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Modelling and simulation of the sea-landing of aerial vehicles using the Particle Finite Element Method

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ABSTRACT

In this paper the Particle Finite Element Method (PFEM) is applied to the simulation of the sea-landing of an unmanned aerial vehicle (UAV). The problem of interest consists in modelling the impact of the vehicle against the water surface, analyzing the main kinematic and dynamic quantities (such as loads exerted upon the capsule at the moment of the impact). The PFEM, a methodology well-suited for free-surface flow simulation is used for modelling the water while a rigid body model is chosen for the vehicle. The vehicle under consideration is characterized by low weight. This leads to difficulties in modelling the fluid–structure interaction using standard Dirichlet–Neumann coupling. We apply a modified partitioned strategy introducing the interface Laplacian into the pressure Poisson's equation for obtaining a convergent FSI solution. The paper concludes with an industrial example of a vehicle sea-landing modelled using PFEM.

1. Introduction and outline

The sea-landing of aerial vehicles is one important practical application where numerical simulation of fluid–structure interaction (FSI) is of great importance since the preliminary physical tests turn out to be excessively expensive. The simulation tests can provide both qualitative and quantitative insight into the movement of the vehicle and predict the impact forces.

It is worth mentioning that up-to-date there exists a rather sparse literature on the sea-landing studies. Experimental investigations of the water landing were presented in Vaughan (1959). Numerical studies can be found e.g. in Littell (2007) where the commercial software LS-DYNA was used. However, several of the existing fluid–structure interaction techniques can be applied to the problem of interest. One such possibility is the Arbitrary Lagrangian Eulerian (ALE) approach known for its accuracy (see e.g. Donea et al., 1982 or Souli et al., 2000). Unfortunately, even the most advanced ALE formulations arrive to their limits when the domain shape deformations are large, which is the case for the problem at hand. In such situations, re-meshing becomes inevitable. Another alternative are the fixed grid approaches equipped with the volume of fluid (VOF) or the Level set method (Legay et al., 2006; Rossi et al., 2013). Although possible, the use of fixed grid methods is not trivial for the problem at hand, since it would require dealing with an FSI boundary cutting the grid elements at arbitrary positions. This would require implementing some sort of embedded technique (Codina et al., 2009; Ryzhakov and Oñate, 2010). Smooth Particle Hydrodynamics (SPH)-based approaches (see e.g. Liu, 2003; Antoci et al., 2007) represent a viable alternative and we verify our formulation against one of the few available benchmark examples (Oger et al., 2006). The problem of the majority of SPH methods is related to the artificial compressibility they usually introduce, which leads to the generation and propagation of non-physical pressure waves in the fluid domain. Such effects may be relevant when estimating the impact forces.

Yet another possibility relies on applying the Particle Finite Element Method (PFEM) (Oñate et al., 2004; Idelsohn et al., 2004; Larese et al., 2008; Ryzhakov et al., 2010). PFEM is a class of Lagrangian Finite Element methods developed for treating free-surface flows and it enables efficient treatment of such complex FSI problems. This option is explored here. We present an approach where the PFEM fluid formulation is coupled to the rigid body model representing the vehicle. The rigid body approximation is a reasonable choice considering that the deformations of the solid are of no interest in the study.

In the present study the unmanned aerial vehicle (UAV) under consideration is characterized by a low weight. The average density, when empty, is some three times lower than that of water. In such case standard Dirichlet–Neumann FSI strategies require excessive number of coupling iterations or do not converge

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at all. There are several techniques for tackling this problem. Among them there are the under-relaxation techniques (Kuettler and Wall, 2008), Robin–Robin coupling strategies (Badia et al., 2009), methods based on introducing slight compressibility to the fluid (Ryzhakov et al., 2010) and others. We adopt here the FSI coupling equipped with the so-called "interface Laplacian technique" (Idelsohn et al., 2009; Rossi and Oñate, 2010) which ensures convergence. This technique accounts for the structural motion within the pressure Poisson's equation of the fluid. It can be easily implemented within an existing Dirichlet–Neumann coupling.

