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A SIMULATION TOOL FOR PARACHUTE/PAYLOAD SYSTEMS

R. FLORES[†1], E. ORTEGA[*], J. VALLES[†2] AND E. OÑATE[†3]

[*] International Center for Numerical Methods in Engineering (CIMNE)
Universidad Politécnica de Cataluña
Campus Norte UPC, 08034 Barcelona, Spain
e-mail: eortega@cimne.upc.edu, www.cimne.com

[†1] CIMNE, e-mail: rflores@cimne.upc.edu

[†2] CIMNE-ETSEIAT Classroom, e-mail: jvalles.fluvia@gmail.com

[†3] CIMNE, e-mail: onate@cimne.upc.edu

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Abstract. The design and evaluation of parachute-payload systems is a technology field in which numerical analysis tools can make very important contributions. This work describes a new development from CIMNE in this area, a coupled fluid-structural solver for unsteady simulations of ram-air type parachutes. For an efficient solution of the aerodynamic problem, an unsteady panel method has been chosen exploiting the fact that large areas of separated flow are not expected under nominal flight conditions of ram-air parachutes. A dynamic explicit finite element solver is used for the structure. This approach yields a robust solution even when highly non-linear effects due to large displacements and material response are present. An added benefit of the proposed aerodynamic and structural techniques is that they can be easily parallelized for increased performance in multi-core and multi-CPU architectures. The main features of the computational tools are described and several numerical examples are provided to illustrate the performance and capabilities of the technique.

1 INTRODUCTION

The numerical simulation of parachutes is a challenging coupled problem. From the structural point of view, parachutes are complex in design and behaviour. Braced membranes, such as parachute canopies, cannot equilibrate an arbitrary set of loads unless drastic geometrical changes take place; thus, the structural response is extremely nonlinear. The lack of bending stiffness of the structural components makes them buckle (wrinkle) under compressive loads, exhibiting an asymmetric behaviour. The flow surrounding the parachute is also complex and often unsteady. The aerodynamic model adopted should also account for the presence of large unsteady wakes and aerodynamic interactions between the different parts of the canopy. The nature of the applied forces, which depend heavily on the structural response of the parachute, adds an extra layer of complexity to the analysis. As the magnitude and direction of the aerodynamic forces (mainly follower pressure loads) are not known in advance but are a function of the deformed parachute shape, they must be computed as part of the solution in an iterative process. This poses additional difficulties for the convergence and robustness of the coupled solution.

The magnitude of the challenges to be faced in the numerical simulation of parachutes explains why the current design process relies mostly on empirical methods. As an example, 15 worldwide parachute manufacturers were surveyed about the use of computational tools in the design and evaluation of parachute systems [1]. None of those 10 who provided feedback declared using simulation tools, with exception of CAD packages for geometry modelling. This is a clear indication of the fact that computational mechanics does not yet enjoy wide acceptance among the parachute industry. On the other hand, it should be noted that empirical design methods are not exempt from limitation. From the point of view of the parachute design, two features of outmost importance are the in-flight shape (which guides the rigging design, i.e. the distribution of suspension lines) and the stresses on the fabric and cables. This requires a multitude of prototypes to be built to find a suitable configuration; therefore, the process relies heavily on the intuition of the designer and becomes lengthy as well as costly. Matters are further complicated by the inherent difficulty of instrumenting the canopy without interfering with its natural behaviour. As a result, the experimental measurements are scarce and subject to large levels of uncertainty.

Regarding numerical simulation, an effective model for parachutes must deal with all the issues listed above with robustness, but also with an acceptable computational cost. From the mid-nineties onwards, a steady development of numerical models with increasing simulation capabilities has been observed. A comprehensive description of existing techniques was recently presented by Takizawa and Tezduyar in [2]. The methods in use rely on combinations of Finite Element and Finite Volume techniques for the structural and aerodynamic problem (with a full discretization of the surrounding fluid). While they have demonstrated ample capabilities and potential they also suffer from severe shortcomings that limit their practical application. The large geometric changes of the structure force frequent remeshing steps which are costly and compromise the robustness of the solution. On the other hand, even without the need to remesh, the solution techniques adopted for the aerodynamic field are inherently intensive from the computational point of view and need long run times that prevent their use as a basic design tool. Boundary methods based on potential approaches offer an alternative to the modelling of the surrounding fluid. As only the surface of the parachute (and payload) is employed in these methods, only changes to the nodal position are required and the mesh topology remains unchanged. This reduces the computational requirements drastically and increases the robustness and stability of the coupled simulation (see for instance [3]). Moreover, the pressure field obtained from the inviscid potential solution is usually appropriate to obtain a reasonable approximation of the deformed canopy geometry and fabric stresses, and, therefore, the approach can provide valuable data for the parachute designer. Even in those cases when extensive flow separation occurs (e.g. round decelerators) potential approaches based on vortex methods could still be used, see [4].

