Multiphysics feasibility study of an aerial-aquatic spacecraft's plunge into Kraken Mare

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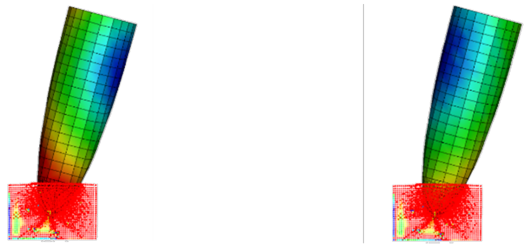
- Results of multiphysics fluid-structure interaction (FSI) CFD simulations using a coupled meshfree smoothed-particle hydrodynamics (SPH) and finite element method (FEM) approach in LS-DYNA.
- Completed as part of ongoing pre-phase A studies into the *ASTrAEUS* aerial-aquatic spacecraft for Titan.
- Sloshing, wave-structure interaction, and projectile impact simulations on finite domain free-surface fluid show comparative behaviour of nitrogen-ethane-methane mix and water.



(a) Projectile entry at time t

(b) Projectile at time $t + 3.6 \times 10^{-3}$ s

Figure 1: Oscillation of projectile during fluid entry seen with nodal acceleration displayed.

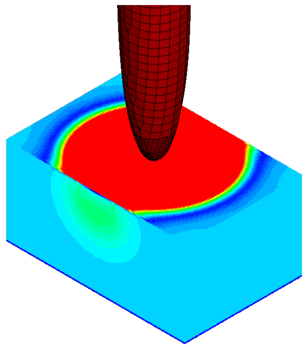


Figure 2: Shockwave propagation in $\mathrm{N/C_2H_6/CH_4}$ mix with nodal acceleration displayed.

Sponsors and partner institutions

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The Spacecraft

- The *ASTrAEUS* (Aerial Surveyor for Titan with Aquatic Operation for Extended Usability) spacecraft is an aerial-aquatic robotic probe in pre-phase A studies which will further explore the Saturnian moon of Titan.
- It is the first platform of its kind ever proposed in the context of space exploration, and will offer unprecedented *in-situ* access to both the surface lakes and atmospheres of one of the most intriguing environments in the Solar System.
- The spacecraft will operate as a heavier-than-air atmospheric flying vehicle, also performing 'plunge diving' manoeuvres to land in surface lakes before relaunching itself back to flight.
- Science will be performed while landed in lakes, and whilst traversing the body's atmosphere.
- Taking more bespoke and powerful instrumentation than the proceeding *Huygens* probe and by journeying into the unknown of Titan's lakes, *ASTrAEUS* holds the key to understanding the surface liquid's composition and role in Titan's volatile cycles.

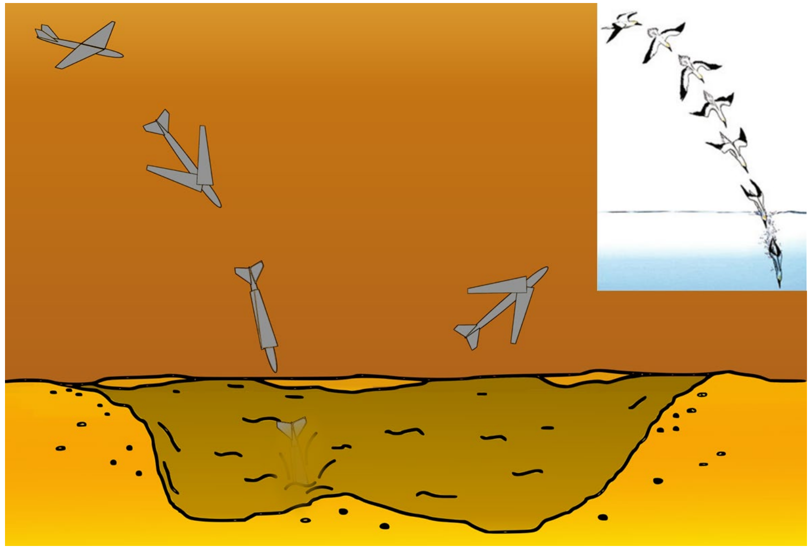


Figure 3: Impression of a 'plunge diving' manoeuvre by an aerial-aquatic spacecraft inspired by the gannet seabird (inset). Inset adapted from Liang et al. (2013).

