Full aircraft ditching simulation: a comparative analysis of advanced coupled fluid-structure computational methods

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Abstract

The communication concerns advanced numerical simulations of the transient fluid structure-interaction occurring during aircraft ditching. While the structural model used the Finite Element method, either the Arbitrary Lagrangian-Eulerian or the hybrid Smoothed Particle Hydrodynamics-Finite Element approaches were considered for the fluid model. Both computational methods were comprehensively compared using data of guided ditching experiments. The numerical results were satisfactory in terms of local pressures, local strains, and global force to consider further applications to full-scale structures. In this communication, these computational methods are applied to full spacecraft and aircraft (full-scale) ditching problems.

Keywords: Ditching, Spacecraft, Aircraft, CEL-FE, SPH-FE

1. Introduction

Most of air traffic operates over water, airports are mostly located around water, and near-airport operations (such as takeoff, final approach, and landing) take place above water [1]. Fortunately emergency landings on water, comprising ditching and crash on water, do not occur frequently. Passenger safety under dynamic loads being of key importance in modern aerospace vehicle design, ditching analysis is part of aircraft design. The landing of an airplane on water is an emergency situation that an aircraft faces only once. Loss of the aircraft is acceptable, provided the crew and the passengers can safely escape and be rescued. For a water contact to qualify as a ditching, it is necessary that the touchdown follows a prudent approach and acceptable procedures. The design must: provide structural integrity to protect the occupants, ensure that no excessive decelerations will be experienced by the occupants, and provide sufficient time for safe egress from a damaged aircraft; see CS-25 and §25.801 on ditching for more detailed information [2].

In order to quantify the structural capacity of aircraft structures under hydrodynamic loading, the prediction of global and local structural loads and resulting deformations is of fundamental importance. The ditching analysis, however, is very challenging as ditching is a time-dependent, highly nonlinear multi-physics problem with different length and time scales resulting in complex loading conditions and coupled fluid-structure interaction. The analysis of ditching has been widely based on experimental testing of sub-scale models in order to assess the aircraft motion under various impact conditions with the objective to demonstrate that the aircraft can make a safe landing. However, effects related to the structural deformation are rarely considered in experimental campaigns because of the financial and temporal effort associated. Such experiments require costly prototypes, limiting the number of designs to be investigated, and they only allow for a certain number of probes, which results in comparatively little insight into involved physical phenomena.

With growing availability of powerful computers in recent years, simulations are increasingly employed to analyze the structural behavior under ditching conditions. The analysis of ditching can be based on advanced numerical simulations of the transient fluid-structure (FS) interaction. Therefore, fluid and structure models are coupled. The structural models used the Finite Element method and the fluid domain was based on either the Arbitrary Lagrangian-Eulerian (ALE) or the hybrid Smoothed Particle Hydrodynamics-Finite Element (SPH-FE) approaches. Both computational methods were comprehensively compared using data of guided ditching experiments [3]. The numerical results were satisfactory in terms of local pressures, local strains, and global force to consider further applications to full-scale structures [4].

In this communication, these computational methods were applied to spacecraft and aircraft ditching problems in full scale. The ditching of the Apollo Command Module was considered first because experimental data were available in the open literature for different impact conditions (i.e. purely vertical drop tests and oblique (with a high horizontal velocity component) ditching tests, initial pitch angle, and initial velocities). The ditching of a generic transport aircraft was simulated using both numerical approaches. The generic aircraft model is typical of a short- to medium-range commercial passenger twin-engine jet. Different parameters of the ditching, such as the initial pitch attitude, the initial horizontal and vertical velocities, or the initial yaw angle, were varied in order to analyze their influence on the impact severity.

2. Numerical approaches

The Lagrangian formulation is classical in solid mechanics and structural analysis. The mesh and the material points are tied and the mesh and material deformations are consequently linked. Sliding between material (structure) and mesh is not allowed. Loads and boundary conditions can easily be applied to the material points (nodes). The Lagrangian description tracks easily the free surfaces and interfaces between different materials. However, when the structure is severely deformed, Lagrangian elements become similarly distorted since they follow the material deformation. Therefore, in those cases the accuracy and robustness of the Lagrangian simulations decrease severely. The Eulerian formulation is classical in fluid mechanics. The mesh is fixed and the material flows through the mesh. Equations are modified with respect to Lagrangian formulation in order to take into account the convective terms. The treatment of moving boundaries and interfaces is difficult with Eulerian elements. The Eulerian formulation cannot be used in many cases where the boundaries of the domain move. In the Arbitrary Lagrangian-Eulerian (ALE) formulation, the material flows through an arbitrary moving mesh. Both the material and the mesh move with respect to a fixed frame of reference. It equals a combination of Lagrangian and Eulerian formulations. Grid velocities and displacements are arbitrary. In practice, built-in algorithms determine smooth grid deformation according to displacements of the ALE domain boundaries. Note that the ALE formulation can be degenerated in Lagrangian (the grid velocity is equal to the material velocity) or in Eulerian (the grid velocity is set to zero). The fundamentals of the adopted computational methods to simulate the fluid are not repeated here; the reader can refer to [5] and to [6] for the ALE and the SPH formulations respectively. Both formulations are based on the Euler equations (conservation of mass, momentum, and energy) for the fluid modeling.