In the present work a cost-effective methodology for the analysis of parachutes is presented. The method is based on an unsteady potential flow model (panel) coupled to a dynamic FE explicit solver for the structure, and it is mainly intended for the simulation of in-flight ram-air parachutes (though extensions are also possible).

2 ARCHITECTURE OF THE COUPLED SOLVER

Regarding structural modelling, it was decided to use a FE explicit dynamic solver. An unsteady analysis is not affected by the problems caused by the lack of a definite static equilibrium configuration and the solution is always unique (the structure is constantly in equilibrium with the inertial forces). Even when only the long-term static response is sought, the dynamic approach offers some advantages. Furthermore, the extension to transient dynamic problems becomes trivial. In view of the expected difficulties, an explicit time integration scheme was adopted. Although explicit methods are conditionally stable (the stability limit is determined by the material properties and the model geometry) the cost per time step is low. Moreover, the explicit method is extremely insensitive to highly nonlinear structural behavior and requires a number of time steps that does not change substantially as the system response becomes more complex. Material nonlinearities and large displacements, which are detrimental for the convergence of an implicit scheme, do not affect adversely the explicit method [5]. A further benefit is the fact that the algorithm can be easily vectorized, so it will not be difficult to port the code to large parallel computers in the future should the need arise. A local co-rotational reference frame is used for each cable and membrane element in order to remove the rigid-body displacements and isolate the material strains. Inside each element a simple small-strain formulation is used. Tensile deformations are always small and even when compressive strains become extremely large due to the inclusion of a wrinkling model (zero compression stiffness), there is no stress associated and, correspondingly, no strain energy. Therefore, the small-strain formulation is adequate since only the tensile deformations must be considered to calculate the stress state.

In spite of the fact that the structural solution approach described above is general and can be applied to any kind of parachute system, the higher computational cost of a general flow solution was not considered cost-effective in the context of the present development. Thus, a potential flow model was adopted, reducing the scope of the aerodynamic solution. In order to solve the potential problem, a low-order time-marching (unsteady) panel method was selected due to its simplicity, low computational cost and robustness [6]. Note that this simplified flow model is deemed acceptable for the simulation of gliding parachutes (the focus of this work) during normal operation because no extensive flow separation regions are normally present. Moreover, the modular approach adopted for the code allows changing the flow solver with minor modifications to adapt it to problems going beyond the scope of potential methods.

To couple the aerodynamic and structural solvers a sequential strategy was adopted [7]. Each solver runs a determined amount of (simulated) time and then transfers control to the other field. As the stability limit of the explicit structural solver is very small, each time step of the coupled analysis corresponds to many time increments of the structural part. The aerodynamic code, on the other hand, is implicit and can therefore run the complete time step in just one increment. While the sequential solution strategy may not be the most efficient alternative, it allows separate development and maintenance of the structural and flow solvers and thus simplifies coordination of the different activities.

2.1 The structural model

As stated above, the structural behavior is modeled using an explicit finite element solver. The element library includes two-node linear cables, three-node linear triangular membranes and four-node linear tetrahedral solids. All elements are formulated in a corotational frame of reference and are thus suitable for large-displacement analysis. Given the materials used for parachute manufacture, it was decided that a linear elastic constitutive model is sufficient to obtain an accurate solution. However, the no-compression behavior of the membrane must be accounted for in order to obtain realistic results.

