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A Monolithic Lagrangian Meshfree Approach for Thermo-Fluid-Structure Interaction problems

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The numerical solution of Thermo-Fluid-Structure Interaction (TFSI) problems involving large structural deformation, free surface flow, multiphase transition and mixing, material discontinuity and dynamic contact represents one of the greatest challenges in computational mechanics. Typical examples arise in a wide range of applications in manufacturing, defence, national security and new energy technologies, such as Direct Metal Laser Sintering (DMLS), explosive loading, high- and hyper-velocity impacts, shale gas extraction and hydraulic fracturing. In this work, we present a monolithic Lagrangian meshfree approach for a robust and efficient solution of the strong coupling problems of general solid and fluid flows.

In contrast to conventional FSI solvers [1], the approach we present uses a single governing equation system in Lagrangian description for both the fluid and structure which is solved simultaneously for the entire field by the Optimal Transportation Meshfree (OTM) method [2]. As a consequence, the fluid structure interface becomes an internal surface of the problem domain which automatically ensures the continuity of kinematic fields and equilibrium on the interface and leads to a more stable and accurate solution. Further, the use of a Lagrangian formulation for fluid eliminates the problem of free surface and interface tracking and results in symmetric system matrices due to absence of convective term in the momentum conservation equations. The Lagrangian solver, the OTM method, is an incremental updated Lagrangian meshfree scheme constructed through an integration of optimal transportation theory [3] with Local Maximum Entropy (LME) meshfree interpolation [4] and material point sampling. The optimal transportation variational framework also results in proper treatment of mass and inertia as well as exact linear and angular momentum conservation. The introduction of material points provides an effective numerical integration rule. Fields requiring differentiation, such as deformation and velocity fields, are interpolated from nodal values using LME shape functions to avoid mesh entangles. We note that these shape functions have the key property of possessing a Kronecker-delta property at the boundary, which enables the direct imposition of essential boundary condition and the coupling of fluid flows to highly deformable structures.

In addition, the Lagrangian nature of the simulation facilitates the use of sophisticated constitutive models at each material point. For instance, in our calculations, a variational thermomechanical coupling formulation that applies to a wide range of dissipative materials including general solids and fluids is solved at the material points to predict the local deformation, motion and temperature fields [5][6][7]. The variational thermomechanical coupling framework employs the Equation of State to describe the volumetric response of the continuum media in the pressure-temperature regime covering multiple phases, accounts for thermo-elasticity and internal dissipative processes as well as arbitrary viscous potentials. Due to the complexity of the monolithic simulations, a massively parallel implementation of the TFSI solver has been developed to realize a successful utilization of high performance computing systems [8]. The proposed methodology has been extensively validated against high and hypervelocity impact experiments in which melting and vaporization takes place in the penetration and perforation region [9]. Thus a strong Thermo-Fluid-Structure coupling problem is solved in the vicinity of the dynamic contact zone. Good agreements between the simulation results and experimental measurements, such as the shape of the debris cloud, perforation areas and temperature distributions, are achieved.

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