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Review

Coupled Ship Simulation in Hydrodynamics and Structural Dynamics Induced by Wave Loads: A Systematic Literature Review

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Abstract: Coupled ship simulation in hydrodynamics and structural dynamics provides a comprehensive approach to understanding the dynamic behavior of ships under wave-induced loads. Improvements in computer power have made it much easier to create coupled simulation methods that combine structural and hydrodynamics analyses. A literature review based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 is used to look at future trends in this literature review. We have filtered 1440 articles in PRISMA 2020, including 93 articles for analysis. The bibliographic analysis reveals that China emerged as the first according to the first authors due to significant industrial and funding support. Based on 93 articles, computational methods can be grouped by the coupling method (one-way and two-way), the hydrodynamic analysis approach (potential flow and CFD), the structural analysis approach (FEM, TMM, and DMB), the hydrodynamics element type (2D and 3D), and the structural element type (1D and 3D). As an outcome of the review, it can be concluded that the most common approach is a two-way connection of the potential flow and FEM methods, which both use 3D elements for structural and hydrodynamic analyses. Future trends of this research should be explored based on the application of variables, reducing computational resources, and using artificial intelligence.

Keywords: systematic literature review; ship hydroelasticity; fluid structure interaction; coupled simulation; ship motion

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1. Introduction

According to statistical data, adverse weather conditions caused 755 maritime accidents between 2001 and 2010, accounting for approximately 20% of all ship-related incidents during that period [1]. Various meteorological factors, including wave height, ocean currents, wind speed, precipitation, visibility, and ice conditions, significantly influence the safe navigation of vessels. This study aims to explore the impact of wave-induced loads on ship structural integrity by reviewing the pertinent literature on coupled hydrodynamics and structural analysis.

Researchers have used both numerical and experimental methods in several approaches to investigate ship strength under wave loads. In experimental methods, numerous research studies have employed three primary techniques: flexible backbone systems, flexible joint models, and fully elastic bodies. Flexible backbone systems use a backbone structure to support a segmented ship model. Initial experiments utilized a single longitudinal backbone system [2,3]. Subsequent research applied a combination of lateral and longitudinal stiffness to the experiment [4–7]. A higher number of segments in the backbone system leads to better energy distribution and improved capture of whipping and springing phenomena [8]. However, the flexible joint model divides the ship into several segments, each connected by a flexible joint [9,10]. This method has an advantage over others because it allows for the adjustment of the joint's stiffness. Initially, a joint system at the midship connected the ship's two-segment body [11,12]. To achieve more accurate results, subsequent models divided the ship into more segments [13]. The final method used the fully elastic ship model to capture the ship's deformation under wave loads. Transversal, horizontal, and torsional stiffness similarity are used to scale the model [14,15].

Numerical approaches for evaluating ship hydroelasticity have evolved significantly over time. An initial method involves transferring pressure and acceleration loads from the hydrodynamic rigid-body analysis to a quasi-static structural analysis. This preliminary approach serves as a link between hydrodynamics and structural simulations but does not inherently achieve equilibrium. As a result, manual adjustments to acceleration are required to establish a model in equilibrium [16]. Subsequent developments have introduced more advanced methods. Roruf expanded the Eisen method to incorporate fatigue analysis, broadening its applicability [17]. Bishop and Price [18] advanced the integration of structural and hydrodynamic calculations using the two-dimensional potential flow theory. This was later extended by incorporating 2.5D hydrodynamics with the one-dimensional beam theory, offering an enhanced version of strip theory [19]. The evolution of hydrodynamic simulations culminated in the development of three-dimensional hydrodynamic methods based on radiation and potential flow theories [20]. These advancements enabled more sophisticated analyses of ship hydroelasticity, accounting for the complex interactions between structural and hydrodynamics components.

There have been several literature reviews on ship hydroelasticity. Hirdaris et al. [21] noted that developing a fully 3D model is a challenge in the field of hydroelasticity. Consequently, several papers in the last 15 years have conducted 3D modeling, as discussed in Section 4.2 of this study. Then, Temarel et al. showed how ship hydroelasticity had improved in 2016 [22], explaining the change from a 2D to a 3D hydrodynamics model. Temarel et al. discussed beams (1D elements) and 3D structural elements. Liu et al, in 2023, described hydroelasticity with a focus on the progress of the CFD and FEM methods [23]. However, this paper describes a new method that was not present in the previous paper. In addition, this paper presents a statistical analysis of all the ship hydroelasticity simulation methods conducted over the last 15 years.

A comprehensive literature review on coupled ship hydrodynamics and structural simulations is necessary to identify the gaps, existing knowledge, and research trends. This study focuses on methods of ship hydroelasticity, output parameters, statistical data, and potential research directions. Compared to previous studies, the current study describes a new method that is not present in previous studies. In addition, this study presents a statistical analysis of all the ship hydroelasticity simulation methods conducted over the last 15 years. Below, the research objectives of this study are summarized as follows:

(1) To describe the methods used in the coupled simulation of hydrodynamics and structures.
(2) To provide a bibliographic analysis through a systematic literature review.
(3) To outline trends and suggest future work in the field of hydroelasticity.

