

NUMERICAL TOOLS FOR THE ANALYSIS OF PARACHUTES

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Summary. 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. The numerical results show considerable accuracy and robustness. An added benefit of the proposed aerodynamic and structural techniques is that they can be easily vectored and thus suitable for use in parallel 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 problem as the geometry is complex in design and behaviour and, in addition, is continuously changing in time. Factors contributing to the complexity and unsteadiness of the aerodynamic field are massive flow separations, complex aerodynamic interactions between the structural components and the presence of large unsteady wakes. The structural analysis requirements are also challenging. Braced membranes, such as parachute canopies, cannot equilibrate an arbitrary set of loads unless drastic geometrical changes take place. The structural response is thus extremely nonlinear. In the case of follower loads (e.g. pressure loading) the matter is further complicated by the fact that the equilibrium solution may not exist at all (i.e. the structure is in fact a mechanism). This extreme geometrical nonlinearity can give rise to severe numerical convergence problems. Due to the lack of bending stiffness of the structural components, the materials are able to resist tensile stresses but buckle (wrinkle) under compressive loads^{1,2}. This asymmetric behaviour should also be accounted for. Finally, 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 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.

An effective numerical model of parachutes must deal with all the issues listed above in a robust way while keeping computational cost at an acceptable level. The magnitude of the challenges faced explains why the current design of parachute systems relies mostly on empirical methods. As an example, 15 worldwide parachute manufacturers were recently surveyed about the use of computational tools in the design and evaluation of parachute systems³. None of those 10 who provided feedback declared using computer tools beyond CAD packages for geometry modelling. This is a clear indication that computational mechanics does not yet enjoy wide acceptance among the parachute design industry. The numerical simulation tool described in this work is intended to address the needs of this sector.

In the following, the main features of the parachute simulation tool currently being developed at CIMNE are described and several numerical applications are presented with the aim of illustrating the performance and potential of the proposed techniques. The rest of the document is organized into 4 main sections. The core features of the coupled fluid-structural solver are given in section 2. Next, validation cases for the structural and flow solvers are presented in section 3 and numerical applications are shown in section 4. The main conclusions are summarized in section 6.

2 COUPLED SOLUTION STRATEGY

In view of the important challenges involved in modeling parachute systems, the choice of the structural and aerodynamic solvers as well as the coupling methodology were thoroughly examined from two different points of view. First, considering the capabilities of the techniques to deal with the typical situations encountered during the flight of parachutes; second, evaluating its robustness and the chances of achieving low computational costs through efficient numerical implementations.

Regarding structural modeling, it was decided to use a FE dynamic structural solver. An unsteady analysis is not affected by problems caused by the lack of a definite static equilibrium configuration. In fact, since for dynamic problems the structure is constantly in equilibrium with the inertial forces the solution is always unique. 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.

There are two basic kinds of dynamic solvers, implicit and explicit⁴. Implicit solvers can be made unconditionally stable, which allows for large time steps although the computational cost is high because a non-linear problem must be solved at each time step. When the structural response does not show a high deviation from linearity the implicit treatment is usually preferred, as it allows for large time steps. Also, the static equilibrium (when it exists) can be reached after a small number of iterations. However, it should be stressed that the radius of convergence of the iterative algorithms employed for solving the non-linear system is limited. Thus, the time step cannot be made arbitrarily large. In addition, when the structural behavior is heavily non-linear, the time increment must be cut back to ensure convergence of the iterative algorithm and the computational cost is rapidly increased. Implicit solvers also exhibit a lack of robustness due to the possibility of the scheme failing to

converge. On the other hand, although the explicit solvers are conditionally stable (the stability limit is determined by the material properties and the geometry of the FE mesh) the cost per time step is low. 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 extremely detrimental for the convergence behavior of the implicit scheme, do not affect adversely the explicit algorithm. In view of the difficulties expected, the choice was made to use an explicit FE structural solver. A further benefit is the ability of the algorithm to be easily vectored and thus take advantage of modern parallel processing architectures. Linear cable and membrane elements were selected due to their ease of implementation. The fabric is modeled using three-node membrane elements due to their geometric simplicity. The three nodes of the element will always lie in the same plane so the definition of the local coordinate systems is straightforward. 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 due to the properties of the fabric. Tensile deformations are always small; on the other hand compressive strains can become extremely large due to the inclusion of a wrinkling model (zero compression stiffness). There is, however, no stress associated with the compressive strains and, correspondingly, no strain energy. Therefore, the small-strain formulation is adequate as only tensile deformations must be taken into account to calculate the stress state.

