collect wake velocity profiles and shedding frequencies at freestream velocities of 45 fps, 51 fps, 76 fps, and 93 fps, with tensions between 10-55 lbs. Tests included single lines at several angles of attack as well as multi-line streamwise- and spanwise-Y configurations. Measurements are made at several heights along each configuration and the variation due to the geometry, including line spacing (T/D and S/D) and profile, shows significant variation in the associated momentum deficit.

Johari and Desabrais (2005) and Desabrais (2002) measured the detailed flow field in the near wake of a small-scale flexible parachute model to better understand the aerodynamics of parachutes. A fabric parachute model was mounted in a low speed water tunnel and the temporal evolution of the two-dimensional flow field along the centerline of the canopy was measured using the PIV technique.

Simultaneous measurements of the force on the model and the cross-sectional profile of the canopy were also carried out with the flow field measurements. An image of the canopy mounted in the tunnel is presented in Fig. 9.1 and a sequence of phased average vorticity fields showing the progression of a vortex ring is shown in Fig. 9.2. It is clear from these plots that the shear layer originating from the canopy skirt rolls up into a nearly symmetric vortex structure and proceeds downstream. This vortex structure separates from the canopy shear layer and gets convected downstream of the canopy where it becomes distorted and loses its symmetry. The flexible nature of the canopy allows its shape to be altered by the formation and motion of the vortex structure given its close proximity to the canopy surface. This in turn also alters the way the vortex structure is formed as compared to the aerodynamics of a rigid model which would have similar geometry to the canopy. This close coupling of the temporal evolving geometry and flow field is an example of an experiment which could be utilized to validate the fluid-structure coupling module of the numerical simulations.

The conclusions of this research were that the flat circular parachute canopy model exhibited a periodic variation in the canopy diameter ("breathing") caused by the shedding of vortex structures from the canopy. The flexible nature of the parachute canopy allows for the periodic vortex shedding from the canopy at a unique frequency which is not observed in rigid axisymmetric bluff bodies such as disks or cups. This shedding also creates a cyclic loading on the canopy which was identified by independent force measurements. Whereas this experimental research was not explicitly designed for use as a validation experiment, there is sufficient data available and of adequate fidelity that it could be used for validation of numerical simulations with fluid-structure interaction capabilities.

Both of the preceding examples of validation experiments are considered small or laboratory scale experiments. While capable of acquiring high fidelity data, the scale of these experiments is a limitation. For V&V purposes, it is desired to acquire data at various canopy scales. Thus, a series of indoor parachute drop experiments were recently conducted at a larger scale (Desabrais et al., 2007). The experiments consisted of dropping an instrumented payload parachute under a medium-scale canopy (3.5-ft to 9.0-ft diameter) inside a tall enclosed environmentally isolated structure. The parachute canopies used in the tests were either a flat circular, solid cloth canopy or a ring slot canopy. A schematic of the experimental setup is shown in Fig. 9.3. The parachute system was dropped along a vertical guide wire which was attached to the floor and ceiling of the test chamber to ensure the system fell along a vertical trajectory with minimal lateral displacement. The instrumented payload measured the forces on the suspension lines, the acceleration of the payload, and the descent velocity of the payload. It was deemed important to measure the three-dimensional geometric shape of the canopy during descent using an innovative photogrammetric shape measurement technique developed in collaboration with NASA Langley Research Center (Jones et al., 2007). A series of six cameras were placed on the floor around the drop location which recorded the position of retro-reflective targets mounted on the interior of the parachute canopy as the parachute dropped through a spatially calibrated volume of space. For a limited set of experiments, a pair of cameras was also mounted on the payload to record the shape of the canopy in detail. Figure 9.4a shows an image of a canopy dropping with the retro-reflective targets (Desabrais et al., 2007) and Fig. 9.4b shows a sample image which was used to calculate the shape of the canopy from an onboard camera (Jones et al., 2007). A target tracking image processing routine (Shortis et al., 2009) was used to calculate the locations of the retro-reflective targets on the canopy and a sample of the results is shown in 9.5.

A detailed study of the structural response of parachute fabrics to applied loads was conducted to provide experimental data for validating the structural portions of the numerical simulations (Carney et al. 2007). These experiments examined the strain distribution through three simple test articles of increasing geometric complexity and made from parachute fabrics under an applied load. A simple fabric cylinder was bi-axially loaded from the inside by a latex bladder pressurized to a constant pressure as an axial load was applied to the cylinder. The strain distribution through the fabric was measured using the Image Correlation Photogrammetry (ICP) technique described in Section III. The effects of fabric wrinkling were examined by pressurizing a parachute fabric pillow or airbag and measuring the three-dimensional shape and strain using the ICP technique. Lastly a complex geometry was created by inverting a small scale parachute canopy and filling it with water which generates a static pressure distribution through the interior of the canopy surface. ICP strain and shape measurements were made over a portion of the canopy under this known pressure distribution.