2. Materials and Methods

This study employs a systematic literature review process consisting of three primary stages: database searching, data selection, and filtering. Following the PRISMA guidelines, these steps align with the established methodologies used in previous literature reviews on ships [24–26]. To ensure transparency and reproducibility, this study is structured as a PRISMA report, encompassing the title, abstract, methods, results, and discussion sections.

2.1. Database Searching

Data for this study were gathered using the Scopus search engine, a well-established and comprehensive source for academic publications. Scopus was chosen for its extensive coverage of peer-reviewed articles from leading publishers such as Elsevier, Springer, Taylor & Francis, MDPI, and others.

To ensure a thorough search, the strategy extended beyond titles and keywords to include abstracts. The search terms used included "ship AND motion OR hydrodynamics AND strength OR FEM", "ship fluid-structure interaction", and "ship hydroelasticity". Additionally, alternative terms for hydroelasticity, such as fluid–structure interaction, were incorporated as search keywords. The search spanned a 15-year period (2009 to 2023) to capture recent and relevant research. Only English-language articles were considered for inclusion in this study to maintain consistency and accessibility.

2.2. Data Filtering and Screening

This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines to conduct a systematic literature review. PRISMA 2020 is an updated version of the 2009 guidelines [27,28] designed to enhance transparency and reproducibility in reporting systematic reviews. PRISMA provides a comprehensive framework, including a checklist and flow diagram, to guide the review process. The checklist encompasses key sections such as the title, abstract, methods, results, and discussion. Widely recognized for its clarity and adaptability, PRISMA is frequently applied across various fields, including maritime and ship-related research [29]. Numerous literature reviews in the ship and marine domain have adopted PRISMA for its structured and systematic approach [26,30–32]. Figure 1 presents a detailed application of the PRISMA methodology as implemented in this study.

In the initial stage of data filtering, 1428 articles were identified, of which 1291 were deemed relevant for further review. During this stage, an automated tool identified 89 articles as duplicates, and 2 articles were excluded for unspecified reasons. Additionally, 58 articles were excluded due to the following issues: being non-final versions, inaccessible, unavailable in online databases, or not written in English, despite the search criteria being limited to English-language publications.

In the record screening phase, the titles and abstracts of the remaining 1291 articles were reviewed. These elements provided preliminary information for excluding articles that did not meet the criteria for this systematic literature review, which focuses on the numerical analysis of ship hydroelasticity. The articles were filtered based on the following criteria:

(a) Relevance to Marine Structures: Articles unrelated to marine structures were excluded. Although the term "ship" was used in the search, some papers unrelated to marine structures (e.g., those discussing helicopters, plates, or ice) were retrieved and subsequently excluded.
(b) Discussion of Fluid–Structure Interaction: Articles that did not address fluid–structure interactions were excluded, including papers focusing solely on ship structures, ship hydrodynamics, or unrelated topics.

(c) Numerical Simulation Focus: Articles lacking numerical simulations of ship hydroelasticity, such as those based solely on experimental studies, were excluded.