In spite of the fact that the structural solution approach is general and can be applied to any kind of parachute system, the computational cost of a general flow solution was not feasible from a practical point of view (at least during the first stages of the work) and a decision had to be taken regarding the scope of the aerodynamic solution. Consequently, following previous in-house developments, the focus was initially placed on ram-air type parachutes for which a potential flow approach is valid as no extensive separation regions are present during nominal operation. The main advantage of the potential model is that boundary methods can be employed. Hence, most problems related to grid generation can be avoided. Due to the large geometric changes expected, methods based on discretization of the surrounding air volume would need multiple remeshing steps. For the boundary mesh, however, only changes to the nodal position are required as the topology remains unchanged. As an added benefit, the computational cost is significantly reduced with respect to volume techniques (e.g. Finite Differences, Finite Volumes and Finite Elements). Even in cases when extensive flow separation occurs, alternative potential approaches such as vortex methods could be used. In other cases, for problems going beyond the scope of potential methods, the modular approach adopted for the code allows changing the flow solver with minimal modifications.

3 VALIDATION EXAMPLES

The accuracy of the structural and aerodynamic solvers has been tested with widely accepted benchmark cases. Two validation examples are shown next.

3.1 Structural solver validation

The most challenging aspects of the structural response are the large displacements

involved and the asymmetric material behavior due to wrinkling. The airbag inflation test is commonly used to assess these capabilities. This benchmark computes the vertical displacement at the centre of an initially flat square airbag of side length 840mm. An internal pressure of 5kPa is applied. The deformed configuration is strongly affected by the no-compression condition on the fabric, so this is a very popular benchmark for wrinkling models. The textile properties are:

$$E=588MPa \quad t=0,6mm \quad \nu=0,4b \tag{1}$$

A mesh composed of 16x16 squares is used for each side of the airbag. Each square has then been divided into 4 equal triangles in order to eliminate mesh orientation effects (**Error! No se encuentra el origen de la referencia.**). The total number of triangular elements is therefore 2048.

	Contri	Ziegler	Hornig	PARA_STR
Deflection (mm)	217,0	216,0	216,3	216,2

Table 1 : Central displacement of the airbag (mm)

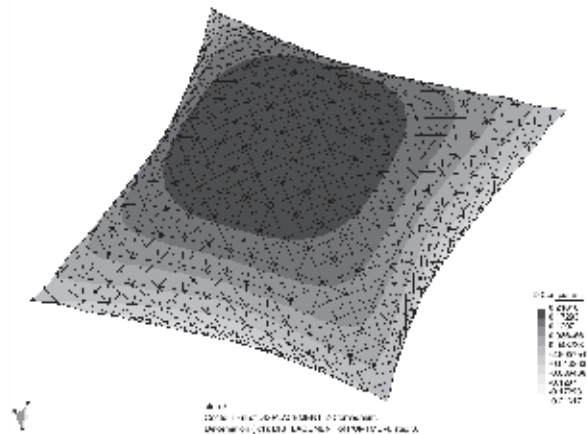


Figure 1: Square airbag inflation test. Final deformed geometry

Table 1 shows the comparison of the result from the parachute simulation tool (named PARA_STR in the table) with several sources^{5,6,7}. The differences are negligible.

3.2 Aerodynamic solver validation

A two-bladed rotor for which experimental results are available⁸ is solved. This is a case which needs an accurate representation of the wake shape. The rotor geometry is discretized with a structured mesh of 4000 quadrilateral panels (40 along the span and 25 in the chordwise direction). Figure 2 shows the C_p distribution computed for a collective pitch angle $\theta_c = 8^\circ$.