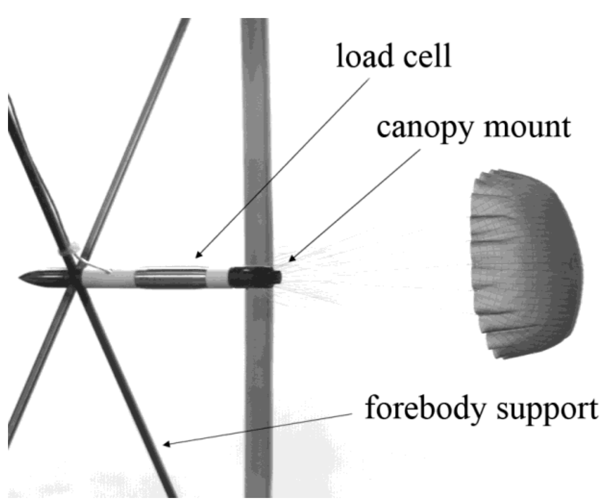
C. Recommendations

As seen in these examples of parachute validation experiments, the complete physics of the parachute aerodynamics is not examined but only portions of the problem are studied in great detail. While this provides validation data for only components of the simulations tools, the ability to fully quantify all parameters of a parachute system and the associated flow is not possible given the current state of the art instrumentation and measurement technology. These limitations are particularly true for full-scale parachute systems. It is important to be able to quantify the environment in which the parachute system is exposed during its descent. For laboratory experiments, the environmental conditions are either controlled or closely monitored. However, an aircraft airdrop with a full-scale parachute system occurs in the open atmosphere where the environmental conditions are either unknown or there is very limited information. Knowledge of the air density, temperature, pressure, and atmospheric turbulence levels are important parameters. Perhaps the most important unknown during an airdrop is the wind vector along the trajectory of the parachute system. The current methods for quantifying the winds during an airdrop are adequate for developing and validating the performance of a parachute system; these methods are insufficient for obtaining experimental validation data. Typically, the wind measurements are low fidelity and taken at a time well in advance of the actual time of the airdrop resulting in the possibility that the wind conditions may change between the measurement time and the airdrop. Additionally, depending on the parachute system, it is possible the airdrop will occur in a different spatial location from where the wind measurements were made.

In addition to the difficulties in characterizing the environmental drop conditions, the types of measurements available for the full-scale parachutes are very limited. As mentioned previously, globally integrated measurements of the parachute system performance are readily achievable on full-scale systems. However, the technology and methods for collecting high fidelity data on the structural and aerodynamic performance of full-scale systems, which is required for validation purposes, is unsatisfactory based on the current state-of-the-art of instrumentation and measurement technology. These limitations will restrict the use of full-scale parachute systems for use in collecting experimental validation data.

Other experimental research efforts are currently underway which should yield additional data which can be used for validation of numerical simulations. However, these results have yet to be disseminated. Development of sensor systems for measuring the pressure around a parachute canopy and for monitoring the strain in the canopy fabric would aid in collecting experimental validation data. Similarly development of new innovative measurement techniques are needed to quantify the temporally and spatially evolving flow field around the parachute canopies of medium and large scales. Continued development and evolution of measurement technologies for collecting validation data across the spectrum of measurement environments will help assure that computational simulation suites being developed provide stable and reliable solutions on the performance of a wide range of parachute systems and other airdrop technologies.

Figure 9.1. Flexible parachute canopy with mounting support structure.



