様　式　C－１９、F－１９－１、Z－１９　（共通）

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研究課題名（和文）Development of a next-generation IGA-BEM based on T-splines to investigate the performance of complex-shaped wave energy devices undergoing strong mutual interactions in large arrays

研究課題名（英文）Development of a next-generation IGA-BEM based on T-splines to investigate the performance of complex-shaped wave energy devices undergoing strong mutual interactions in large arrays

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研究成果の概要（和文）：本研究では、波力発電装置（WEC）配列の中に存在する流体相互干渉現象の解明、合成最適化に達成する可能性を検討することを目指す。 そのため、改良された境界要素法と相互干渉理論を組み合わせることにより、効果的な数値法を開発し、さまざまなレイアウトにしてWEC配列に適用した。レイアウトをよりランダムに配置することにより、最大出力の最適条件を実現するのは難しいが、最大出力をより高めることができることが分かった。

研究成果の学術的意義や社会的意義
海洋波エネルギーは、従来の燃料に代わる有望な資源である。本研究の結果に基づき、局所的な海の条件下での大規模な波力発電装置配列間の物理的メカニズムがよく理解される。無償で公開されているオープンソースコードは、海洋再生可能エネルギー及び海洋工学分野の研究コミュニティと業界にとって有益である。エネルギーの脱炭素化に貢献することが期待される。

研究成果の概要（英文）：This research aims to study the wave interaction phenomenon amongst arrays of wave energy converters (WECs) and the possibility of achieving synthetical optimization. For this purpose, by coupling a refined boundary element method and the interaction theory with newly proposed improvements, an effective numerical method was successfully developed and applied to WEC arrays in various layouts. It was found that by arranging the layout in a more randomized manner, the optimal conditions for maximized power output can be challenging to reach, but the maximum power output can be increased to a higher level.

研究分野：海洋再生可能エネルギー、浮体流体工学、計算力学

キーワード：波力発電　装置配列　境界要素法　相互干渉理論

１．研究開始当初の背景

Increasing energy shortage is a rising global issue that sets a bottleneck in the supply of energy resources to the society's economy. In Japan, after the Fukushima accident in 2011, renewable energies attract a growing concern as they can provide alternative resources to conventional energies, such as fuels, etc.

Wave energy, as one of the ocean renewable energies, is prospective to help mitigate the energy shortage in the near future. WECs (wave energy converters), used as the devices for absorbing powers, are typically designed to be deployed in large arrays at a coastal or offshore site, creating a "WEC farm". One significant advantage of the "WEC farm" is that all the devices can share some common infrastructures such as power substations, mooring systems and cables, which can substantially reduce the cost of construction and maintenance. In addition, the electricity generated by arrays of WECs can be far more stable than that generated by a single individual device.

However, in such arrays, each individual device strongly interacts with all the other bodies through diffracting and radiating waves. These mutual interactions amongst the devices can significantly affect the power absorption efficiency of the entire array. For this reason, it is necessary to develop a synthetic methodology for hydrodynamic analysis of WEC arrays considering the localized sea conditions.

２．研究の目的

The present study aims to solve the problem described in the research background. This involves two aspects: (1) develop a reliable and accurate numerical method for the fast evaluation of the WEC farm performance; (2) perform comprehensive studies to study the effect of device spacing, wave incident direction, water depth, wave frequency, number of devices, etc., on the wave loading and power performance of WEC arrays. In (2), the impact of different layout possibilities will be considered.

３．研究の方法

(1) ***Development of efficient and accurate numerical algorithms for the finite-depth free-surface Green function***

Considering that WECs are usually installed at coastal or offshore sites under a limited water depth, developing an efficient and accurate algorithm for the finite-depth free-surface Green function becomes necessary. This is extremely important because: ① the finite-depth free-surface Green function has a complex singular nature leading to difficulty in numerical evaluation; ② it is a prerequisite in the modeling of (2), since the interaction theory assumes generally a finite water depth.

(2) ***Development of a reliable numerical method for fast evaluation of array interactions***

The interaction theory of Kagemoto and Yue (1986) is applied to BEM (boundary element method). It should be noted that the majority of previous studies considered using the source-distribution method for the BEM. Kashiwagi (2000) considered using the hybrid source-dipole distribution, however, based on a higher-order BEM scheme. In the present study, the interaction theory is combined with a constant panel method that has been developed by the author for a decade, using the hybrid source-dipole distribution.