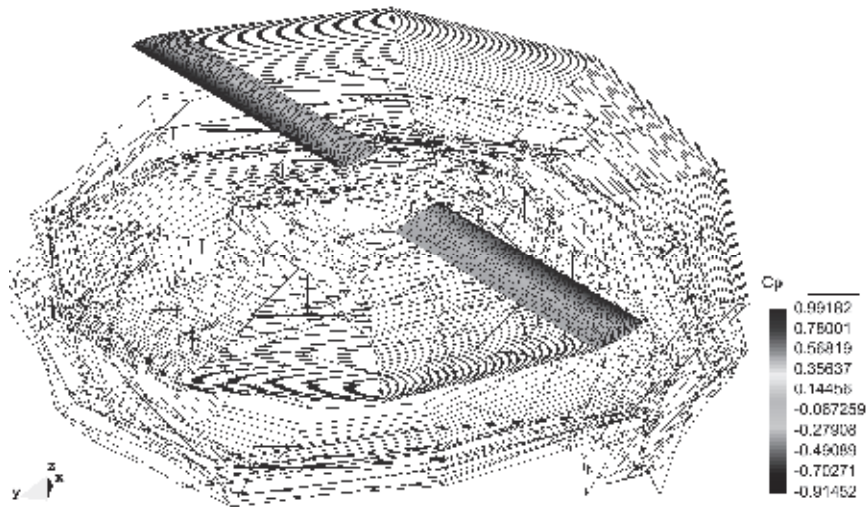


Figure 2: Wake shape and pressure distribution for spinning rotor

Comparisons of the experimental measurements and the computed pressure distribution at several spanwise stations are given in Fig. 3. Numerical predictions closely match the measured values.

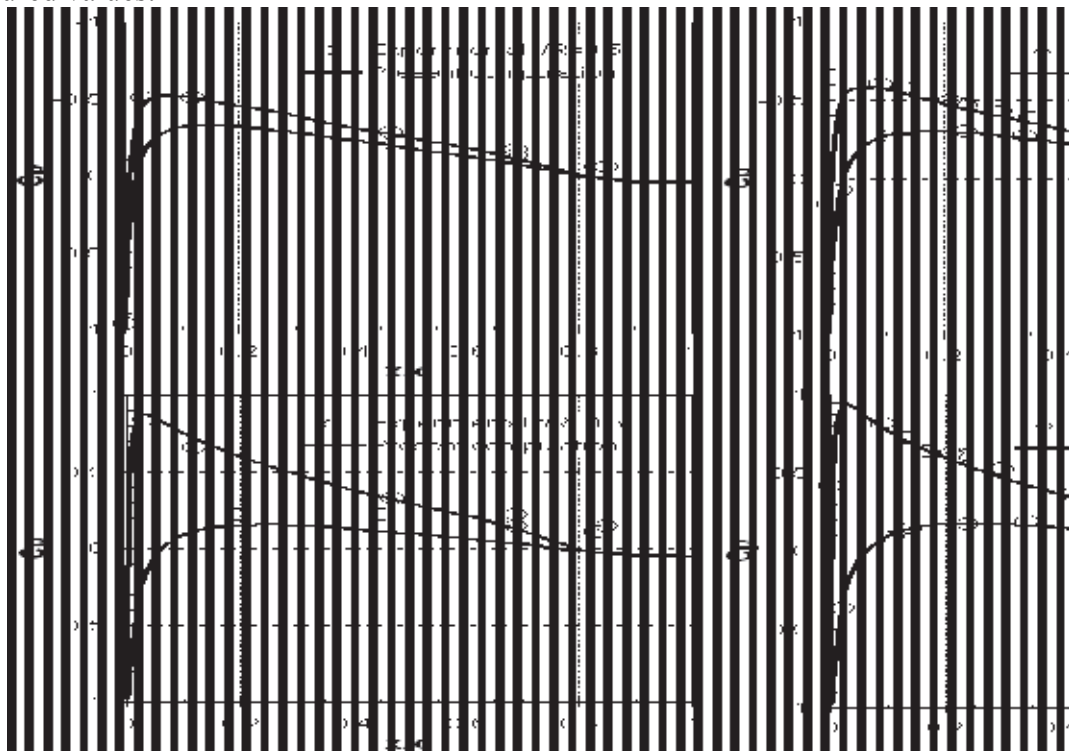


Figure 3: Numerical and experimental C_p distributions at different sections along a blade

4 EXAMPLES OF APPLICATION TO PARACHUTES

In this section some application examples are presented to demonstrate the capabilities of the simulation software.

