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Reprint of: The particle finite element method for the numerical simulation of bird strike☆,☆☆

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ABSTRACT

The Particle Finite Element Method (PFEM) is evaluated in the context of the numerical simulation of bird strike events. To assess the possibilities of the method, theoretical analyses are initially performed based on the impact of a water jet on a rigid surface. Then, the influence of the geometry of a more realistic projectile is analyzed and the capability of the method to take into account separation and fragmentation is highlighted. Finally, the method is tested for impacts against deformable targets, using a partitioned algorithm with dynamic relaxation for the fluid-structure interaction, combining the PFEM for the description of the bird with a non-linear Finite Element approach for the description of the impacted structure, which can undergo large plastic deformations. To assess the quality of the obtained results a series of numerical examples from the literature has been selected and used as a reference throughout the paper. Among the studies presented in this work also a novel numerical benchmark for the evaluation of bird impact simulations is proposed.

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1. Introduction

In the last decades the advancements in numerical simulation techniques together with the necessity to improve aircraft performance without excessively increasing costs have made numerical methods an essential tool both in design and certification phases of aircraft components. When it comes to bird strike, the most difficult task from a numerical standpoint is the modeling of the bird, which undergoes extremely large deformations. Moreover, as well known, when high velocity impact is concerned, the bird is often reduced, even experimentally, to a surrogate projectile modeled as a weakly compressible fluid (typically a mixture of water and air), as discussed by Wilbeck [1]. From a numerical standpoint, the presence of a free surface and the strong interaction with the aircraft structure represent a challenge for traditional computational fluid dynamics methods based on an Eulerian grid. On the other hand, classical Lagrangian methods cannot cope with the extremely large deformations experienced by the projectile during the impact, and in practice some artifacts have to be introduced to control the element distortion, often leading to a loss of generality and robustness. Moreover, since explicit time integration is usually employed, the presence of distorted elements would lead to a drastic reduction in the time step size, degrading the computational efficiency. As an alternative to Finite Elements, the Smoothed Particle Hydrodynamics (SPH) [2] is often employed for the simulation of bird strike [3,4]. SPH is a Lagrangian meshless method that can naturally account for extremely large deformations. Unfortunately this method is cursed with consistency and stability issues [5,6] that can sometimes compromise the entire simulation. Moreover, it is usually more expensive than Finite Element approaches (see e.g. [7]). The Particle Finite Element Method (PFEM), initially introduced in the field of civil engineering [8,9], is a Lagrangian particle method that has proven to be a powerful tool to solve complex free-surface fluid-structure interaction. The method can account for very large deformations, but preserving the robustness and generality of the Finite Element method, and thus owning a key advantage over other approaches. The key idea of the PFEM is the use of classical Finite Elements combined with a very fast remeshing procedure that allows the treatment of extremely large deformations, including separation and fragmentation. In this work a preliminary assessment of this method in the framework of bird strike is proposed. First of all, a short description of the PFEM is given. In the second part some academic tests are conducted for impacts on rigid surfaces. First, the case of a water jet impacting a rigid surface is considered and then the one of a more realistic bird impact. Results are compared to available theoretical and experimental data. The capabilities of the method to take into account separation and fragmentation are also highlighted through a bird impact over a rigid pseudo wing leading edge. Then, the method is tested on more demanding cases, involving deformable targets and strong interaction between the bird and the impacted

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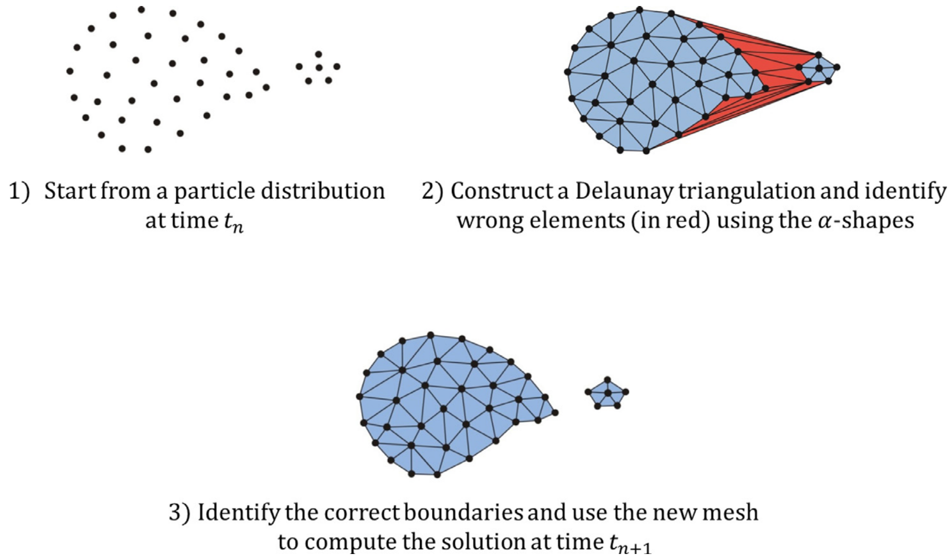