(3) ***Investigation of the array effect in wave interactions amongst WEC arrays***

The numerical method developed in (2) is capable of simulating arrays of an individual offshore structure in general type, including arbitrary-geometric WEC devices. By validating with theoretical methods, this method is then applied to WEC arrays to study the parametric effect on the array performance, including the wave loading and the power output. The power performance is measured by the well-recognized q-factor.

4．研究成果

(1) ***Elaboration of a BEM method and public release of the open-source code***

The numerical BEM code HAMS, developed by the author for a decade, is finally made open-source which is publicly available via GitHub: https://github.com/YingyiLiu/HAMS. The code is enhanced in the performance through the years on many aspects, such as removing irregular frequencies, exploitation of symmetrical properties, solution of the linear algebraic system, and OpenMP parallelization on multi-core machines, etc. HAMS is the 2nd released BEM code in offshore hydrodynamics in the world, released after Nemoh that is developed by LHEEA, École Centrale de Nantes, France. After its public release, HAMS has received increasing attention and reputation in ocean renewable energy and engineering communities around the world. A visual interface (https://github.com/BEMRosetta/BEMRosetta) for it has been developed by Spanish researchers. In the floating wind turbine toolset WEIS developed by National Renewable Energy Laboratory, US (https://github.com/WISDEM/RAFT), HAMS serves as the tool for the hydrodynamic analysis of wind turbine floating foundation. The comparison of accuracy and performance between HAMS and other commercial software (e.g., WAMIT) is also widely reported (Sheng et al., 2022). Figure 1 exhibits the overall flow chart of hydrodynamic analysis on floating wind turbines or wave energy converters using HAMS.

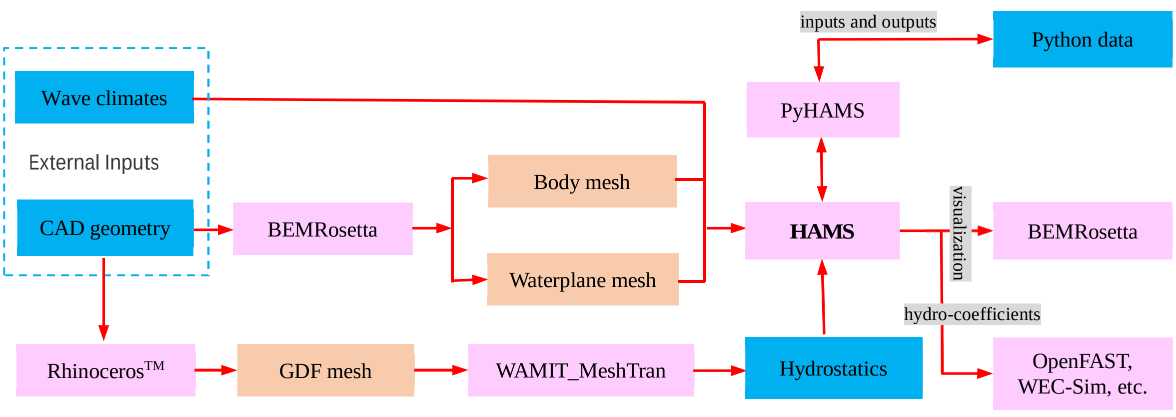

Figure 1. Hydrodynamic analysis flowchart with the open-source boundary element method framework.

(2) ***Efficient and accurate algorithms for the finite-depth free-surface Green function***

Two such numerical algorithms have been developed. One is using asymptotic or power series, such as the eigenfunction expansion, rapid convergent series, or a combination with other numerical acceleration algorithms in different subregions. This algorithm is wrapped into an open-source package FinGreen3D (https://github.com/YingyiLiu/FinGreen3D) that is publicly available. Figure 2 displays the hierarchical code structure of FinGreen3D. The 2nd algorithm is an enhanced version of Endo's approach dealing with the singularities in the denominator of the integrand function. It is free of the "weird frequencies" that exist in the original approach. This algorithm runs faster than FinGreen3D, but is slightly numerically unstable in some special cases. The algorithm is also in the process of public release as an open-source code.

