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科学研究費助成事業　　研究成果報告書

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研究課題名（和文） Development of a reliable and adaptive multi-physics computational method for fluid-structure interactions encountered in ocean/coastal engineering

研究課題名（英文） Development of a reliable and adaptive multi-physics computational method for fluid-structure interactions encountered in ocean/coastal engineering

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研究成果の概要（和文）：本研究では，流力弾性連成解析のための高度なマルチフィジックス・マルチスケール計算の可能な高精度粒子法型数値計算手法の開発を主目的とした．研究の初段階としてNewtonianおよびHamiltonian，SPH法およびMPS法に基づくモデル化を提案した．複合材料を伴うFSI解析のためにロバスト性に優れたHamiltonian型構造体モデルと高精度粒子法による流体モデルを連成したISPH-HSPH法を開発した．さらに提案手法を異方性体への解析へ拡張し，複合材料・異方性材料を伴う2次元および3次元の流力弾性連成解析を実現した．これらの成果は主要国際学術誌へ投稿・掲載された．

研究成果の学術的意義や社会的意義
持続可能な粘り強い海岸構造物の設計のためには複雑な流体と構造物の相互作用（FSI）に関する深い知見が不可欠である．本研究で提案した計算手法はメッシュフリーかつラグランジュ的な解析手法であり，流体・構造体およびその連成のモデル化を厳密な数学的・物理的背景に基づいて導出した，海岸工学FSI現象の高精度かつロバストな解析が可能な手法である．FSI現象の詳細なメカニズムを数値的に検討可能な高精度数値計算手法を開発したことに本研究の社会的意義がある．さらに学術的な意義として，近年世界中で盛んに研究される粒子法の更なる高精度化の実施およびマルチフィジックス現象への高い潜在的適応性の証示があげられる．

研究成果の概要（英文）：The target of this research, i.e. development of an advanced adaptive and multi-physics computational method for hydroelastic FSI, has been achieved through coherent and rigorous developments made with respect to aspects of reliability, adaptivity and generality. A computational method has been developed capable of reproducing hydroelastic FSI including those corresponding to anisotropic composite structures in both 2D and 3D.
The computational method provides possible selection of either Newtonian or Hamiltonian structure model as well as SPH or MPS formalism. With material discontinuities in composites, a robust Hamiltonian structure model was developed and coupled with a fluid model, resulting in ISPH-HSPH FSI solver as the first entirely Lagrangian meshfree method for hydroelastic FSI corresponding to composite structures. The solver was also extended to 3D and carefully modified for structural material anisotropy. These developments are published in a set of international journals.

研究分野： Computational mechanics, hydrodynamics

キーワード： particle method　FSI　hydroelastic　composite structures　adaptivity　anisotropic　multiphysics

１．研究開始当初の背景

For the design of resilient and sustainable structures in ocean and coastal regions, precise and in-depth understanding of the complex Fluid-Structure Interactions (FSI) is of substantial importance. On the other hand, considering the coastal/ocean structures against extreme waves or severe slamming, precise realization of coastal/offshore fluid-structure systems would be significantly challenging on account of their large scale and limitations of experimental or field measurements. Therefore, computational modelling would be considered as a robust and potentially reliable approach. Meanwhile, presence of violent fluid flow fields, complex moving boundaries and topological changes, complex fluid-structure interactions and intense non-linear structural responses would result in distinct challenges for reliable computational modelling of FSI in coastal/ocean engineering. Considering these challenges, new generation computational methods, namely, Lagrangian meshfree or particle methods are advantageous for reliable computational modelling of hydroelastic FSI. In specific, Entirely Lagrangian Meshfree hydroelastic FSI solvers provide substantial potential as reliable computational tools for hydroelastic FSI due to their flexibility, robust extendibility and precise impositions of interface boundary conditions.