Fig. 1. Schematics of the PFEM.

structure. In this case, the structure is modeled using a distinct Finite Element solver and the coupling is enforced using a partitioned algorithm. For the structural part the software employed in this work is Metafor, an object-oriented Finite Element solver developed at the University of Liège.[1] It is worth underlining that, to the best of the authors' knowledge, this is the first attempt to use PFEM in combination with FEM in large plastic deformations in a partitioned way. A partitioned coupling of PFEM with FEM was already proposed in [10] but it included only elastic material behavior. The method is first validated on a dam break against an elastic obstacle. Then, a pseudo bird impact on a clamped beam and a bird impact on a deformable metallic panel are analyzed. Whenever possible, the results are compared to those available in the literature. It is also to be underlined that no damage or failure of the structural parts (targets) are taken into account in any of the examples presented in this work.

2. The PFEM

2.1. PFEM general ideas

In the PFEM the fluid is discretized using a set of points, hereafter referred to as *particles*, which actually represent material points of the body. In order to evaluate the forces acting on each particle, a new mesh is built at each time step from the entire set of particles using a Delaunay triangulation combined with the so-called α*-shape* technique [11] for the correct identification of the external boundaries (see Fig. 1). This allows a fast evaluation of nodal connectivity even when the total number of particles becomes very large [12]. Classical Finite Element (FE) shape functions can then be defined on this new mesh to solve the corresponding weak form of the governing equations (see Section 2.3).

The concept of α*-shapes* is the following: given a Delaunay triangulation, all the triangles whose circumradius is larger than αh, α being a scalar user-defined parameter and h being the average size of the elements in the triangulation, are discarded. For most applications, a good choice of the parameter α is usually between 1.2 and 1.5 (see [13] for a thorough analysis of the role played by this parameter in the PFEM).

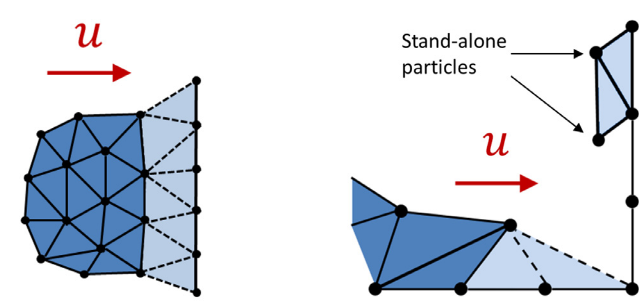
Given a set of particles, the main steps of the PFEM within one time step can be thus summarized as follows:

1. Define the particle connectivity through a Delaunay triangulation;
2. identify the domain boundaries using the α*-shape* technique;
3. solve the governing equations making use of *linear* FE shape functions;
4. use the solution obtained from the previous step to update the particle positions.

This procedure is schematically described in Fig. 1 for better understanding. In the following, several technical aspects of the implementation are omitted. For a complete description of the method, the reader is referred e.g. to Idelsohn et al. [8] or Oñate et al. [9]. Finally, it is important to note that the present work focuses on two-dimensional cases.

2.2. Fluid-solid contact in the PFEM

Classically, PFEM employs no-slip conditions for the fluid at fluid-solid boundaries, that is a fluid that comes into contact with a solid surface sticks to it, i.e. its velocity is the same as the solid at the fluid-solid interface. To detect the contact the method takes advantage of the remeshing procedure by creating new fluid elements every time that a particle approaches a solid boundary, or flows over it, as illustrated in Fig. 2. Once the fluid elements are created, the particle is forced to move tangentially to the walls due to the incompressibility constraint: in this way it cannot penetrate the solid boundary. One drawback of this technique is that some mass is added to the system



(a) Fluid approaching a solid. (b) Fluid flowing over a solid.

Fig. 2. Fluid-solid contact detection in PFEM. Newly created fluid elements are in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[1] http://metafor.ltas.ulg.ac.be/dokuwiki/.

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