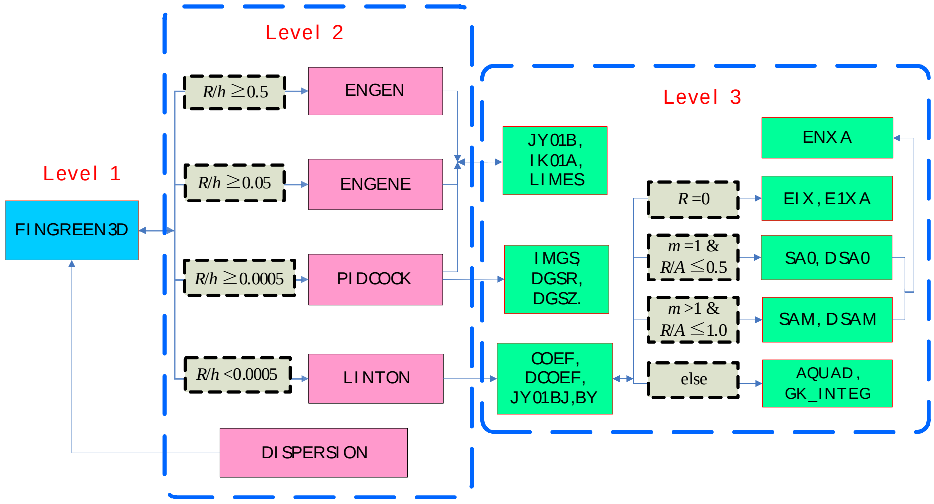

Figure 2. Multi-level subroutines in the hierarchical code structure of the open-source package FinGreen3D

(3) ***A reliable numerical method for fast evaluation of arrays using the interaction theory***

The interaction theory first presented by Kagemoto and Yue (1986) is further applied to the constant panel method. A complete set of mathematical formulations for hybrid source-dipole distribution (also named as "direct boundary integral equation") is derived rigorously and presented in Liu et al. (2021). Additional boundary integral equations are also given to remove the irregular frequencies. Two alternative approaches to solve the diffraction problem have been compared to assess both their accuracy and efficiency.

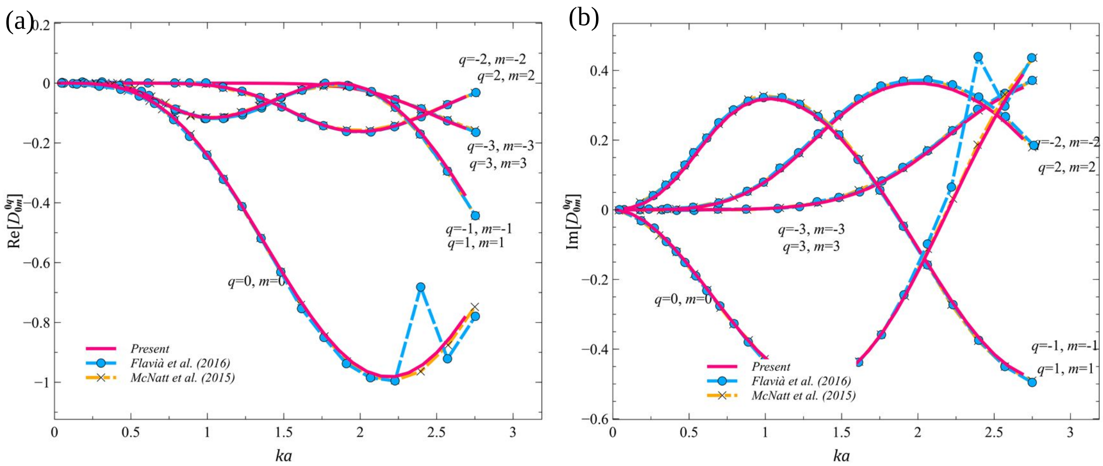

Figure 3. DTM progressive terms for a truncated vertical cylinder of 3m radius, 6m draft in a 10m water depth: (a) real part; (b) imaginary part.

It is found that the two approaches based on respectively Neumann-type and Dirichlettype boundary conditions for the incident wave potential present similar levels of numerical accuracy but very different computational burdens. DTM (diffraction transfer matrix) and RC (radiation characteristics) terms are computed and validated with the published results, as shown in Figure 3. Graf's addition theorem is applied to evaluate the wave loads on each individual body in the array and validated with the existing theoretical methods.