Methodology

- Two-stage approach taken to first validate modelling techniques using previously documented test rig (Yreux, 2018) refined with experimental data (Gomez-Gesteira *et al.*, 2012) (**Figure 4**), before completing projectile impact simulations.
- Murnaghan equation of state (Murnaghan, 1944) implemented using Kraken Mare properties from Hartwig *et al.* (2018).
- Additional bulk viscosity, hourglass mode controls included to counteract overly dissipative behaviour of fluid.
- Projectile approximated by rotated NACA-0010 aerofoil.
- Computational limitations mean relatively high resolution differential between fluid SPH particles and projectile mesh, leading to non-physical behaviour at projectile tip (**Figure 5**). Problems partially mitigated by FEM surface interpolation.
- Accuracy of projectile simulations limited to before shockwave reflects from boundary (**Figure 2**) due to finite volume caused by computational limits. Non-reflecting boundaries unable to produce stable response under incident particle velocity so disregarded.

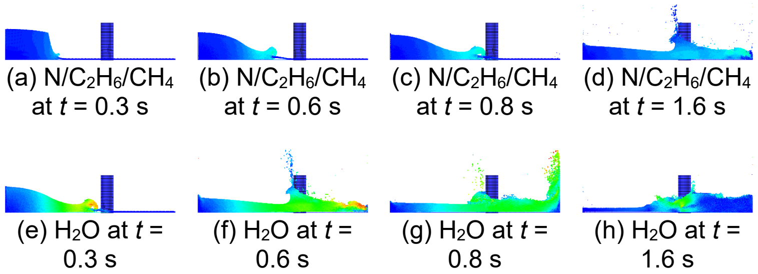


Figure 4: Wave development and FSI of Kraken Mare liquid and Earth water with velocity displayed. Red corresponds to a higher relative velocity.

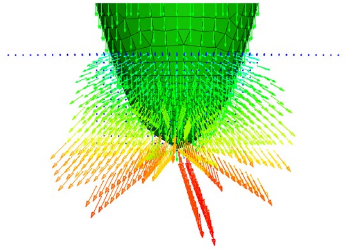


Figure 5: High SPH resolution, double-precision solved solution with nodes travelling over a specific velocity shown and with attached velocity vectors.

Results and Conclusions

- Valid model produced which can simulate projectile entry into Kraken Mare, in view of being used for more accurate spacecraft geometries and impact trajectories.
- Force on projectile in both water and $N/C_2H_6/CH_4$ modelled comparatively (**Figure 6**). Divergence in behaviours becomes increasingly pronounced before shockwave return and subsequent simulation invalidity. Results allow for understanding of 'plunge-diving' feasibility.
- Further observations include high-frequency observations on projectile (**Figure 1**) and a more unstable wake in $N/C_2H_6/CH_4$ during wave-structure interaction simulation (**Figure 7**).

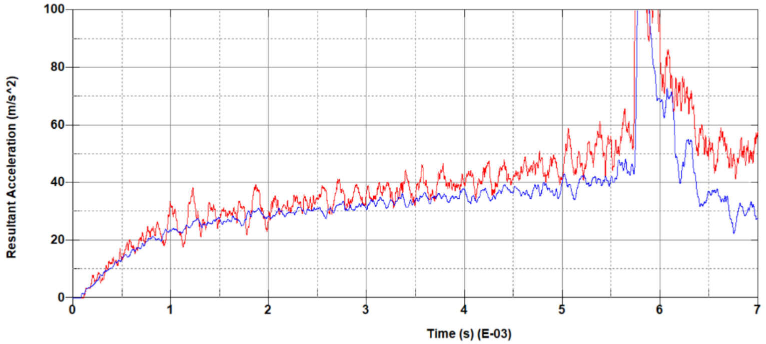
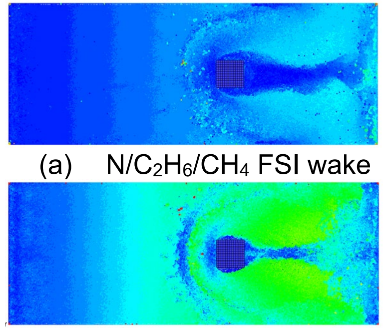


Figure 6: Projectile deceleration due to water and $N/C_2H_6/CH_4$ mix. Shockwave return, therefore invalid results, present at $t \approx 5.75 \times 10^{-3}$ s.



(a) $N/C_2H_6/CH_4$ FSI wake

(b) H_2O FSI wake

Figure 7: Wave-structure wake formation of Kraken Mare liquid and Earth water with velocity displayed.

References

Yreux, E. (2018) 'Fluid Flow Modeling with SPH in LS-DYNA', in *15th International LS-DYNA Users Conference*. Detroit: Livermore Software Technology Corperation.

Gomez-Gesteira, M. *et al.* (2012) 'SPHysics - development of a free-surface fluid solver - Part 2: Efficiency and test cases', *Computers and Geosciences*. Pergamon, 48, pp. 300–307. doi: 10.1016/j.cageo.2012.02.028.

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