２．研究の目的

The purpose of this research was to develop an advanced, adaptive and multi-physics computational method for hydroelastic FSI encountered in ocean/coastal engineering. In this development, several important aspects of reliability, adaptivity and generality were systematically targeted. Regarding reliability, achievement of unconditional stability, high accuracy as well as excellent conservation, convergence and consistency of the overall FSI solver were carefully considered. As for aspect of adaptivity, achievement of an adaptive FSI solver capable of handling different computational resolutions for fluid and structure sub-domains, with preserving the reliability of the solver, was targeted. As for the aspect of generality, applicability of the solver for reliable modelling of FSI corresponding to composite laminated structures characterized by large material discontinuities was targeted.

３．研究の方法

Since precise models for the fluid part had already been developed, the main focus was devoted to rigorous development of a precise structure model and its consistent coupling with the fluid model so that the solver could reliably and adaptively reproduce complex FSI corresponding to elastic structures including composite laminated ones. A distinct challenge corresponding to composite laminated structures correspond to presence of discontinuities in material properties including density and Young's modulus of lamina. In this regard, Newtonian structure models were initially tested, and acceptable reliability could not be achieved due to presence of stress discontinuities at material interfaces. Considering the importance of variational consistency, i.e., rigorous consistency of dynamics and kinematics of the structure system, in providing excellent stability, accuracy and conservation properties, a Hamiltonian SPH structure model was developed. The model was scrupulously validated and was then coupled with an ISPH fluid model, resulting in a so-called ISPH-HSPH FSI solver capable of accurately handling FSI corresponding to laminated composite structures.

In parallel, an FSI solver was developed in the MPS context, namely, MPS-HMPS and was successfully applied for accurate reproductions of hydroelastic FSI in both 2D and 3D.

Hamiltonian structure models provide distinct advantageous features corresponding to variational consistency, excellent stability, accuracy, conservation and convergence properties. In addition, Hamiltonian formalism would provide distinctive advantages for convenient and rigorous extensions to model non-linear and large-strain elastic and inelastic structural responses in a mathematically-physically consistent and variational manner. However, careful considerations need to be made with respect to selection of a proper material constitutive equation including preciseness of the energy potential defined for the specific problem of interest. Hence, simultaneously, efforts were dedicated for development of thoroughly Newtonian particle-based FSI solvers, such as ISPH-SPH along with incorporation of precise and consistent multi-resolution schemes to ensure reliable adaptivity of the FSI solver. Regarding the aspect of generality, 3D extensions as well as careful modelling of structural material anisotropy were targeted in the last year of this project. In addition, to ensure reliability of the Newtonian SPH structure model for FSI corresponding to composite structures, a new SPH structure model incorporating staggered integration was developed in the last year of this project.

４．研究成果

The main achievements of this project include sets of novel and reliable hydroelastic solvers:

(1) Development of an entirely Lagrangian meshfree ISPH-SPH FSI solver in both 2D and 3D (Fig. 1a)

(2) Development of an entirely Lagrangian meshfree 3D *adaptive* ISPH-SPH FSI solver (Fig. 1b)

(3) Development of an entirely Lagrangian meshfree 3D MPS-HMPS FSI solver (Fig. 1c)

(4) Development of an entirely Lagrangian meshfree 2D ISPH-HSPH FSI solver targeting FSI corresponding to *laminated composite structures* (Fig. 1d)

(5) Development of an entirely Lagrangian meshfree 3D ISPH-HSPH FSI solver targeting FSI corresponding to *anisotropic* laminated composite structures (Fig. 1e)

Fig. 1 portrays representative snapshots by a set of novel computational methods developed throughout this project. These methods include (1) ISPH-SPH [1], as the first entirely Lagrangian meshfree hydroelastic FSI solver with projection-based fluid model developed in both 2D and 3D; (2) 3D ISPH-SPH (MR or Multi-Resolution) [2], characterised by refined adaptive schemes; (3) 3D MPS-Hamiltonian MPS [3], as the first 3D entirely Lagrangian meshfree projection-based hydroelastic FSI solver; (4) 2D ISPH-Hamiltonian SPH [4] as the first entirely Lagrangian meshfree hydroelastic FSI solver for composite structures; and (5) 3D ISPH-HSPH [5] for anisotropic composite structures. The snapshots correspond to water slamming by homogeneous as well as composite marine panels as well as dam break on an elastic plate.