In the Coupled Euler-Lagrange (CEL) method, the coupling between fluids and structure relies, in the computations presented here, on an immersed interface also referred to as embedded interface. The structure and the fluids are meshed in a completely different manner and the structure mesh is immersed within the mesh of the fluids. An unstructured fluid mesh (conforming or non-conforming) is no longer necessary. With this technique, the fluid mesh can be even regular. In this case, an ALE formulation is no longer necessary in the fluid sub-domains, which can be Eulerian so that the fluid mesh will never entangle (fixed mesh). The immersed interface allows slave nodes (material grid) belonging to the Euler or ALE fluid media to interact with the master surfaces of the Lagrange solid medium. In the hybrid SPH-FE method, a weak coupling using a node-to-surface penalty contact algorithm is typically adopted. Therein, the particles represent the slave nodes and the structural elements are the master segments. The contact algorithm checks for any penetration of slave nodes into the contact zone around the master segments. In both approaches, upon penetration, a repulsive force is applied using the penalty method. The force is distributed to the element's nodes in opposed direction. The contact force magnitude is proportional to the penetration depth and to the contact stiffness.

3. Application to diching problems in full scale

3.1 Ditching of the Apollo Command Module

The model was released at the lowest point of a pendulum and the free fall gave the desired vertical velocity. The position of the center of gravity and dimensions of the prototype Apollo spacecraft, from which the model was scaled, are given in [7]. The gross mass of the prototype Apollo spacecraft at full scale, shown in Fig. 1, was 3900kg. The roll, pitch, and yaw moment of inertia at full scale were 5560 10^6kg/mm^2, 5270 10^6kg/mm^2, and 4180 10^6kg/mm^2, respectively. Accelerations were given at the center of gravity of the Apollo spacecraft. Pressure transducers were implemented on the heat shield and were located in groups of three in order to obtain mean pressures from arbitrary circular panel areas of approximately 2ft^2 at full scale. Two initial pitch attitudes were selected for the simulations: -30^o and -14^o. Pressures and accelerations were rather low and high for pitch attitudes at -30^o and -14^o, respectively. Drop and ditching tests were performed at -9.5m/s initial vertical velocity (at full scale). The initial horizontal velocity was 15m/s (at full scale) in the diching test cases. A pendulum was released from a predetermined height to produce the desired horizontal velocity.

The maximum mean pressures were quite significantly overestimated (underestimated) by SPH-FE (CEL) simulations. The computational results were improved by decreasing the mesh size of the fluid in the impact area. The difference with experimental data remained, however, large despite the large additional computational effort. Maximum accelerations were contrary correctly approximated by both numerical approaches. The maximum accelerations were slightly overestimated (underestimated) by SPH-FE (CEL) simulations. Accelerations in peaks were highest in the longitudinal direction and around the pitch axis. Accelerations were also highest for the test case with the lowest initial pitch attitude. The influence of the horizontal velocity (comparing drop and ditching test) was limited in terms of maximum acceleration. These tendencies were confirmed by experimental measurements [7].

3.2 Ditching of the generic transport aircraft

The generic aircraft model is shown in Fig. 1. The length and the radius of the fuselage was 37.5m and 2.05m, respectively. The wingspan was 34m. The generic aircraft model had a quasi-rigid mechanical behavior. The mass, the position of the center of gravity, and moments of inertia were computed using physical databases. The gross mass of the generic transport aircraft at full scale was 72.5 10^3kg. The roll, pitch, and yaw moment of inertia at full scale were 1070 10^9kg/mm^2, 3100 10^9kg/mm^2 and 4100 10^9kg/mm^2, respectively. Ditching simulations were performed in the nominal/reference configuration at -1.5m/s and 70m/s initial vertical and horizontal velocities, respectively. The initial pitch attitude was 8°. Initial pitch attitude, initial horizontal and vertical velocities were varied to analyze their influences on the impact severity. Additionally, non-zero yaw angles were considered in other computations. The influence of the aerodynamic forces (i.e., lift in particular) was studied for some configurations. The aircraft kinematics, velocities, and accelerations obtained with both computational methods were compared.