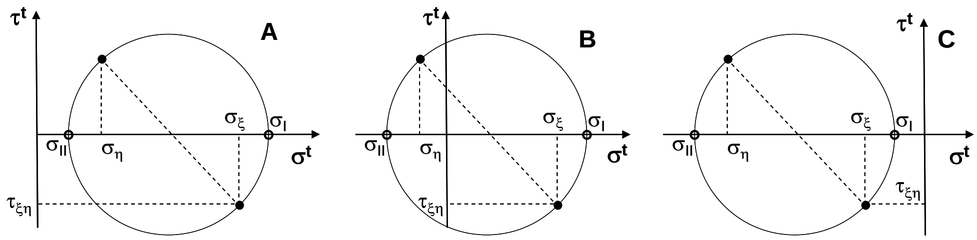

Figure 1: Trial membrane states: taut (A), wrinkled (B) and slack (C).

To this effect a trial stress is computed first assuming purely linear elastic behavior and then a correction is applied to obtain the proper membrane response [8]. Three possible membrane states are considered (see Fig. 1):

1. Taut: the minimum principal trial stress is positive. No corrections are needed.
2. Wrinkled: membrane is not taut, but the maximum principal strain is positive. Trial state is replaced with a uniaxial stress state.
3. Slack: the maximum principal strain is negative. The corrected stresses are zero.

These three cases are depicted in figure 1. When the textile is in the wrinkled state the trial stress is corrected as shown in Fig. 2.

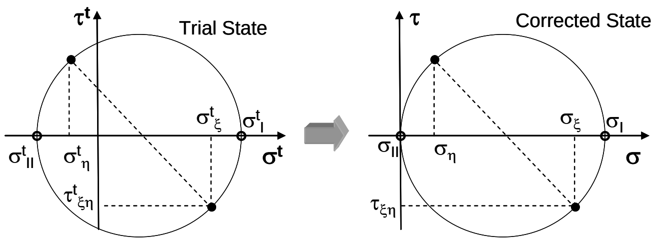

Figure 2: Stress correction for wrinkled membrane.

The discrete equation for the motion of the system is given by

$$\mathbf{M}\frac{d^2\mathbf{u}}{dt^2}=\mathbf{b}+\mathbf{t}-\mathbf{I} \tag{1}$$

here **M** denotes the mass matrix, **u** is the nodal displacement vector, **b** denotes the body forces, **t** the surface tractions and **I** is the vector of internal forces (due to the stresses inside the elements). Using a lumped mass matrix the system is advanced in time using the explicit central difference scheme which yields second order accuracy. Given a series of points in time $t^{(i)}$, the change in midpoint velocity can be computed as:

$$\frac{d\mathbf{u}}{dt}^{\left(i+\frac{1}{2}\right)} - \frac{d\mathbf{u}}{dt}^{\left(i-\frac{1}{2}\right)} = \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2} \cdot \frac{d^2\mathbf{u}^{(i)}}{dt^2} \tag{2}$$

where $\Delta t^{(i)} = t^{(i)} - t^{(i-1)}$. Using the midpoint velocity the displacements are updated using:

$$\mathbf{u}^{(i+1)} = \mathbf{u}^{(i)} + \Delta t^{(i+1)} \cdot \frac{d\mathbf{u}}{dt}^{\left(i+\frac{1}{2}\right)} = \mathbf{u}^{(i)} + \Delta t^{(i+1)} \cdot \left[\frac{d\mathbf{u}}{dt}^{\left(i-\frac{1}{2}\right)} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2} \cdot \frac{d^2\mathbf{u}^{(i)}}{dt^2} \right] \tag{3}$$

The stability limit for the explicit integration scheme can be approximated by:

$$\Delta t \le \min\left(\frac{L_e}{c_d}\right) \tag{4}$$

In the expression above L_e denotes a characteristic element dimension and c_d is the dilatational wave speed in the material. While the time given by Eq. (4) is usually short, the time integration scheme is not affected by the nonlinearities present in the system, yielding a robust solution.

To improve the convergence in steady-state simulations and also to smooth noisy solutions, a certain amount of numerical damping is introduced in the model. Two forms of user-adjustable damping are included to improve control over the solution process: Rayleigh damping and bulk viscosity.