4.1 Stationary analysis of a large ram-air parachute

Steady aerodynamic characteristics of a large ram-air parachute are investigated in this example. The model is a high glide-performance parachute aimed at delivering very heavy payloads designed and manufactured by CIMSA in the framework of the FASTWing Project⁹. The model canopy discretization consists of an unstructured distribution of 11760 triangular elements and 11912 cable elements model the suspension and control lines as well as the reinforcement tapes integrated into the canopy. The movement of the suspension line's confluence points is restricted to follow the experimental setup. To obtain a faster convergence to the equilibrium position of the parachute, some degree of under-relaxation is employed when transferring the aerodynamic loads to the structure. Initial and equilibrium parachute configurations are shown in Fig. 4.

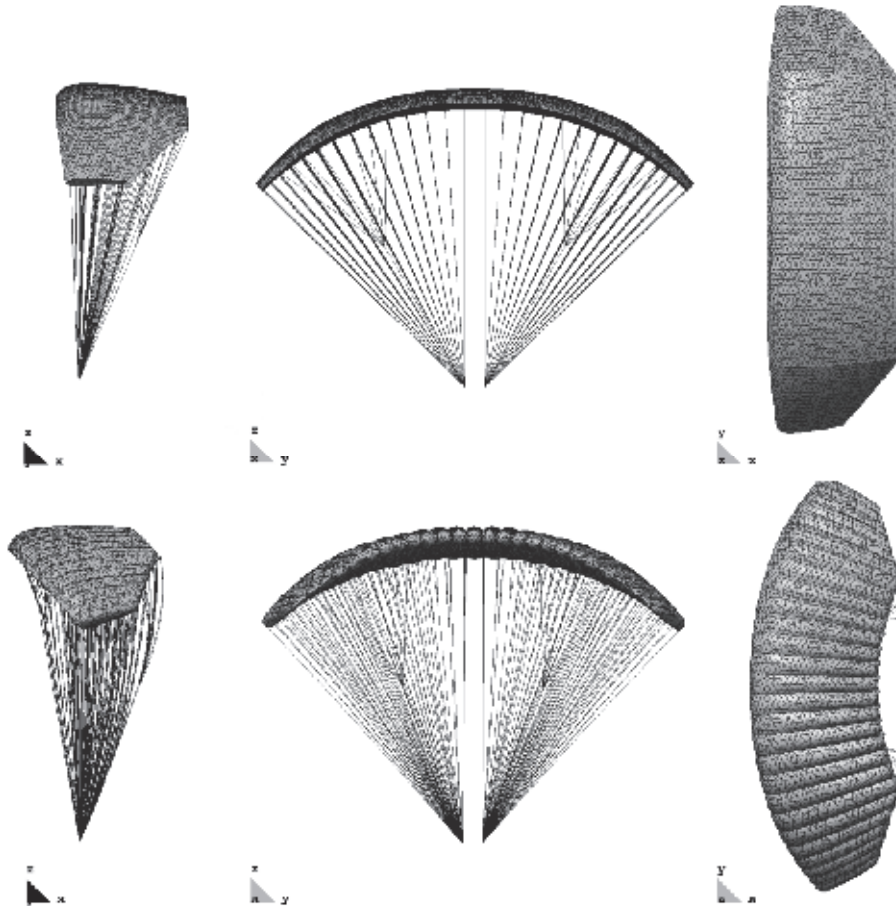


Figure 4: Initial (top) and equilibrium (bottom) configurations

The time history of force and moment coefficients is displayed in Fig. 5, where the moment coefficients are computed about a point located between the suspension line's confluence points. Note that the moments plotted include only the contribution due to the canopy; if the contribution of the drag from the suspension lines were included the total value would be zero. It must also be stressed that the transient behaviour lacks real physical meaning as under-relaxation has been employed to accelerate convergence to the steady state.