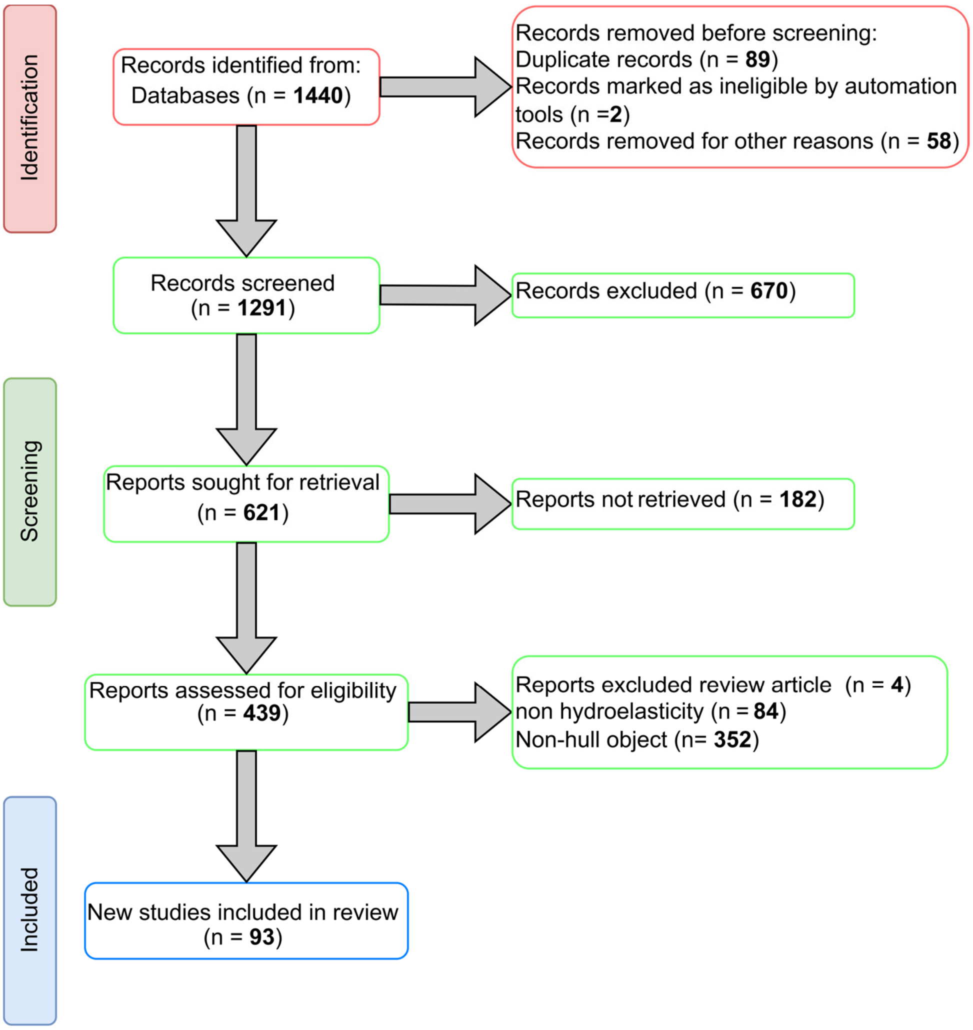

Figure 1. Systematic literature review process using PRISMA method.

Based on these criteria, 670 articles were excluded, leaving 621 articles for further analysis.

Due to the limitations of title and abstract screening in providing detailed filtering, the second stage involved an in-depth review of the full-text articles. Using the same parameters established in the first stage, an additional 182 articles were excluded, resulting in 439 articles eligible for subsequent evaluation.

In the third stage, further exclusions were made based on refined parameters specific to hydroelasticity research:

(a) Literature Reviews: Four articles were excluded as they were review papers rather than original research.
(b) Lack of Coupled Structural and Hydrodynamics Simulations: A total of 84 articles did not include the coupling of structural and hydrodynamics simulations. Simulations involving blasting and noise, while part of ship fluid–structure interactions, were excluded as they fell outside the scope of this study, which focuses on coupled structural and hydrodynamic simulations.
(c) Irrelevant Primary Objects of Study: In total, 352 articles were excluded because their primary objectives of study were not ship hull structures. Examples include studies on

propellers, partial hull bodies, wedge structures, and hull–ice interactions. Hull–ice interactions were excluded as their primary focus was on ice rather than the ship hull structure.

In conclusion, 93 articles met all the established criteria and were included in the systematic literature review. The next section provides a detailed discussion of these selected studies, highlighting their diverse sources, regional focus, and methodological approaches.

3. Bibliometric Analysis

3.1. Summary of Selected Articles

Table 1 provides a detailed breakdown of the articles categorized by journal. For clarity, abbreviations are used to simplify the journal names throughout the discussion. Journals publishing the most articles related to hydroelasticity in ship hulls under wave loads accounted for 63 articles, representing approximately 68% of the total.

The 16 journals listed can be grouped based on their aims and scope. The majority (12 journals) focus on marine engineering or related fields, including *OE*, *MS*, *AOR*, *JMST*, *JOMAE*, *JMSE*, *SOS*, *IJNAOE*, *IJOPE*, *IJRTE*, *JMSA*, and *JSPD*. This predominance aligns with the study's focus on ships. Additionally, five journals cover broader engineering topics: *AS*, *CMAME*, *EABE*, *AMR*, and *AMM*. Another journal, *JFS*, specializes in fluid–structure interactions. Among publishers, Elsevier contributed the most articles, followed by Springer, MDPI, ASME, Taylor & Francis, OnePetro, Trans Tech Publications, and BEIESP, in descending order.

Three main metrics analyzed in this study consist of the number of published articles, publication ratio, and citation analysis. Journals focusing on marine engineering and fluid–structure interactions dominated the number of publications. Among the 93 articles included in this review (as shown in Figure 1), journals such as *OE*, *JFS*, *MS*, *AOR*, *JMST*, and *JOMAE* featured the highest frequency of included articles. The remaining articles were distributed across 12 other journals. Journals with specific aims in marine engineering and fluid–structure interactions exhibited a higher publication ratio compared to general engineering journals. Notably, *JMST* demonstrated the highest ratio, at 1.15%. While journals with more included articles had higher citation counts, *JMSA* stood out with a disproportionately high number of citations despite only one included article.

In summary, the journals listed in Table 1, particularly those focused on marine engineering and fluid–structure interactions, are the most suitable venues for submitting articles on numerical coupled ship simulation of hydrodynamics and structural dynamics. However, the remaining journals in this list also present viable opportunities for publishing research on ship hydroelasticity simulations.

A total of thirty conference proceedings contributed to this literature review is shown in Table 2. Most of these articles were presented at two key conferences: OMAE (Offshore Mechanics and Arctic Engineering) and ISOPE (International Society of Offshore and Polar Engineers). These conferences are widely recognized in the field of naval architecture and remain influential today. OMAE began in 1982, while ISOPE was established in 1991. Other conferences, such as Coupled Problems, OTC (Offshore Technology Conference), and SMC (Symposium on Mechanics and Control), contributed the remaining articles.

Most conferences have a relatively small publication ratio, with the Coupled Problems conference being an exception. This conference stands out due to its focus on coupled simulations, including ship hydroelasticity.