2.2 Rigid body modeling

In many cases the effects of the deformation of the payload are negligible and large computational savings can be obtained by considering the payload rigid. A rigid body has only 6 degrees of freedom and there is no upper bound on its allowable time step, therefore it can be included in the model at virtually no extra cost. The code allows for arbitrary element sets of the model to be converted into rigid bodies, whose motion is fully characterized by their orientation and the position of their center of mass. The motion of the center of mass is computed using Eqs. (2) and (3). The attitude of the solid is calculated by means of:

$$\mathbf{I}^{\mathrm{G}} \cdot \frac{d\mathbf{\Omega}}{dt} = \mathbf{M}^{\mathrm{G}} - \mathbf{\Omega} \otimes \left(\mathbf{\Omega} \cdot \mathbf{I}^{\mathrm{G}}\right) \tag{5}$$

where $\mathbf{I^G}$ denotes the tensor of inertia of the solid with respect to its center of mass, $\mathbf{\Omega}$ is the angular velocity, $\mathbf{M^G}$ is the torque acting on the solid (due to both external loads and internal forces exerted by surrounding deformable elements). Expression (5) is evaluated in a corotational frame which coincides with the principal axes of inertia of the rigid body. Therefore, the angular acceleration can be computed without matrix inversion because the moment of inertia tensor is diagonal. The inertial properties of the elements making up the rigid body are automatically computed during preprocessing and the elements themselves are removed from the analysis. The trajectories of the nodes belonging to a rigid body are computed at the end of each step using information about the translation of the center of mass and the total rotation of the rigid body.

2.3 Aerodynamic modeling

An unsteady panel has been chosen to model the aerodynamic field around the parachute. The aeroelastic solver was developed to help with the design of ram-air parachutes (parafoils) where large areas of separated flow are not expected. Therefore, the potential solution provides a reasonable estimation of the pressure field under nominal flight conditions with a low associated computational cost. The code includes triangular and quadrilateral low-order (constant source and doublet intensity) panels which allow modeling of arbitrary thin and thick bodies (see [9]). As only the surface of the solid has to be meshed, most of the problems associated with excessive grid distortion under large geometrical changes typical of conventional volume-based methods are avoided. The algorithm includes the effect of wake roll-up in the computations to improve the accuracy of the solution. The potential solver calculates only the pressure acting on the external surface of the canopy. The internal pressure, needed to simulate the structural behavior, is taken as a known fraction of the stagnation pressure of the external flow. To solve the linear system of equations which yields the doublet intensities both direct and iterative solvers are provided. When the flow field variation in one step is small (e.g. when approaching a steady state configuration) the iterative solver is capable of quickly updating the solution using the last result as initial guess. On the other hand, when the iterative solver converges slowly (of fails to converge) the code automatically switches to the direct solver to increase robustness. Both the influence coefficient matrix assembly and the system solving steps are run in parallel to improve efficiency.

The aerodynamic forces acting on the suspension lines are computed using empirical data for the drag of a cylinder. These computations are carried directly inside the structural solver in order to account for the associated aerodynamic damping.

For bluff payloads the potential solver does not yield a realistic solution. Therefore the aerodynamic loads are computed using empirical data tabulated as a function of the angles of attack and slip. This computation is also carried out inside the structural solver. During the preprocessing stage the tabular data is automatically regularized (converted to equally-spaced data points) to speed up the process of interpolation.

3 EXAMPLES OF APPLICATION

This section shows results obtained for models of existing parachutes. The geometric models have been provided by CIMSA Ingeniería y Sistemas.

3.1 Steady-state analysis of a large ram-air parachute

The model corresponds to a series of high glide-performance parachutes intended to deliver heavy payloads, designed and manufactured in the framework of the FASTWing Project [10]. The discretization consists of an unstructured distribution of 11760 triangular elements for the canopy and 11912 cable elements for the suspension and control lines as well as the reinforcement tapes integrated into the canopy. The simulation is initialized with a partially inflated parachute configuration. To obtain a faster convergence to the equilibrium position of the parachute, an under-relaxation technique is employed where the changes in pressure at each step are scaled down in order to keep the canopy from overshooting the equilibrium position. Fig. 3 shows the initial the equilibrium configurations while Fig. 4 depicts the evolution of the forces and moments acting on the canopy. The problem was solved in a in a desktop computer with an Intel Core2 Quad Processor Q9550 @ 2.83 GHz on a Windows 32-bit operating system and using one running core (serial computation). The total CPU-time for the simulation was about 20 minutes (approximately 25 seconds per aerodynamic-structural step) showing the ability of the software to analyze complex geometries in a short time using modest hardware.