The paper is organized as follows. First, the basic concepts of the PFEM are introduced. The fractional step technique is applied to solution of the governing system. Next, a rigid body model is described and the FSI coupling scheme is presented. The paper concludes with an example section, where the method is validated first and then applied to a problem of sea-landing of a UAV. Two stages of analysis are presented: the impact of the capsule against water and the floating of the capsule in water.

2. The PFEM-based model for the fluid

The PFEM adopts an updated Lagrangian framework for the description of the fluid, where the mesh nodes are treated as particles that can freely move and even separate from the main fluid domain (Oñate et al., 2004; Idelsohn et al., 2004). The key idea of the PFEM is that the variables of interest are stored at the nodes instead of the Gauss points. This results in a hybrid between a standard FE and a mesh-free method. A finite element mesh is created at every time step of the dynamic problem and the solution is then stored at the nodes. The nodes move according to their velocity obtaining their new position and then the finite element mesh is re-generated using a Delaunay triangulation (Delaunay, 1934). In our approach we use simplicial triangular/tetrahedral meshes. In treating problems involving free surface flows the boundary is determined at every time step using the alpha-shape technique (Akkiraju et al., 1995; Oñate et al., 2004).

It is important to remark that the convective term of the momentum equation disappears in the Lagrangian description. Therefore the problem remains elliptic and the discrete system is symmetric. Thus the stability problems faced in Eulerian methods due to the presence of the convective term do not exist in PFEM.

Governing equations for an incompressible fluid in a Lagrangian framework: A viscous incompressible flow is described by Navier–Stokes equations, which in the Lagrangian framework can be written as (a Newtonian fluid is considered):

$$\rho\frac{\partial \mathbf{v}}{\partial t} + \nabla p - \nabla\cdot(\mu\nabla\mathbf{v}) = \rho\mathbf{g} \tag{1}$$

$$\nabla\cdot\mathbf{v} = 0 \tag{2}$$

where $\mathbf{v}$ is the velocity vector, p the pressure, t the time, $\mathbf{g}$ the body force, ρ the density and dynamic viscosity μ.

We define the residual of the momentum and continuity equations as

$$\mathbf{r}_m = \rho\mathbf{g} - \left(\rho\frac{\partial\mathbf{v}}{\partial t} + \nabla p - \nabla\cdot(\mu\nabla\mathbf{v})\right) \tag{3}$$

$$r_c = \nabla\cdot\mathbf{v} \tag{4}$$

The problem to be solved becomes finding $\mathbf{v}$ and p such that

$$\mathbf{r}_m = 0 \tag{5}$$

and

$$r_c = 0 \tag{6}$$

A discrete version of the governing system obtained using linear equal order velocity–pressure finite elements in space and Backward Euler time integration scheme[1] reads (note that the discrete variables are distinguished from their continuous counterparts by an over-bar)

$$\overline{\mathbf{r}}_m = \overline{\mathbf{F}}^{n+1} - \left(\mathbf{M}\frac{\overline{\mathbf{v}}_{n+1} - \overline{\mathbf{v}}_n}{\Delta t} - \mathbf{G}\overline{\mathbf{p}}_{n+1} + \mu\mathbf{L}\overline{\mathbf{v}}_{n+1}\right) = 0 \tag{7}$$

$$\overline{\mathbf{r}}_c = \mathbf{D}\overline{\mathbf{v}}_{n+1} + \mathbf{S}\overline{\mathbf{p}}_{n+1} = 0 \tag{8}$$

where $\overline{\mathbf{v}}$ and $\overline{\mathbf{p}}$ are the velocity and pressure respectively, $\overline{\mathbf{F}}$ is the body force vector, $\mathbf{M}$ is the mass matrix, $\mathbf{L}$ is the Laplacian matrix, $\mathbf{G}$ is the gradient matrix and $\mathbf{S}$ is the stabilization matrix necessary for ensuring pressure stability whenever equal order velocity–pressure interpolation is used. Discussing details of the pressure stabilization lie outside of the scope of this work and the ideas presented here can be applied in conjunction with any stabilization technique such as Galerkin/Least squares (GLS) (Hughes et al., 1989), finite calculus (FIC) (Oñate, 2000, 2004), algebraic sub-grid scales (ASGS) or orthogonal sub-scales (OSS) (Codina, 2002). In the present implementation the FIC stabilization method was used.