In terms of the number of articles included, conferences generally have a lower publication ratio and fewer citations compared to journals. This trend suggests that journals have a greater impact on the field of ship hydroelasticity than conferences. However, conference proceedings remain a viable alternative for publishing research on ship hydroelasticity.

Table 1. Publication statistics in journals.

Journal (Abbreviation Code)	Publisher	References	Included Article	Total Whole Published Article	Publication Ratio (%)	Number of Citation
Ocean Engineering (OE)	Elsevier	[33–49]	17	12,688	0.13	446
Journal of Fluids and Structures (JFS)	Elsevier	[50–57]	8	2335	0.34	248
Marine Structures (MS)	Elsevier	[58–64]	7	1216	0.34	307
Applied Ocean Research (AOR)	Elsevier	[65–68]	4	2605	0.15	135
Journal of Marine Science and Technology (JMST)	Springer	[69–72]	4	349	1.15	39
Journal of Offshore Mechanics and Arctic Engineering (JOMAE)	ASME	[73–76]	4	2053	0.19	34
Journal of Marine Science and Engineering (JMSE)	MDPI	[77–79]	3	9493	0.03	34
Ships and Offshore Structures (SaoS)	Taylor & Francis	[80–82]	3	1248	0.24	47
Applied Sciences (AS)	MDPI	[83,84]	2	64,751	0.003	12
International Journal of Naval Architecture and Ocean Engineering (IJNAOE)	Elsevier	[85,86]	2	849	0.24	26
International Journal of Offshore and Polar Engineering (IJOPE)	Onepetro	[87,88]	2	691	0.29	26
Computer Methods in Applied Mechanics and Engineering (CMAME)	Elsevier	[89]	1	6410	0.02	19
Engineering Analysis with Boundary Elements (EABE)	Elsevier	[90]	1	3401	0.03	7
Advanced Materials Research (AMR)	Trans Tech Publ	[91]	1	1103	0.09	1
Applied Mechanics and Materials (AMM)	Trans Tech Publ	[92]	1	660	0.15	6
International Journal of Recent Technology and Engineering (IJRTE)	BEIESP	[93]	1	8496	0.01	0
Journal of Marine Science and Application (JMSA)	Springer	[94]	1	1036	0.10	28
Journal of Ship Production and Design (JSPD)	OnePetro	[95]	1	280	0.35	0
Grand total			63			1415

Table 2. Publication statistics in conferences.

Conference	Publisher	References	Included Article	Total Whole Published Article	Publication Ratio (%)	Number of Citation
Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering (OMAE)	ASME	[96–112]	17	16,336	0.10	59
Proceedings of the International Offshore and Polar Engineering Conference (ISOPE)	OnePetro	[113–122]	10	9833	0.10	21
Proceedings of the Annual Offshore Technology Conference (OTC)	OnePetro	[123]	1	4289	0.02	2
Proceedings of the 6th International Conference on Coupled Problems in Science and Engineering (COUPLED PROBLEMS)	ASNE	[124]	1	121	0.83	4
SNAME Maritime Convention, (SMC)	SNAME	[125]	1	566	0.18	0
Grand Total			30			86

3.2. Keywords Occurrence

The VOS Viewer 1.6.20. version tool was employed to analyze Scopus data from the 93 selected articles for keyword analysis. Figure 2 displays the density visualization of keywords, with the color map ranging from blue to green to yellow. Keywords closer to yellow indicate higher weight values based on their frequency of occurrence. The density around neighboring keywords further highlights cluster associations within the data.

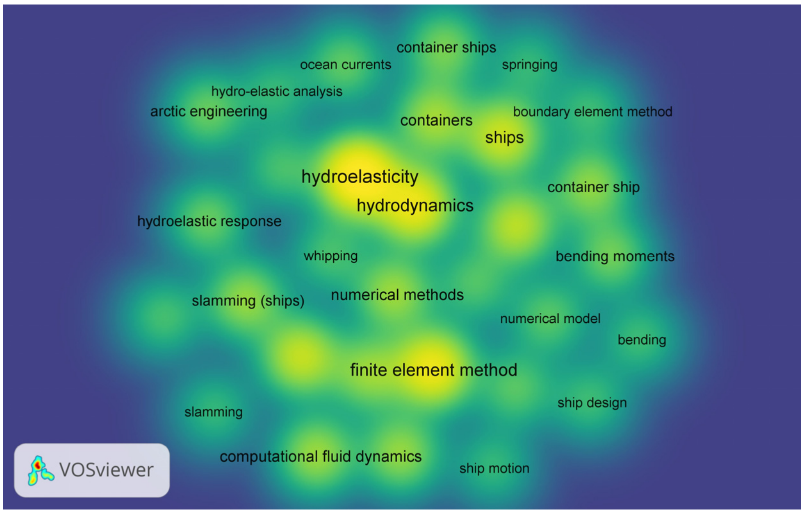

Figure 2. Keywords co-occurrence.

To identify the most critical aspects of ship hydroelasticity simulation, keyword frequency was examined. Figure 2 reveals a total of 31 keywords with a minimum frequency of 10 occurrences. The most frequently occurring keyword is "hydroelasticity" (56 occurrences), followed by "finite element" and "hydrodynamics," each with 41 occurrences.