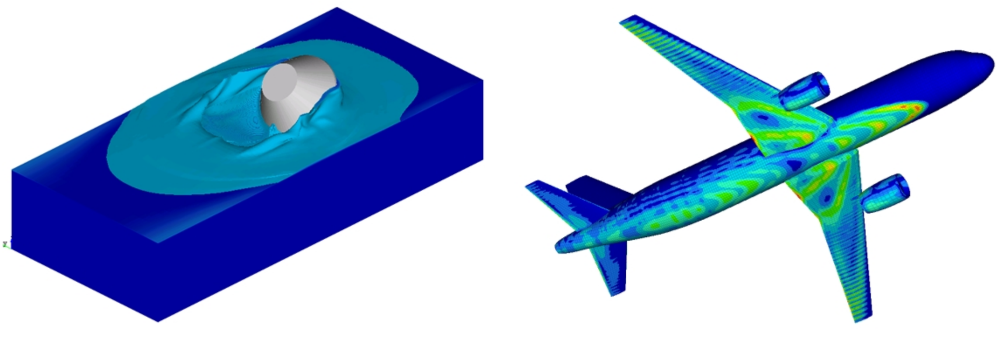

Fig. 1. Full spacecraft/aircraft ditching simulations. Left: ditching of the Apollo Command Module using an ALE approach. Right: Finite Element model of the generic transport aircraft (contour plot: exemplary pressure distribution on the generic transport aircraft).

The aircraft in the SPH-FE simulations stuck to the water with no tendency to skip. The horizontal velocity of the aircraft reduced fast. The CEL simulations showed more complex FS interactions. At the beginning of the ditching, the rear part of the fuselage impacted water in series with a tendency to skip. The horizontal velocity of the aircraft was not reducing as much as in the SPH-FE simulations. The increase in attitude was generally higher in the CEL simulations compared to the SPH-FE results. The pitch attitude was always greater than zero in the CEL simulations. With the SPH-FE simulations, the pitch attitude could be less than zero. The pitch attitude of the aircraft was around 2° at the end of the runs. The length of the runs was very different for both types of simulation: 3 and 5 (in fuselage length) in the case of the SPH-FE and CEL simulations, respectively. The aircraft was mainly decelerated due to the contact between the water and the fuselage and wings. The influence of the impact of the engines on water was limited in the CEL simulations in particular. The second acceleration peak in the vertical and horizontal directions was slightly decreased when the FS interaction was limited to the fuselage and the wing only (i.e. engines not taken into account for the FS interaction).

4. Conclusions

The communication demonstrated the possibility to use advanced numerical simulations to simulate the transient fluid-structure interaction occurring during aircraft ditching. The Coupled Euler-Lagrange and the hybrid Smoothed Particle Hydrodynamics-Finite Element approaches were considered to model the fluid. These computational methods were successfully applied to spacecraft and aircraft ditching problems in full scale: the Apollo Command Module and a generic short- to medium-range commercial passenger twin-engine jet. In the case of the Apollo Command Module, the results obtained with both computational approaches for different impact conditions were very close to the experimental data in terms of accelerations and mean pressures. However, the case of the generic short- to medium-range commercial passenger twin-engine jet has shown differences in the results obtained by both computational approaches.

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References

[1] Patel A A, Greenwood R P. Transport Water Impact and Ditching Performance. Tech. Rep., FAA, Washington D.C., USA, 1996.
[2] European Aviation Safety Agency, Certification specification and acceptable means of compliance for large aeroplanes. CS-25, Amendment 18, 22 June 2016, Decision 2016/010/R.
[3] Iafrati A. Experimental investigation of the water entry of a rectangular plate at high horizontal velocity. Journal of Fluid Mechanics, 2016, 799:637-672.
[4] Siemann M H, Langrand B. Coupled fluid-structure computational methods for aircraft ditching simulations: comparison of ALE-FE and SPH-FE approaches. Computers & Structures, 2017, 188:95-108.
[5] Donea J, Huerta A, Ponthot J P, Rodriguez-Ferran A. Arbitrary Lagrangian-Eulerian methods. Encyclopedia of computational mechanics. John Wiley & Sons, 2004.
[6] Monaghan J J. Simulating free surface flows with SPH. Journal of Computational Physics, 1994, 110(2):399-406.
[7] Stubbs S M. Dynamic model investigation of water pressures and accelerations encountered during landings of the Apollo spacecraft. NASA, Technical Note D-3980, Langley Research Center, 1967.