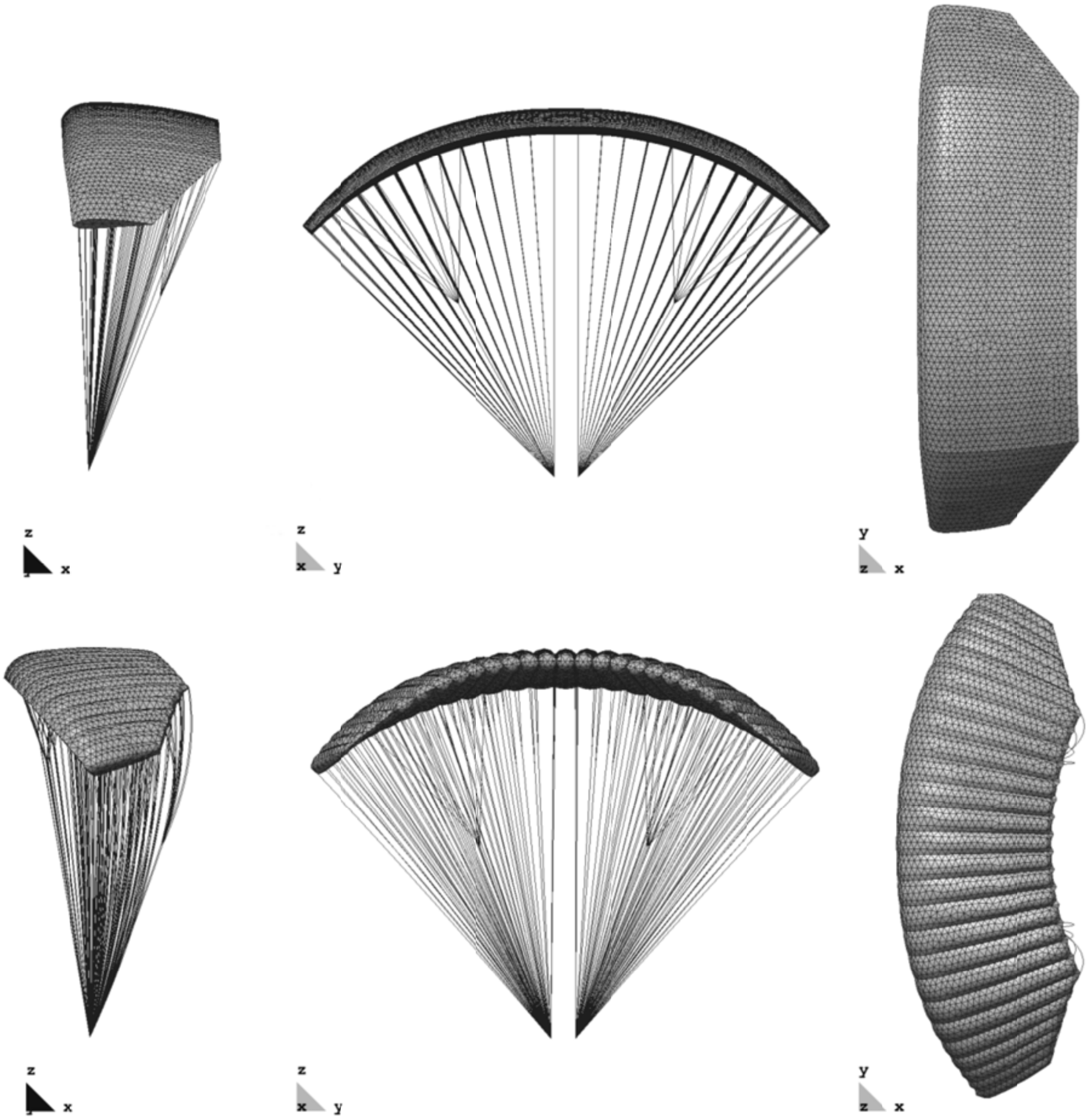

Figure 3: Three views of the initial (top) and computed (bottom) equilibrium configurations