These high-frequency keywords align strongly with the central focus of this study—ship hydroelasticity. Additionally, the dominance of the keyword "fluid–structure interaction" reflects its integral relationship to hydroelasticity.

Keywords related to computational techniques, such as the finite element method, computational fluid dynamics, numerical methods, and numerical models, are also featured prominently. This finding underscores the significance of computational approaches in coupled ship simulations. Specific phenomena, including slamming, springing, whipping, bending, and hydroelastic responses, are also reflected in the keywords. Environmental terms like "ocean current" and "Arctic engineering" suggest that external factors significantly influence coupled ship simulations.

Using this keyword to find future trends can be broken down into three main categories consisting of reducing numerical processes, incorporating environmental variables, and using AI. Simplifying numerical processes could enhance both the quality and scalability of simulations. Given the integration of hydrodynamics and structural simulations, the computational demands remain significant. Streamlining these processes could lead to more efficient simulations. Future studies could explore the influence of environmental factors such as water depth, wind, currents, and waves on ship hydroelasticity. These variables are critical as different regions of the ocean exhibit unique environmental characteristics that impact simulation outcomes. While AI is not explicitly mentioned among the analyzed keywords, its growing relevance across industries presents a significant opportunity. AI could enhance simulation efficiency, optimize parameter selection, and improve predictive capabilities in ship hydroelasticity research.

3.3. Country and Author Analysis

Figure 3 shows how the first 16 authors' articles are spread out by country. China has the most first authors, with 29 articles (about 31%) written by people from China. South Korea and Japan, both from East Asia, are close behind. This shows that the countries with the biggest shipbuilding industries make important contributions to the field of coupled ship hydrodynamics and structural dynamics [126].

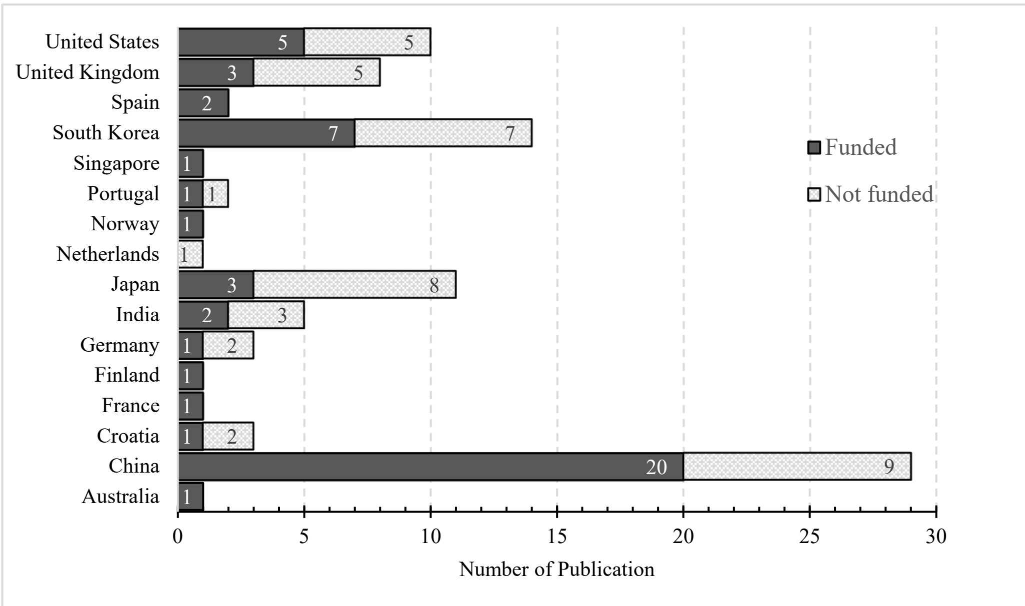

Figure 3. Statistics of first authors based on geographical criteria and corresponding funding information.

In addition, the level of funding within a country significantly influences the number of publications produced [127]. China funds about 70% of its research, making it a leader in first authors. The United States and South Korea have approximately 50% of their papers funded, which has similarly led to a high number of publications. Although Japan and the United Kingdom have less than 50% of their publications funded, they still demonstrate notable publication output.

3.4. Ship Object

Figure 4 reveals that the primary subjects of the coupled ship simulations of hydrodynamics and structural dynamics research include container ships, barges, developed hulls, and multi-hull vessels (such as catamarans and trimarans). Developed hulls are ships that are currently undergoing design and calculation, but their specific hull type remains unspecified. Numerous experiments related to ship motion and hydroelasticity have made container ships the most frequently studied subjects in fluid–structure interaction. Container ships have the most experimental verification, including the ULCS 1 [128], S175 [129–133], 6600 TEU [134,135], Kriso container [136], 100.000 TEU [87], and CSSRC 20,000 TEU JIP [118]. Moreover, numerous experiments were also conducted on several ship types including barges [13,102,103,137], bulk carriers [47], catamarans [138], speed boats [139], frigate series 64 hulls [140], and others [36,47,141–143]. Based on this trend, the analysis shows that in the last 15 years, ship hydroelasticity was still focusing on container ships and barges.