(4) ***Investigation of the array effect in wave-interactions amongst WEC arrays***

Wave interactions between arrays of heaving point absorbers in different layouts are studied using the numerical method developed in (3). The layouts involve a uniform line array, a double array in parallel, and a double staggered array. It is found that trapped waves exist at critical wavenumbers just below the cut-off value $kd=n\pi/2$ in the line array in head waves, which is similar to the bottom-mounted array of vertical circular cylinders in Maniar and Newman (1997). In beam waves, when the number of devices of each line is odd, only the device at the middle of a line experiences a zero (or close to zero) inline force *Fx* in whatever the above layouts, while the other devices do not. For a double parallel array, in head waves, there is no particular load enhancement compared to the uniform line array. Whereas in beam waves, significant load enhancements are found in the longitudinal and vertical forces. As to the power performance, results show that by arranging the array layout in a more randomized way, the optimal conditions for maximized power output can be hard to reach. However, the maximum power output does increase to a higher level. Figure 4 presents an example of the *q*-factor variation of the double staggered array.

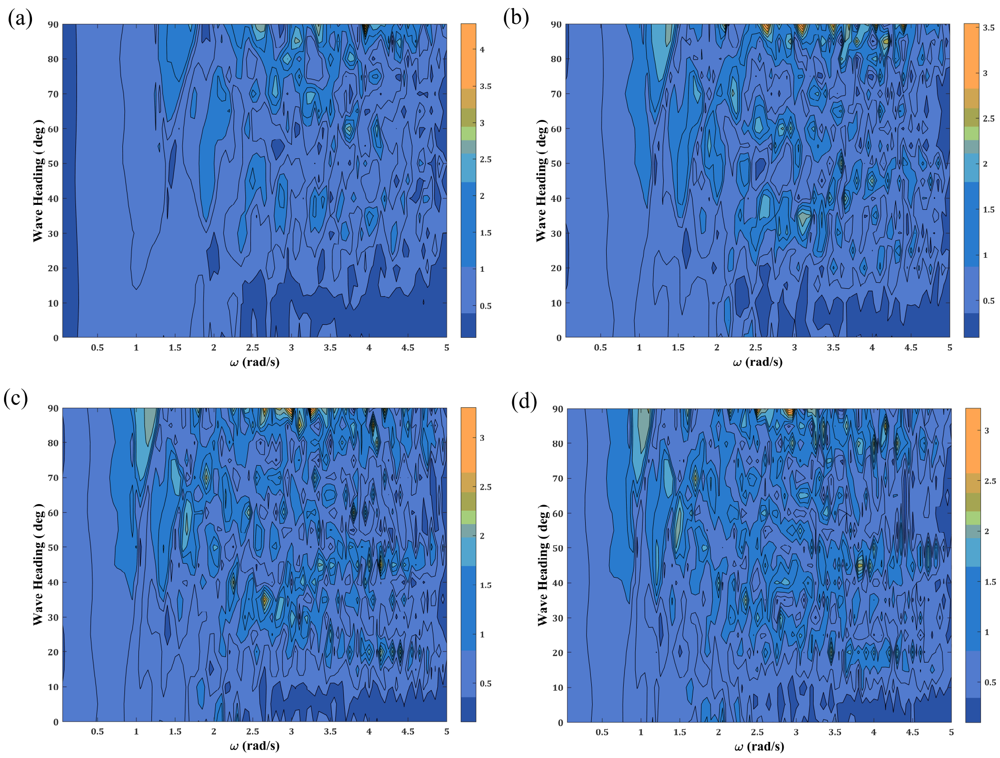

Figure 4. *q*-factor variation of a double staggered array of 14 CorPower-like point absorbers against the angular frequency ω, the wave angle β, and the device spacing s (water depth h = 100m): (a) $s = 2D$; (b) $s = 3D$; (c) $s = 4D$; (d) $s = 5D$, where D is the diameter of the cross-sectional area of the WEC device.

５．主な発表論文等

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３．雑誌名 Applied Ocean Research	６．最初と最後の頁 102769
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.apor.2021.102769	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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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 該当する

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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 該当する

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2．発表標題 Wave energy absorption amongst arrays of point absorbers with a non-regular geometry
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Yingyi Liu

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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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			
シンガポール	Technology Centre for Offshore & Marine			
英国	University of Plymouth			
中国	Dalian University of Technology			