The matrices are assembled from the elemental contributions defined as

$$\mathbf{M} = \mathbf{M}_{IJlk} = \int_{\Omega_e} \delta_{kl}(N_I, N_J)\,d\Omega$$

$$\mathbf{L} = \mathbf{L}_{IJ} = \int_{\Omega_e}\left(\frac{\partial N_I}{\partial x_k}, \frac{\partial N_J}{\partial x_l}\right)d\Omega$$

$$\mathbf{G} = \mathbf{G}_{IJk} = \int_{\Omega_e}\left(\frac{\partial N_I}{\partial x_k}, N_J\right)d\Omega$$

$$\mathbf{D} = \mathbf{G}^T$$

$$\mathbf{F} = \mathbf{F}_{Ik} = \int_{\Omega_e}(N_I, \mathbf{f}_k)\,d\Omega$$

where N stands for the standard linear FE shape functions and δ is the Kronecker delta function. The capital indices stand for the nodal numbers while lower-case indices refer to the spatial components of a vector.

The fractional step method (Chorin, 1967; Temam, 1969) is applied to the monolithic system defined by Eq. (7) permitting an efficient implementation. It is based on the solution of the momentum equations for an intermediate (non-solenoidal) velocity $\tilde{\mathbf{v}}$ and a subsequent correction performed to obtain the end-of-step velocity $\overline{\mathbf{v}}^{n+1}$. Thus the solution of the governing system equation (7) is replaced by three sequential steps:

$$\tilde{\mathbf{r}}_m = \mathbf{F}_{n+1} - \left(\mathbf{M}\frac{\tilde{\mathbf{v}} - \overline{\mathbf{v}}_n}{\Delta t} - \mathbf{G}\overline{\mathbf{p}}_n + \mu\mathbf{L}\tilde{\mathbf{v}}\right) = 0 \tag{9}$$

$$\Delta t\mathbf{L}(\overline{\mathbf{p}}_{n+1} - \overline{\mathbf{p}}_n) + \mathbf{S}\overline{\mathbf{p}}_{n+1} = \mathbf{D}\tilde{\mathbf{v}} \tag{10}$$

$$\mathbf{M}\frac{\overline{\mathbf{v}}_{n+1} - \tilde{\mathbf{v}}}{\Delta t} + \mathbf{G}(\overline{\mathbf{p}}_{n+1} - \overline{\mathbf{p}}_n) = 0 \tag{11}$$

Note that the velocity and the pressure solution steps become decoupled. First, Eq. (9) is solved for $\tilde{\mathbf{v}}$ knowing $\overline{\mathbf{p}}_n$ and $\overline{\mathbf{v}}_n$, then the end-of-step pressure $\overline{\mathbf{p}}_{n+1}$ is computed from $\tilde{\mathbf{v}}$ (Eq. (10)). Finally, the end-of-step velocity is found from $\overline{\mathbf{p}}_{n+1}$ and $\tilde{\mathbf{v}}$ according to Eq. (11).

Re-meshing and boundary definition: As in the PFEM the mesh is moving in time, the computational mesh undergoes deformation. Therefore, the re-meshing and the re-determination of the domain's boundaries must be executed. In the PFEM the mesh is

[1] The time integration using the Backward Euler scheme is assumed for the sake of simplicity. However, all the arguments presented in the paper can be extended to any implicit time integration scheme.