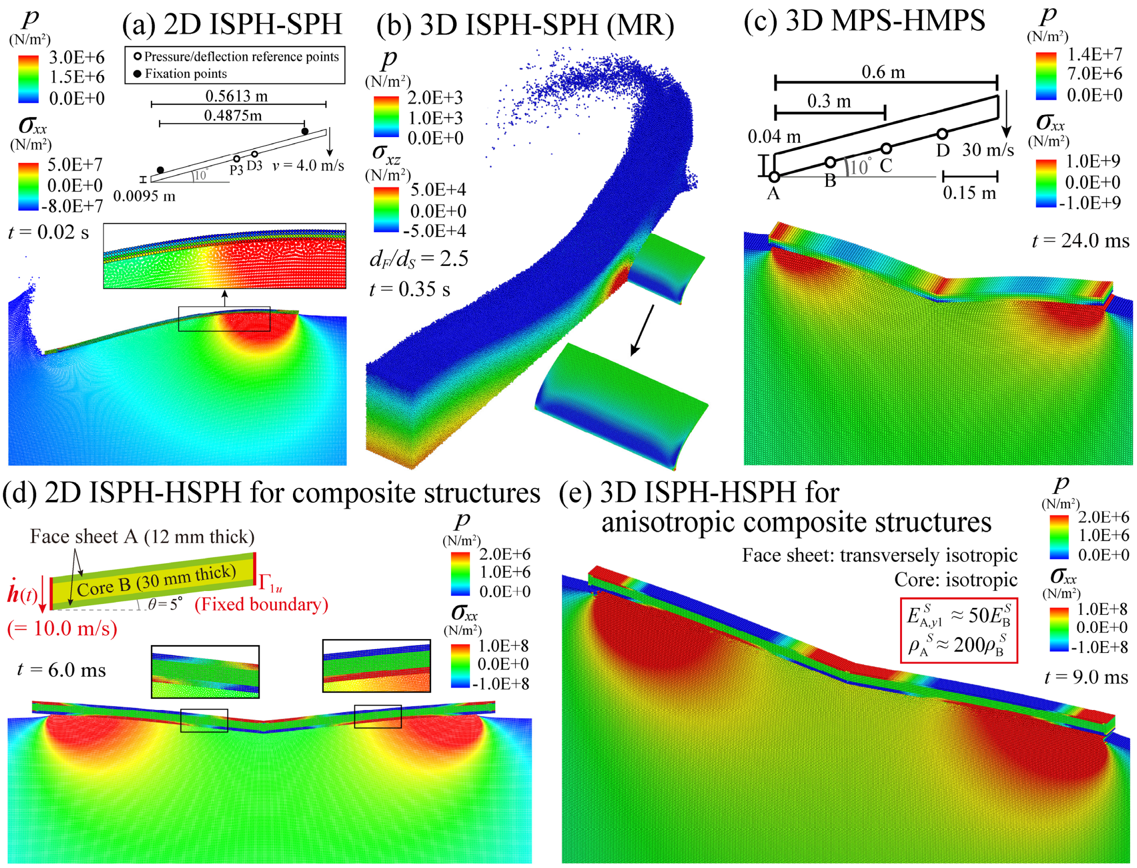

Fig. 1. Representative snapshots by hydroelastic FSI solvers developed throughout this project

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２．論文標題 A coupled incompressible SPH-Hamiltonian SPH solver for hydroelastic FSI corresponding to composite structures	５．発行年 2021年
３．雑誌名 Applied Mathematical Modelling	６．最初と最後の頁 242-271
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.apm.2021.01.011	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 -

１．著者名 Abbas Khayyer, Yuma Shimizu, Hitoshi Gotoh, Shunsuke Hattori	４．巻 226
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関