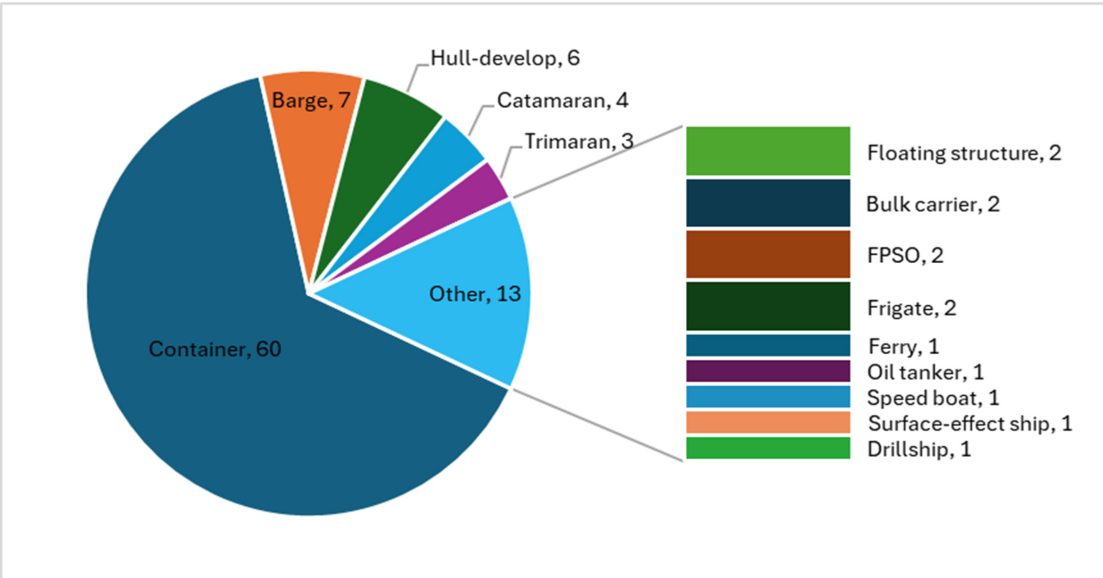

Figure 4. Ship type statistics.

4. Methods for Coupled Simulation of Hydrodynamics and Structural Dynamics

The simulation of coupled hydrodynamics and structural dynamics in ships has utilized a range of methodologies. The classification of ship hydroelasticity methods can be categorized into three primary groups, consisting of the coupling method, the element in simulation, and the computation method.

4.1. Coupling Methods

Coupling methods consist of one-way and two-way coupling. Figure 5 demonstrates the operation of a single coupled simulation of ship hydrodynamics and structural analysis [59]. One-way coupling uses the results from computational fluid computation in a single step for structural computation). This includes pressure and inertia effects. The subsequent fluid simulation uses the rigid body motion (RBM) and hydrodynamics forces from the initial fluid computation step. On the other hand, the FEA simulation utilizes hydroelasticity responses, along with velocity and acceleration at the nodes, for the subsequent time step.

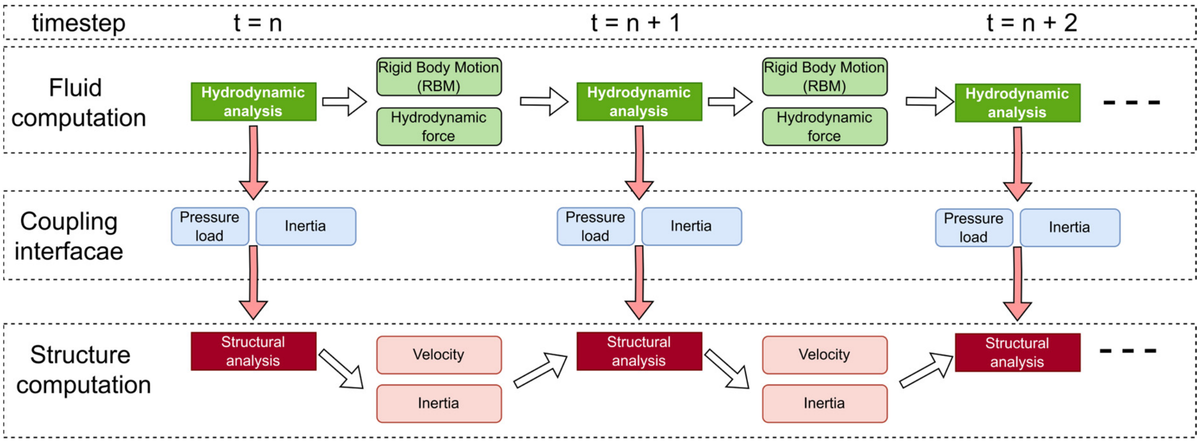

Figure 5. One-way coupling schematic diagram.

Figure 6 illustrates the two-way coupling scheme. We can further categorize two-way coupling into weak and strong methods. The weak two-way coupling applies the ship hull deformation to the fluid computation mesh in each time step [144]. The next stages (t = t_n + Δt) of the fluid simulation incorporate the elastic deformation results from the initial stages (t = t_n) of the structural computation. Several techniques are used for accommodating the deforming of the ship hull from the structural mesh for the next time step in fluid computation consisting of morphing mesh and remeshing. For more accurate results, strong two-way coupling integrates CFD and FEA analyses through sub-step iterations [145,146]. This approach allows for convergence within each timestep by iteratively updating both the CFD and FEA results. Morphing methods, which are faster and more robust than remeshing processes, accommodate structural deformation in hydrodynamics simulations [147,148]. While in remeshing techniques, the entire computational domain is remeshed to account for the hull's deformation, ensuring accuracy but at a higher computational cost.