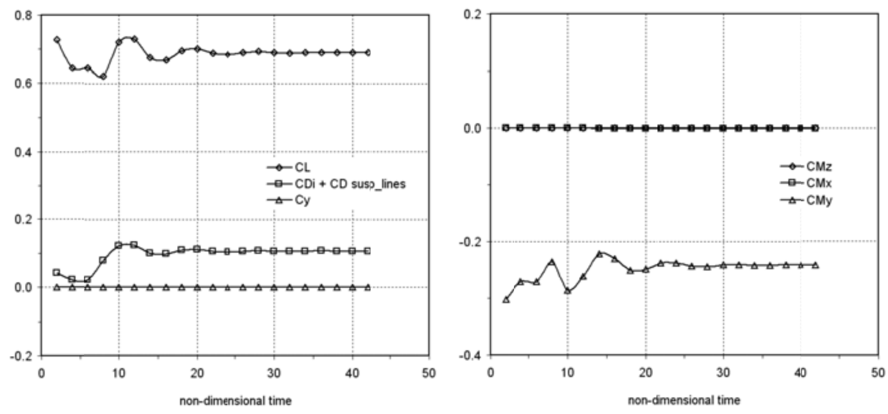

Figure 4: Computed time history of force and moment coefficients

3.2 Unsteady analysis of a ram-air parachute maneuver

In this case the dynamic behavior of a parachute-payload system during a left-turn maneuver is studied. The parachute discretization consists of an unstructured grid of 9548 triangular elements for the canopy and 3077 cable elements for the suspension lines and reinforcement tapes.

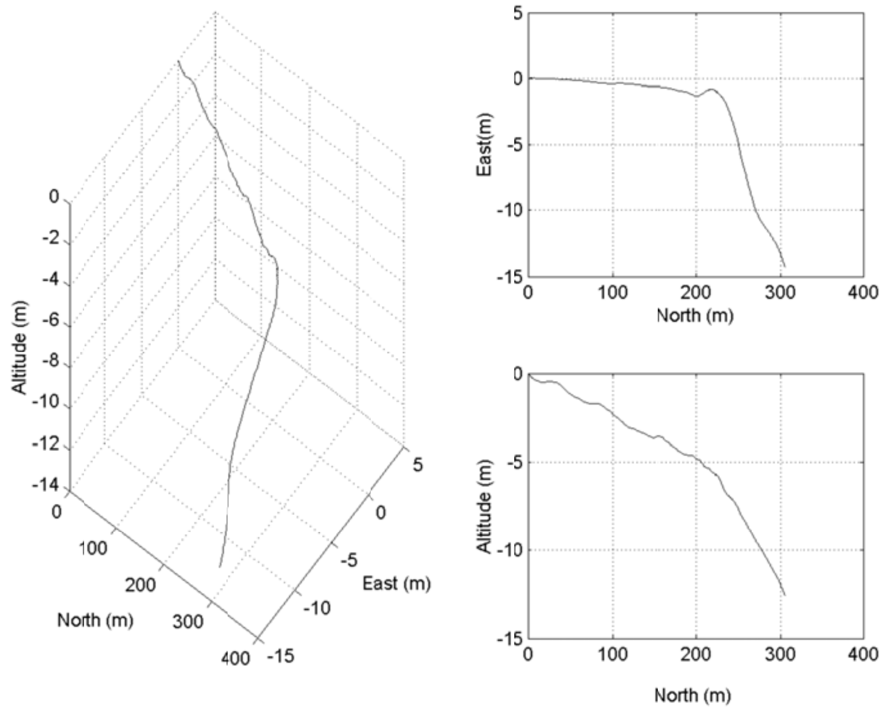

Figure 5: Payload center of mass computed trajectory

The simulation starts with a partially inflated parachute configuration and, once steady descent flight is achieved, the maneuver is initiated by pulling the left brake line. After 5 seconds, the brake line is released and the parachute recovers a straight descent flight. As all the components of the software are fully unsteady no especial treatment is needed for transient simulations; the dynamics of the parachute system are directly computed. The trajectory described by the payload center of gravity during the maneuver is plotted in Fig. 5 while some snapshots of the parachute-payload system taken at different times during the simulation are shown in Fig. 6.