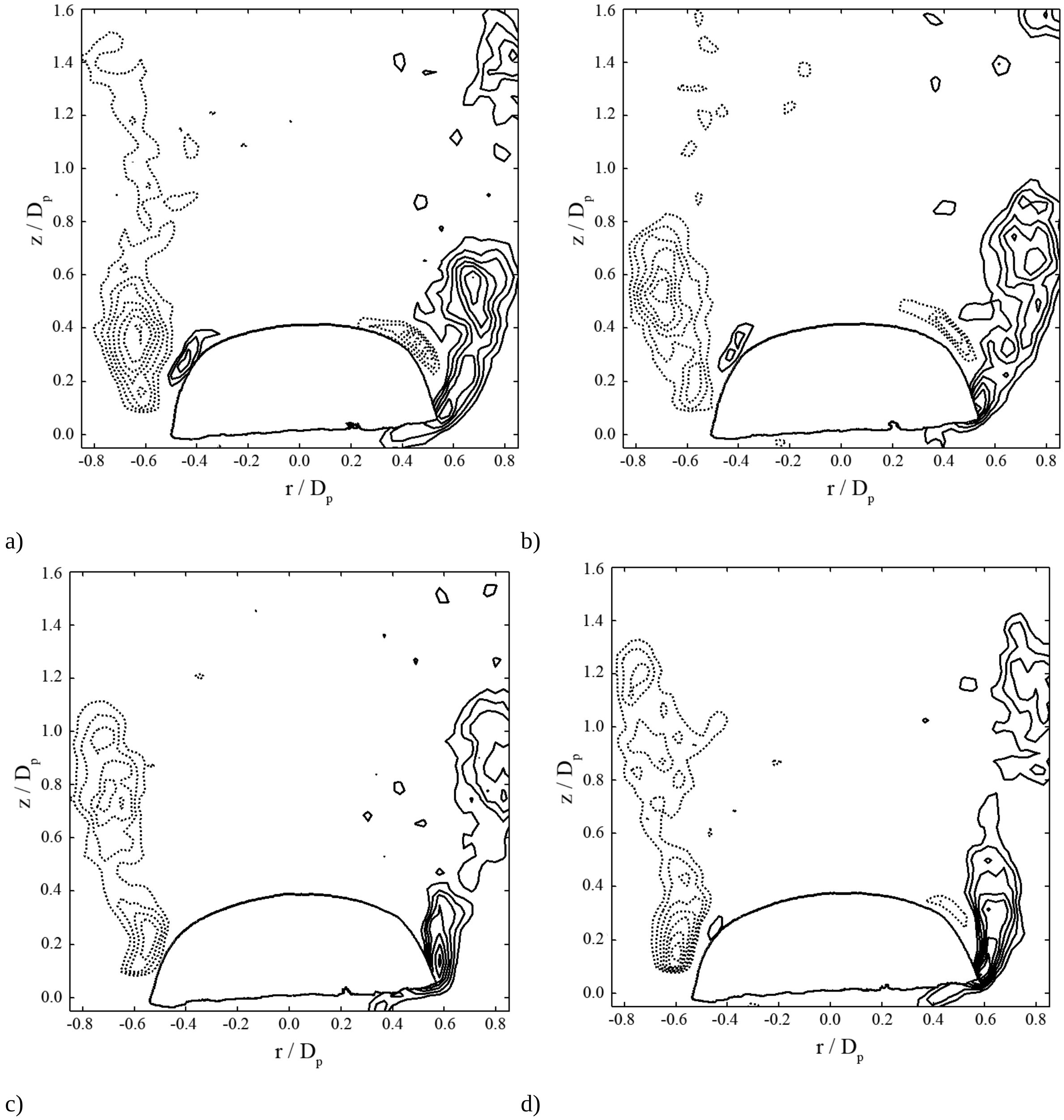


Figure 9.2 Contours of the phased average vorticity field in the wake of the parachute canopy showing the shedding of the vortex ring where D_p is the projected diameter of the inflated canopy (Johari and Desabrais, 2005).

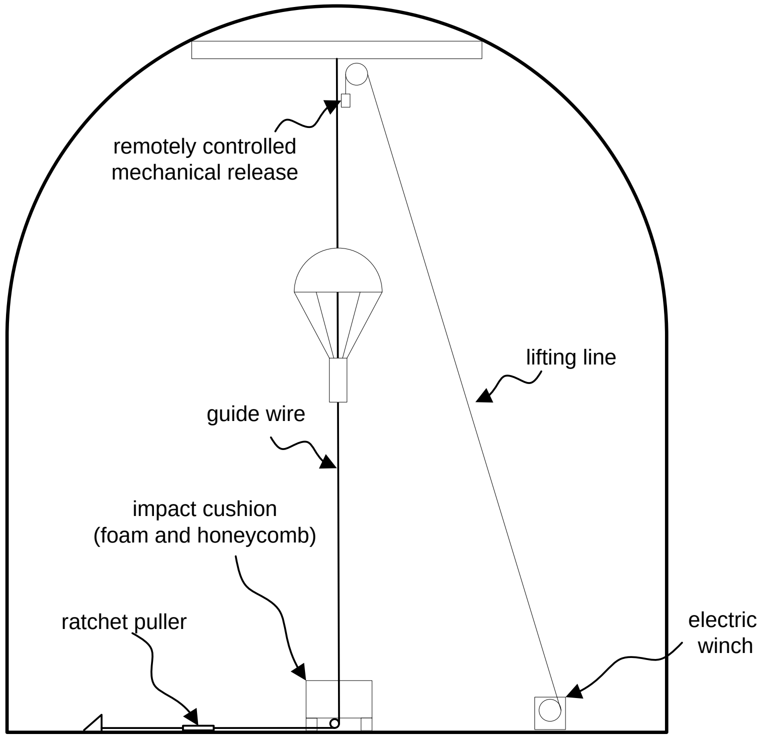
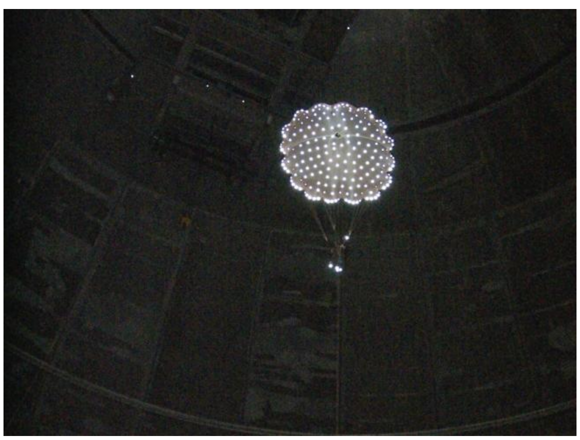