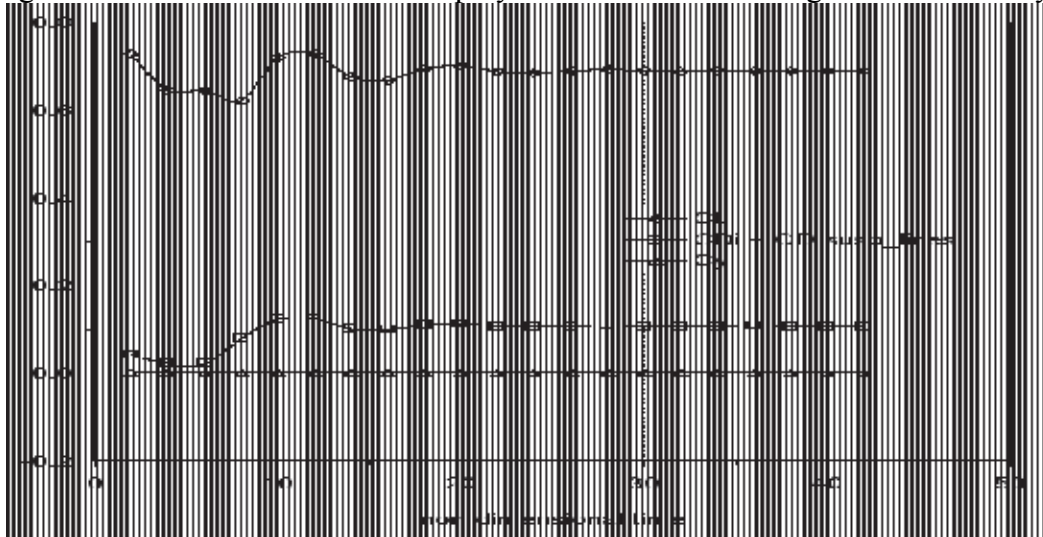


Figure 5: Computed evolution of force and moment coefficients

4.2 Parachute manoeuvre analysis

A left-turn manoeuvre of a small CIMSA parachute-payload system in free-flight is studied in this example.

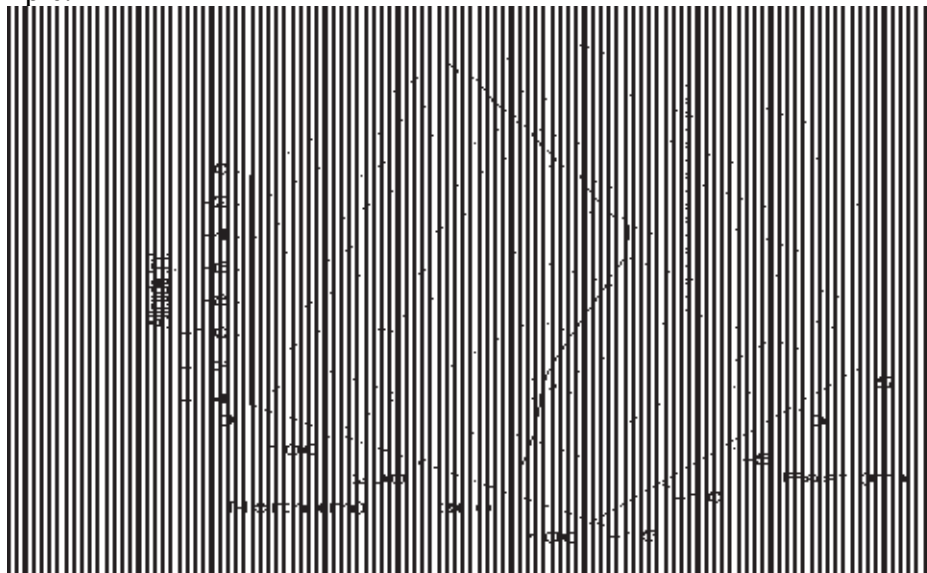


Figure 6: Payload centre of mass computed trajectory

The canopy discretization consists of an unstructured distribution of 9548 triangular elements and 3077 cable elements model the suspension lines and the canopy reinforcements. The payload is 100 kg and the parachute is released with North heading at a velocity of 12 m/s. The simulation starts with a partially inflated parachute configuration and, once steady descent flight is achieved, the manoeuvre is initiated by applying a 0.5 m downward deflection of the left brake line. After 5 seconds, the brake line is released and the parachute recovers a straight down descent flight. The trajectory described by the payload center of gravity during the manoeuvre is displayed in figure 6. Snapshots of the parachute-payload system taken at different times during the simulation are shown in figure 7. The dynamic evolution of the model shows a good agreement with the observed behavior of a real ram-air parachute performing the same manoeuvre. This demonstrates the capability of the present methodology to provide not only aerodynamic and structural data for design but also for performance and trajectory analyses