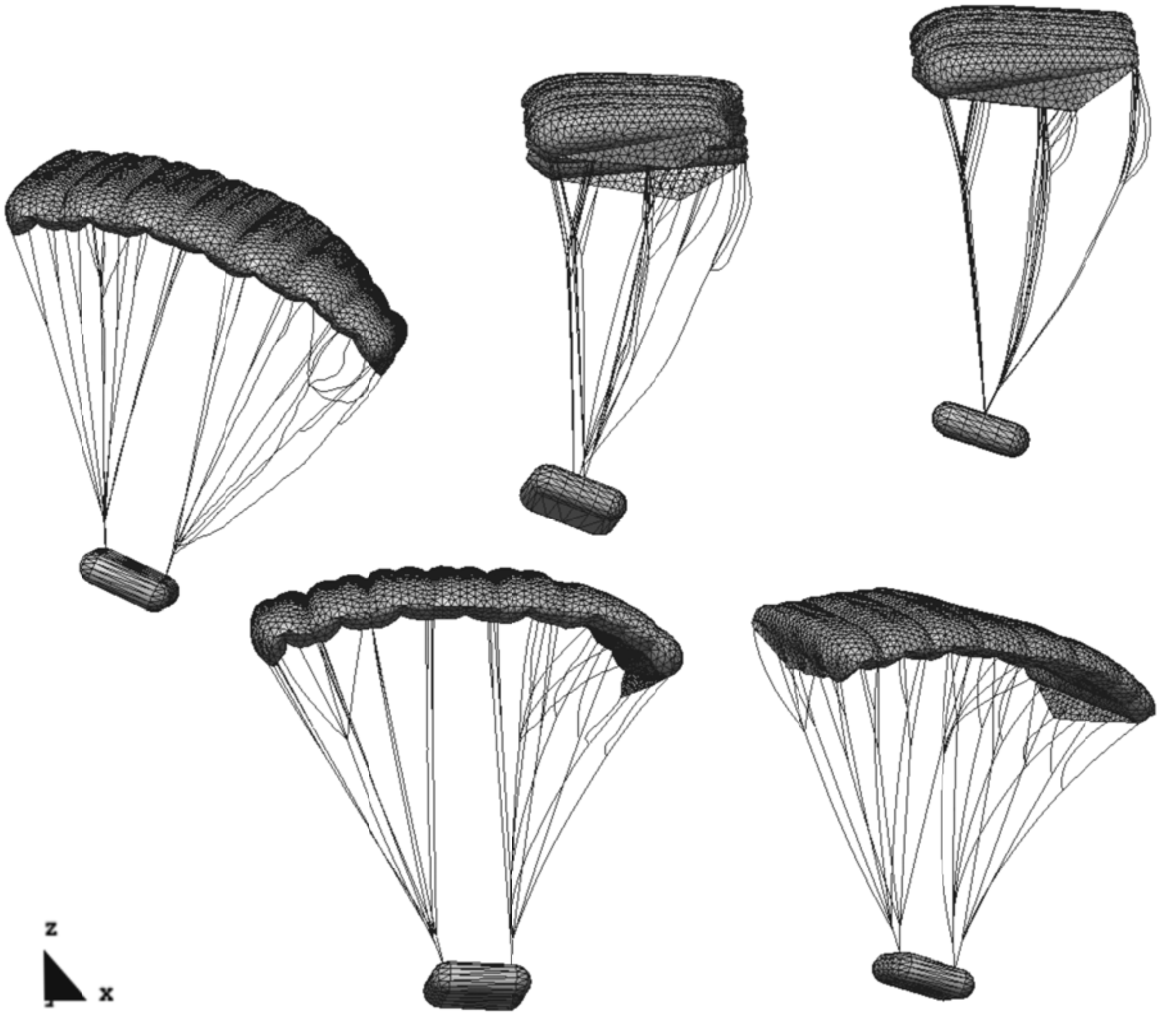

Figure 6: System configuration at five different instants of the maneuver simulation. In counterclockwise order: 3.6s, 15.6s, 19.1s, 19.9s and 23.2s

The total time simulated in this example is 25 seconds, which required 400 time steps and a total CPU time of 7950 seconds (approx. 2.2 hours) using a single core. The hardware platform is similar to that used in the previous example. At each time step, a single aerodynamic iteration is performed but the number of structural iterations required was approximately 2000 (because the stability limit of the structural solver is small). The CPU-time measured for each time step was approximately 20 seconds, of which the aerodynamic solution took the 85 percent of the time. Given that the calculation of the influence coefficients (which represents a large fraction of the computational cost of the panel solver) can be efficiently run in parallel (the coefficients are mutually independent) a large speedup can be obtained when using a multiprocessing platform.