Figure 9.3 Schematic of the medium-scale parachute experiments (Desabrais et al., 2007).

a)



b)

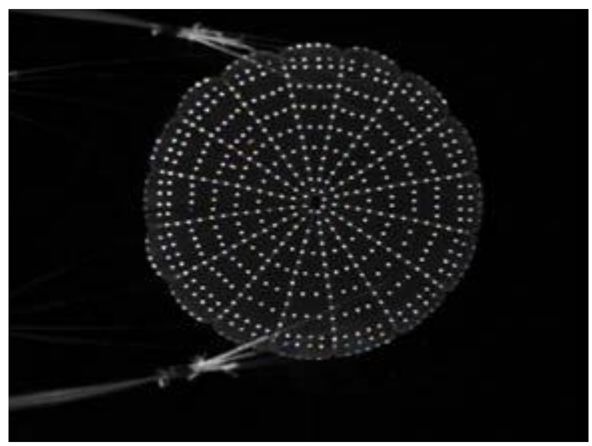


Figure 9.4 a) Photograph of the medium-scale flat circular solid cloth parachute taken with a hand held camera Desabrais et al 2007; b) sample image used to calculate the shape of the parachute, from a onboard camera (flat circular solid cloth canopy) (Jones et al., 2007).

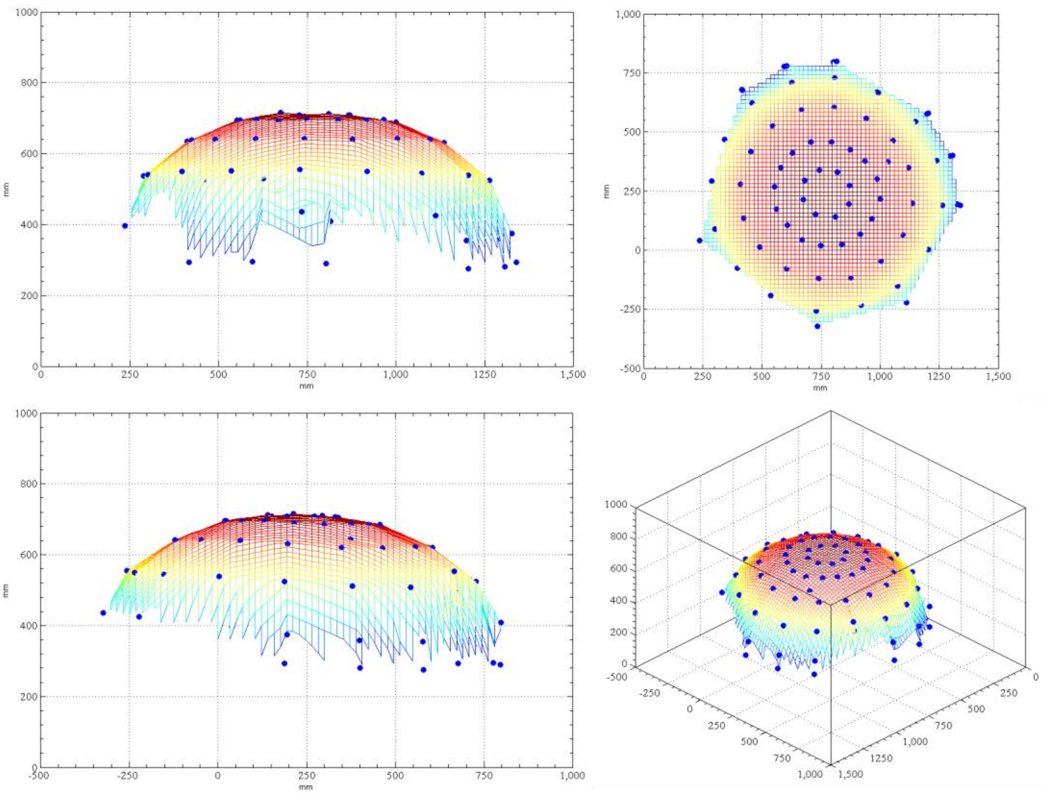


Figure 9.5 Different views of the retro-reflective target locations from a ring-slot parachute drop.