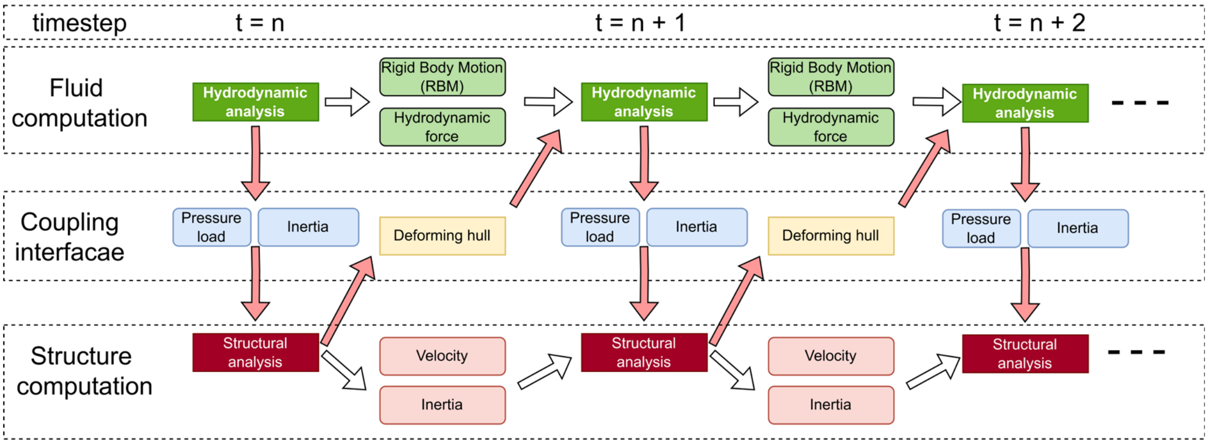

Figure 6. Two-way coupling schematic diagram.

Given the current situation, a one-way coupling approach treats the ship as a rigid body during hydrodynamics simulation. On the other hand, a two-way coupling simulation considers the structural analysis-induced deformation of the ship hull in hydrodynamics analysis.

In this study, the literature review focuses on ship coupling methods, specifically one-way and two-way coupling. Expanding the analysis to include weak and strong two-way coupling methods proved challenging due to limitations in the explanations provided in the articles. Consequently, the review indicates that over 75% of the articles employ two-way coupling, as illustrated in Figure 7. In comparison, approximately 39% of the articles use one-way coupling, while 14% employ both methods (one-way and two-way). The article explores both one-way and two-way coupling methods, indicating that it compares the results between these approaches. Figure 8 displays the distribution of articles by publication year, revealing a consistent dominance of two-way coupling in publications, except for 2016. We attribute this trend to the increased accuracy of flexible body simulations in hydroelasticity analyses.

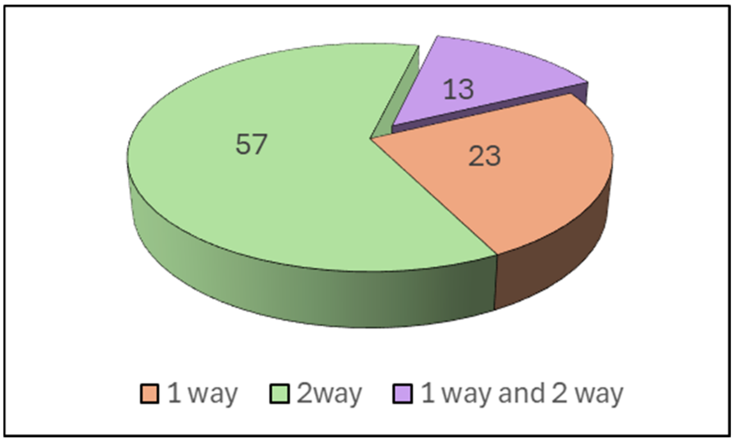

Figure 7. Statistics of one-way and two-way coupling.