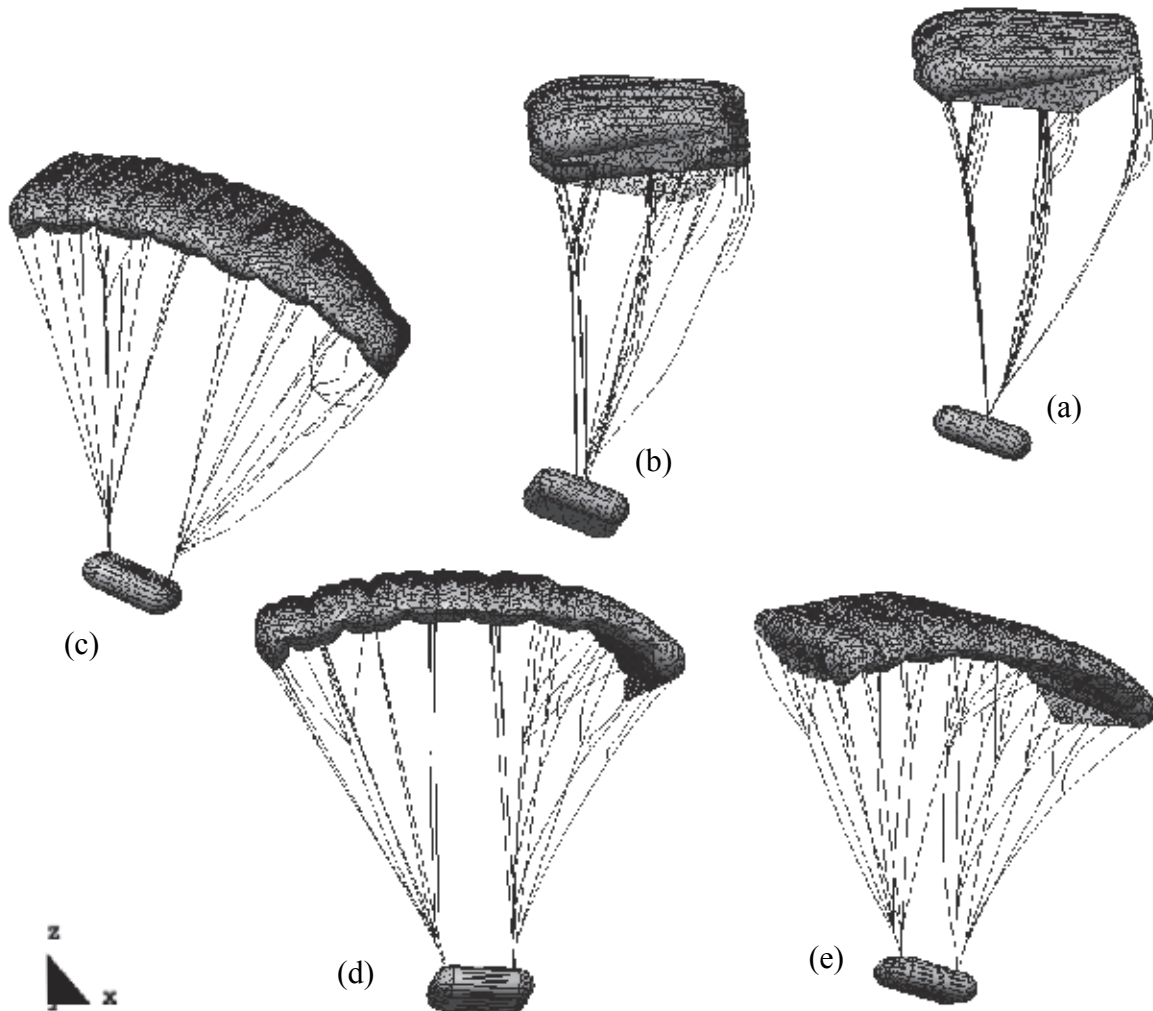


Figure 7: Snapshots of the parachute-payload configuration at different stages of the manoeuvre simulation: (a) 3.564s, (b) 15.58s, (c) 19.05s, (d) 19.88s., (e) 23.17s