Appendix 1. FSI roadmap participants

Editorial note: The list of participants is available in the "long" version of the white paper posted on www.aerodecelerator.org.

Appendix 2. Partitioned FSI – A Mathematical Introduction

A. Introduction

Fluid-Structure Interactions (FSI) is inescapable features of the complicated flow physics where strong coupling between fluid dynamics and structural dynamics occurs. One such example is understand the FSI behavior of parachute during canopy inflation and decent. Such simulations can substantially reduce the design costs of parachutes by reducing the number of rather expensive experiments/airdrop tests required. Additionally, FSI simulations can augment experimental approaches by providing detailed fluid flow and structural deformation characteristics of the parachute systems under various scenarios. FSI modeling of parachutes requires simultaneously solving the Navier-Stokes equations (a set of highly nonlinear Partial Differential Equations (PDEs)) for fluid dynamics, structural mechanics, and mesh motions. Parachutes are made of membrane type structure (usually nylon clothes) that goes through large deformation as a result of aerodynamic forces. This often causes the FSI simulations to break down because of the convergence issues of nonlinear and linear iterative solvers and large mesh stretching/distortions. It is, therefore, difficult to operate and requires in-depth knowledge of numerical techniques, fundamentals of fluid and structure dynamics, coupling behavior, programming languages and environments on High-Performance Computing (HPC) systems. Preparations required before FSI simulations for the parachute-systems are equally challenging and poses tremendous difficulties for novice users.

Some of the greatest challenges for FSI modeling are:

- Preparations required to get started with Fully Coupled FSI systems are very tedious, time consuming, and not-robust.
- FSI modeling requires in-depth understanding of numerical techniques (FEM/FVM/CSD, convergence, singularity of linearized matrix systems, numerical dissipation vs physical dissipations, numerical stability issues, preconditioning/GMRES/other smart linear solver, etc.), high performance computing (HPC, load balancing, compiler flags, GPU based supercomputers, cloud computing, FSI on Laptop, etc), Coupling issues (FEM/FVM-Mesh-CSD coupling, time-substemping, multiphysics, strong coupling, etc.), and the dynamics of systems (Airdrop terminal velocity, Parachute inflation, Breathing of parachutes and skirt' vibrations, Physical Instabilities, etc.)
- Opportunities: Despite challenges, an accurate FSI simulation can shed complex physics of the ADS systems thereby reducing the risks of lives & cargo.
- Workforce: Due to heavy focus on interdisciplinary expertise requirement, there is a minimal interest for students to choose such topics for research. Dedicated funding resources would lead to increase in workforce.

In the following sections we detail the technical approach for numerical modeling of FSI problems. First, we describe the governing equations for compressible flows, mesh deformation, and structural dynamics/rigid-body dynamics. Because of their importance to study the coupled physics, then we present the methodologies in performing each of the research objectives. The technical discussions for analyzing the results of the FSI and its validation with exciting validation problems are also discussed.

B. Governing Equations

Computational Fluid Dynamics (CFD): The physics of fluid dynamics is mathematically represented by the Navier-Stokes equations. These equations represent conservation of mass (continuity), momentum, and energy of a fluid dynamics system. These equations are a set of time dependent non-linear partial differential equations (PDEs)[1].

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{A}_\mathbf{i}(\mathbf{U})\frac{\partial \mathbf{U}}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\mathbf{K}_{\mathrm{ij}}(\mathbf{U})\frac{\partial \mathbf{U}}{\partial x_j}\right) = \mathbf{0}$$

The advective ($\mathbf{A}_\mathbf{i}(\mathbf{U})$) and diffusive matrices ($\mathbf{K}_{\mathrm{ij}}(\mathbf{U})$) are not constant and often strongly depend on the local Mach number of the flows, speed of sound, and viscous dissipation (i.e.; Reynolds number) and hence are strongly dependent on the solution itself. These coefficients are derived in (Le Beau, et al., 1991; Kumar, 2005) for compressible.