3.3 Improved computational efficiency of payload modeling using rigid bodies

In this example a dummy payload typical of parachute flight tests is used. The dummy payload consists of four water-filled barrels tied together between two support platforms. The upper platform is attached to a horizontal spreader beam which hangs from the main suspension lines (see Fig. 7). Due to the intricate geometry of the payload the finite element model contains some slivers (highly distorted elements) which affect adversely the stability limit when using a deformable model. By using rigid elements the correct dynamics of the system where captured in a much more efficient manner. It was found that using rigid bodies for the dummy payload and spreader bar increased the allowable time step by a factor of 5.2. This, coupled with the gains in CPU time per step arising from the reduction in the number of degrees of freedom allowed the total CPU time to be reduced by a factor of 6.3 (an 84% reduction in computational cost). It must be stressed that the dynamical behavior of the simplified system is exactly the same as that of the original model, because the only difference lies on the deformations of the payload (which are completely negligible in this example).

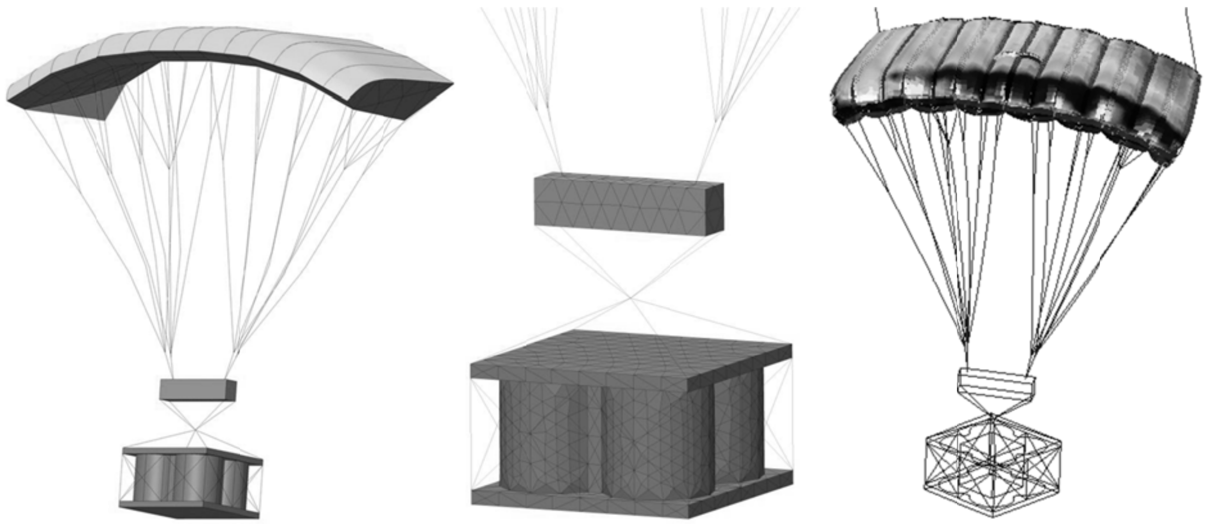

Figure 7: Original CAD model (left), detail of the payload modeled with rigid elements (center) and in-flight parachute deformed shape and pressure field (right)

4 CONCLUSIONS

The important role parachutes play in many civil, humanitarian and military applications calls for new and improved computational tools aimed at tackling the current lack of software applications in the field. A new development from CIMNE in this direction has been presented. The simulation package contains a coupled fluid-structural solver tailored for the unsteady simulation of ram-air type parachutes. The coupled solution approach has been successfully applied to a variety of problems encountered during parachute design activities. The solution strategy is robust and the code shows a notable efficiency, being able to treat complex systems with only limited computational resources (all the examples presented have been run on mid-range desktop computers). As it has been highlighted throughout this work, the challenges involved in the simulation of parachutes are not minor. However, the numerical results obtained to date encourage us to further advance in the development of the software, as it addresses an important need of the parachute industry for which there is currently no established solution.

5 ACKNOWLEDGEMENTS

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