4.3 Inflation process of a conventional parachute

This is a simple inflation test aimed at exploring the capabilities of the computational code to simulate parachute deployment and inflation. The model proposed for the aerodynamic loads is quite simple. The parachute is initially deployed by applying a force at the canopy apex in the direction of the incident wind. The inflation stage, which begins after line and canopy stretching, occurs due to a variable pressure force applied on the canopy accounting for relative wind direction and velocity. In this way, the maximum pressure force corresponds to the fluid stagnation condition and the value is reduced according to the orientation of the elements in relation to the incident wind. The parachute is discretized with an unstructured distribution of 3390 triangular elements and 2040 cable elements modeling the suspension lines and the fabric reinforcements. Some snapshots of the parachute at different times during the inflation process are presented in figure 8.

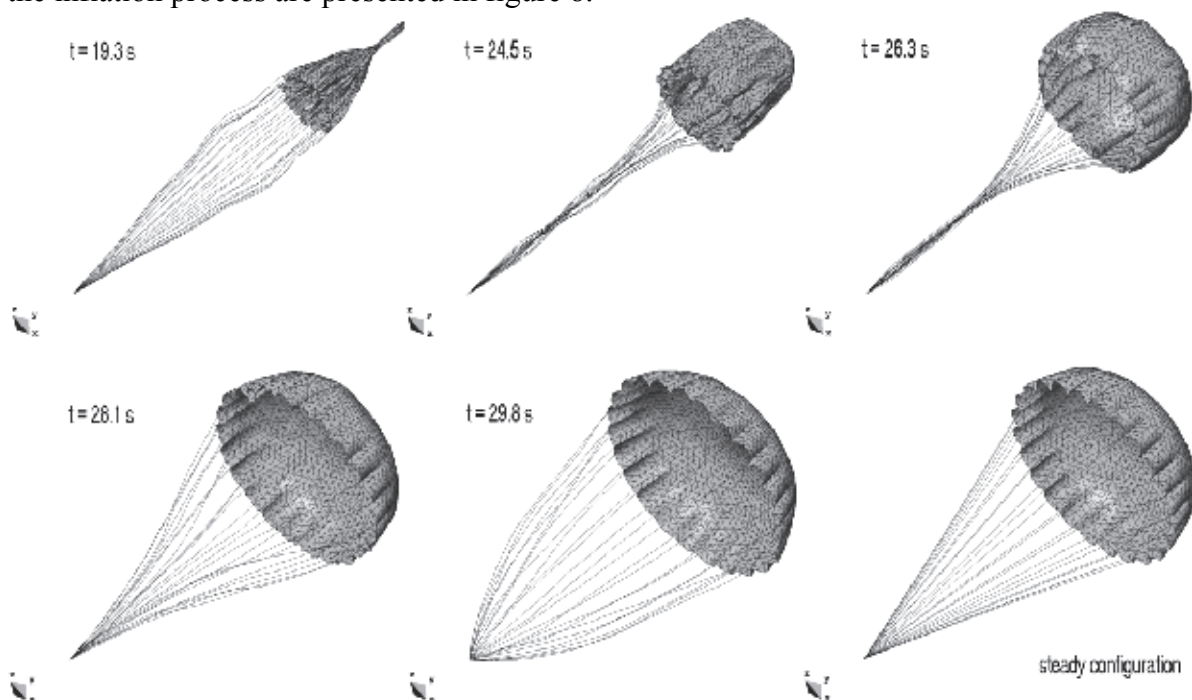


Figure 8: Parachute views at different stages of the inflation process

5 ACKNOWLEDGEMENTS

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6 CONCLUSIONS

- There is currently a severe lack of computational tools for the analysis of parachute systems.
- A new development from CIMNE in this field has been presented. The simulation

package contains a coupled fluid-structural solver tailored for the unsteady simulation of ram-air type parachutes.

- The capabilities of both the dynamic explicit structural code and the unsteady potential flow solver have been successfully validated through relevant benchmark cases.
- 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).

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