Computational Structural Dynamics (CSD): The deformation of the arteries, veins, leaflets, etc. are governed by large deformation in the structure mechanics of these systems with fluid pressure and shear stresses providing the external driving force. The governing equations for structural dynamics are obtained from the conservation of linear momentum and are given by:

$$\rho^s\left(\frac{d^2\mathbf{y}}{dt^2} + \eta\frac{d\mathbf{y}}{dt} - \mathbf{f}^s\right) - \boldsymbol{\nabla}.\boldsymbol{\sigma}^s = 0$$

where ρ^s is the material density, $\mathbf{y}$ is the displacement vector, $\mathbf{f}^s$ is the external force body forces, $\boldsymbol{\sigma}^s$ is the Cauchy stress tensor, and η is the mass proportional damping coefficient. The mass-proportional damping

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[1]Vector containing primitive variables: $\mathbf{U} = \left(\rho, \rho u_1, \dots, \rho u_{n_{sd}}, \rho e\right)^\mathbf{T}$; Viscous flux: $\mathbf{E}_\mathrm{i} = (0, \tau_{i1}\rho, \dots, \tau_{in_{sd}}, -q_i + \tau_{ik}u_k)^\mathbf{T}$; Euler flux: $\mathbf{F}_\mathrm{i} = \left(u_i\rho,\ u_i\rho u_1 + \delta_{i1}\,p, \dots, u_i\rho u_{n_{sd}} + \delta_{in_{sd}}\,p, u_i(\rho e + p)\right)^\mathbf{T}$; Euler-Jacobian advective matrix: $\mathbf{A}_\mathbf{i} = \frac{\partial \mathbf{F}_\mathrm{i}}{\partial \mathbf{U}}$; and diffusive matrix: $\mathbf{K}_{\mathrm{ij}}\frac{\partial \mathbf{U}}{\partial x_j} = \mathbf{E}_\mathbf{i}$;

provides additional stability, but can significantly affect the dynamics of the structure. Here, we assume large displacements and rotations, but small strains for nonlinear analysis. The second Piola-Kirchhoff stress (force per unit area in the original configuration) tensor, **S**, and the Green-Lagrange strain (in the original configuration) tensor, **E**, are used to write the constitutive equations using the total Lagrangian formulation. Thus, stresses are expressed in terms of the 2nd Piola-Kirchoff stress tensor. The 2nd Piola-Kirchhoff stress tensor is related to Cauchy stress (force per unit area in deformed configuration) tensor, $\boldsymbol{\sigma}^{s}$, by the kinematic transformation, $\mathbf{S} = \frac{\rho_0}{\rho^s}\mathbf{F}\boldsymbol{\sigma}^{s}\mathbf{F}^{T}$ where ρ_0 is the density in the original configuration and **F** (=**gG**; **g**=covariant tensor in deformed configuration, **G**=contravariant tensor in original configuration). Firstly, we will assume linear stress-strain relations (Hookean materials) and plane stress conditions. The constitutive equations are given by

$$S^{ij} = \{\bar{\lambda}G^{ij}G^{jk} + \mu(G^{il}G^{jk} + G^{ik}G^{jl})\}E_{kl}$$

where $\bar{\lambda} = \frac{2\lambda\mu}{\lambda+2\mu}$ (λ & μ are the Lame constants). The Lame constants are related to the Young's modulus Y and the Poisson's ν ratio by: $\bar{\lambda} = \frac{\nu Y}{(1+\nu)(1-2\nu)}$ and $\mu = \frac{Y}{2(1+\nu)}$. Dirichlet- and Neumann-type BCs are $\boldsymbol{y}=\boldsymbol{g}^{s}$ and $\mathbf{n}.\,\boldsymbol{\sigma}^{s}=\mathbf{t}^{s}$ where $\boldsymbol{g}^{s}$ is the specified displacements and $\mathbf{t}^{s}$ is traction forces (shear stress from the fluid dynamics). The initial conditions are $\mathbf{y} = \mathbf{0}$ & $\frac{dy}{dt} = \mathbf{0}$.

<u>*Mesh Deformation (MD) for FD*</u>: Fluid mesh is considered as elastic materials which deforms along with SD deformation. The governing equations mesh deformation is given by

$$\boldsymbol{\nabla}.\,\boldsymbol{\sigma}^{M} = 0$$

C. Coupling Process

Let us symbolically write the above partial differential equations (PDEs) and ordinary differential equations (ODEs) for C**F**D, C**S**D, and **M**D as a nonlinear set of equations denoted by scalar functions

$$\mathbf{N}_S(\mathbf{d}_S,\mathbf{d}_M,\mathbf{d}_F)=0,$$
$$\mathbf{N}_M(\mathbf{d}_S,\mathbf{d}_M,\mathbf{d}_F)=0,$$
$$\mathbf{N}_F(\mathbf{d}_S,\mathbf{d}_M,\mathbf{d}_F)=0.$$

where domain "S", "M", and "F" represent CSD, MD, and CFD respectively and $\mathbf{d}_M$, $\mathbf{d}_M$, and $\mathbf{d}_M$ are the unknowns **U**, **y**, and **x**. At a given time, the mesh (**x**) for CFD and MD are assumed to same. The coupling among CFD, MD, and CSD arises from boundary conditions at the interfaces of the SD.

Linearization of them through first order Newton-Raphson iterative approximation results in

$$\left[\frac{\partial \mathbf{N}_S}{\partial \mathbf{d}_S}\right]^i \Delta\mathbf{d}_S^{i+1} + \left[\frac{\partial \mathbf{N}_S}{\partial \mathbf{d}_M}\right]^i \Delta\mathbf{d}_M^{i+1} + \left[\frac{\partial \mathbf{N}_S}{\partial \mathbf{d}_F}\right]^i \Delta\mathbf{d}_F^{i+1} = -[\mathrm{N}_S(\mathbf{d}_S,\mathbf{d}_M,\mathbf{d}_F)]^i$$
$$\left[\frac{\partial \mathbf{N}_M}{\partial \mathbf{d}_S}\right]^i \Delta\mathbf{d}_S^{i+1} + \left[\frac{\partial \mathbf{N}_M}{\partial \mathbf{d}_M}\right]^i \Delta\mathbf{d}_M^{i+1} + \left[\frac{\partial \mathbf{N}_M}{\partial \mathbf{d}_F}\right]^i \Delta\mathbf{d}_F^{i+1} = -[\mathrm{N}_M(\mathbf{d}_S,\mathbf{d}_M,\mathbf{d}_F)]^i$$
$$\left[\frac{\partial \mathbf{N}_F}{\partial \mathbf{d}_S}\right]^i \Delta\mathbf{d}_S^{i+1} + \left[\frac{\partial \mathbf{N}_F}{\partial \mathbf{d}_M}\right]^i \Delta\mathbf{d}_M^{i+1} + \left[\frac{\partial \mathbf{N}_F}{\partial \mathbf{d}_F}\right]^i \Delta\mathbf{d}_F^{i+1} = -[\mathrm{N}_F(\mathbf{d}_S,\mathbf{d}_M,\mathbf{d}_F)]^i$$

where i is the nonlinear iteration counter for the coupled systems. Above equations can be written in simplified linear systems as

$$\begin{bmatrix} \mathbf{A}_{SS} & \mathbf{A}_{SM} & \mathbf{A}_{SF} \\ \mathbf{A}_{MS} & \mathbf{A}_{MM} & \mathbf{A}_{MF} \\ \mathbf{A}_{FS} & \mathbf{A}_{FM} & \mathbf{A}_{FF} \end{bmatrix}^i \begin{bmatrix} \Delta\mathbf{d}_S \\ \Delta\mathbf{d}_M \\ \Delta\mathbf{d}_F \end{bmatrix}^{i+1} = \begin{bmatrix} \mathbf{b}_S \\ \mathbf{b}_M \\ \mathbf{b}_F \end{bmatrix}^i$$

where the Jacobians of the iterative solver are given by: $\mathbf{A}_{SS} = \frac{\partial \mathbf{N}_S}{\partial \mathbf{d}_S}$, $\mathbf{A}_{SM} = \frac{\partial \mathbf{N}_S}{\partial \mathbf{d}_M}$, and so on. The right hand side vector is given by $\mathbf{b}_S = -[\mathrm{N}_S(\mathbf{d}_S, \mathbf{d}_M, \mathbf{d}_F)]$, $\mathbf{b}_M = -[\mathrm{N}_M(\mathbf{d}_S, \mathbf{d}_M, \mathbf{d}_F)]$, and $\mathbf{b}_F = -[\mathrm{N}_F(\mathbf{d}_S, \mathbf{d}_M, \mathbf{d}_F)]$. The above equations represent a system of fully coupled systems for the fluid structure systems. For most real life applications, the cross-Jacobian terms (e.g., $\mathbf{A}_{SM}$ & $\mathbf{A}_{SF}$) represents the coupling terms (e.g., $\mathbf{A}_{SF}$ would represent the instantaneous feedback that the structure gets from the fluid flow for any small deformation in the structure) and are usually not well defined by conservation laws.

Most commercial/open source software treat the systems in diagonally coupled fashion (one way coupling) or completely decoupled fashion. One way coupling terms can written by setting off diagonal terms equal to zeros.

$$\begin{bmatrix} \mathbf{A}_{SS} & \mathbf{0} & \mathbf{0} \\ \mathbf{A}_{MS} & \mathbf{A}_{MM} & \mathbf{0} \\ \mathbf{A}_{FS} & \mathbf{A}_{FM} & \mathbf{A}_{FF} \end{bmatrix}^i \begin{bmatrix} \Delta\mathbf{d}_S \\ \Delta\mathbf{d}_M \\ \Delta\mathbf{d}_F \end{bmatrix}^{i+1} = \begin{bmatrix} \mathbf{b}_S \\ \mathbf{b}_M \\ \mathbf{b}_F \end{bmatrix}^i$$

This implies that CSD is solved first using a forcing terms (shear and pressure coming out from CFD), then mesh is deformed using deformed coordinate systems at the structure boundaries for the CFD systems, and at the end CFD is solved using the deformed mesh from MD and velocity boundary conditions at the interfaces. In this, the coupling terms ($\mathbf{A}_{MS}$, $\mathbf{A}_{FS}$, and $\mathbf{A}_{FF}$) are computed through Least-Square projections.

One way coupling however fails if the coupling between structure and fluid is strong such parachute – aerodynamics systems. Other challenges are addressing the multiscale nature of such problems (e.g., temporal and spatial scales of structure dynamics usually occur at a lot smaller scales that the fluid dynamics).

New advancement in computational technologies such multi-grid preconditioning for multi-physics/multi-scale advance linear solver one massively parallel computers come help address some of these challenges. Numerical convergence of the system can also be enhanced by advanced solvers. We propose to devise a mechanism to estimate the cross coupling term in iterative fashion, e.g., $\mathbf{A}_{SM}^i = \frac{\mathrm{N}_S(\mathbf{d}_S, \mathbf{d}_M^{i-1}, \mathbf{d}_F) - \mathrm{N}_R(\mathbf{d}_S, \mathbf{d}_M^{i-2}, \mathbf{d}_F)}{\mathbf{d}_M^{i-1} - \mathbf{d}_M^{i-2}}$. Similar approximation is also possible for other cross terms.

FSI involves solving the time dependent fluid dynamics (FD) equations together with structural/rigid-body dynamics (SD or RD) equations and mesh deformation (MD) equations as described in the previous section. Coupling between structure and fluid is achieved by exchange of information (i.e., pressure p, velocity v, surface coordinates, and temperature) from the gas dynamics simulations to Interface (through mapping) and from the Interface to structural dynamics (through projections).

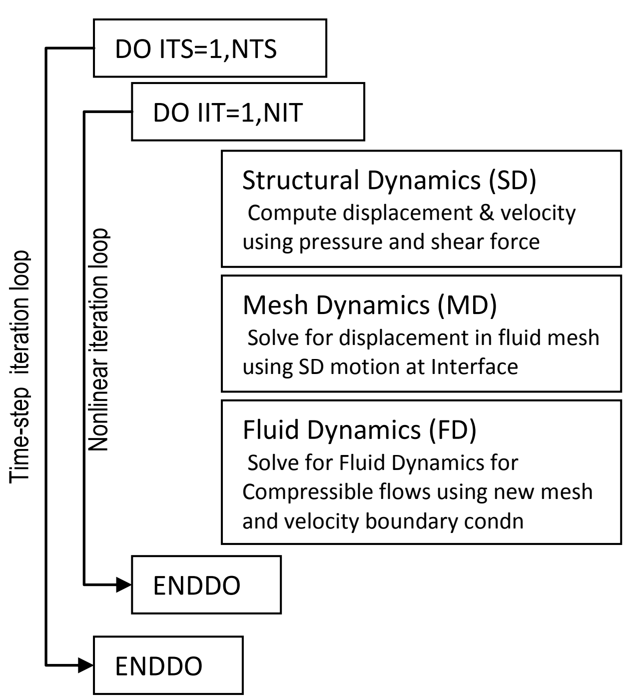

Figure A1: Block Iterative coupling techniques to address the coupled multiphysics problems

Here, we assume that the interface has the same mesh morphology as the fluid dynamics (FD) mesh on the object surface but it differs from structural dynamics (SD) meshes (usually requires higher order finite element meshes to resolves the surface deformations). Fluid dynamics is governed by 3D gas dynamics equations and structural dynamics is modeled as 3D constitutive equations for solid mechanics. Coupling is achieved in block iterative fashion as shown in the figure 6. In block iterative method, first SD is solved using finite element methods for solid mechanics. Then, new mesh coordinates are determined by solving the elasto-dynamics equations for mesh deformation (MD). Note that fluid meshes have no physical physics, so Young's modulus of the mesh elements is adjusted in such way those mesh-motion results in minimal element distortions. After mesh motion, FD is solved using the new coordinates in the fluid domain and velocity boundary conditions and the surface. The whole process is repeated inside a non-linear Newton-Raphson iterations block (as shown in Figure A1) until a desired convergence or maximum number of iterations (set by user) is achieved.

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