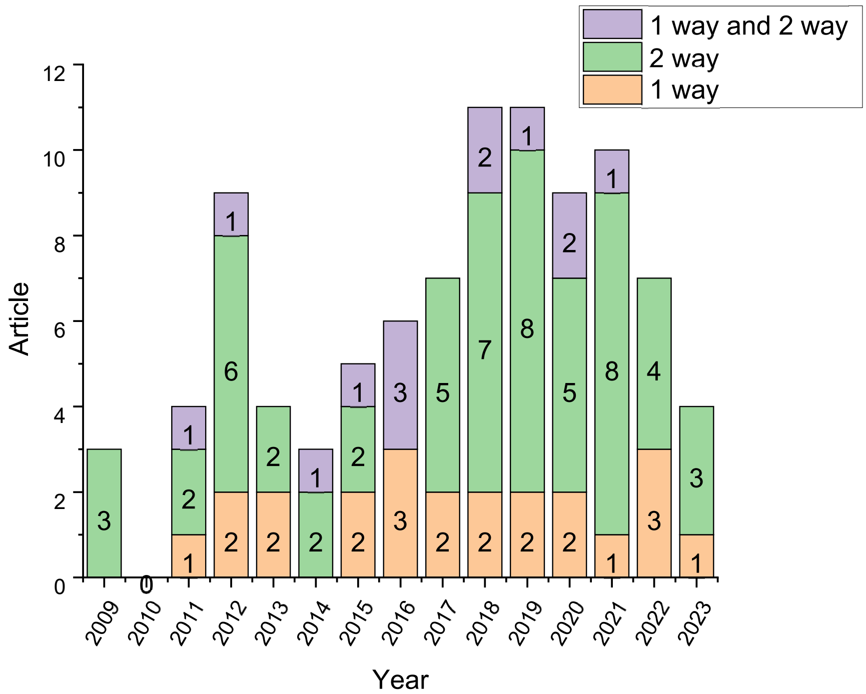

Figure 8. Statistics of one-way and two-way coupling publications by year.

One-way methods are preferable for initial and rapid calculation because they need lower computational resources, faster calculation, and a simple calculation process. This situation is caused by the need to export a variable from ship structural to ship hydrodynamics, which is described in Figure 5. On the other hand, two-way methods are more preferred for detailed simulation. Table 3 shows the details of the comparison between the one-way and two-way coupling approaches.

Table 3. Comparison of 1-way and 2-way coupling approaches.

Variable	One-Way	Two-Way
Preference application	ship body with high stiffness	ship body with low stiffness
Computational process	faster	slower
Computational resource	moderate	high
Calculation process	moderate	complex
Accuracy of results	moderate	higher

Table 4 outlines the distribution of the different ship types used in coupled simulation systems. The selection of a coupling method (one-way or two-way) depends significantly on the ship's structural stiffness and displacement characteristics under wave loads. Ships with lower structural stiffness are more accurately modeled using two-way coupling methods. This is due to their higher displacement under wave load attacks. The characteristics of low-stiffness ships include longer structural forms and open-deck designs, consisting of container ships, barges, bulk carriers, and oil tankers.

Table 4. Distribution of coupling methods based on ship types.

Ship Type	One-Way	Two-Way	One-Way and Two-Way
Container	9	42	9
Barge	3	3	1
Hull-develop	1	3	2
Catamaran	-	4	-
Trimaran	3	-	-
Floating structure	-	1	1
Bulk carrier	-	2	-
FPSO	2	-	-
Frigate	2	-	-
Ferry	1	-	-
Oil tanker	-	1	-
Speed boat	1	-	-
Surface-effect ship	-	1	-
Drillship	1	-	-

Stiffer ships tend to be more suitable for one-way coupling simulations, where the hydrodynamics loads are applied directly to the structural analysis without iterative feedback. These include frigates, Floating Production Storage and Offloading (FPSO) units, speed boats, and drill ships.

Flexible body modeling significantly influences pressure loads on the ship hull in hydrodynamics calculations [80,104]. At lower frequencies, rigid structures often overestimate the vertical bending moment [80]. At higher frequencies, however, the effects of springing and whipping become significant, impacting ship loads [115]. Springing effects are difficult to predict at higher frequencies, leading to the incomplete capture of VBM and stress values [80,84,122]. Additionally, for catamarans, one-way coupling results in stress and displacement predictions that are not as accurate as those obtained from two-way coupling [61]. Two-way coupling provides greater accuracy and efficiency in ship design compared to one-way coupling [57].

In two-way coupled simulations, structural mechanics are categorized as either elastic or elastoplastic. In hydroelasticity, structural deformation is temporary and fully reversible. However, in hydroelastoplasticity, the structure is modeled using elastoplastic materials, allowing for the prediction of structural collapse. Ship hydroelastoplasticity has been initially studied through experiments involving two rigid-body ships connected by a nonlinear spring, which exhibits plastic deformation effects [149]. In numerical simulations, applying a nonlinear elastoplastic material to the ship structure enables the capture of plasticity effects under high deformation conditions. Hydroelasticity is commonly used to assess ship structural collapse. In the case of container ships, buckling has been identified as a dominant factor in structural failure [75]. Comparatively, hydroelastoplasticity results in higher deformation than hydroelasticity [117]. Simulations also indicate that higher wave heights are required to cause significant ship damage under hydroelastoplastic conditions [103].

4.2. Element in Simulation

In the coupled ship simulation of hydrodynamics and structural dynamics, elements are categorized into two main categories: hydrodynamics elements and structural elements. We further divide hydrodynamics elements into two types: 2D and 3D elements. We classify structural elements into two primary types: 1D and 3D elements.

4.2.1. Hydrodynamics Element

In 2D element hydrodynamics, the intersection of 2D panels is utilized to determine the intersection points of the 3D wetted surface derived from faceted 3D finite element models (FEM), as illustrated in Figure 9 [95]. This method enables the transfer of hydrodynamics forces and moments—generated by hydrostatic pressure, incident potential, and diffraction potential—into the structural analysis. The process is carried out by interpolating between the strip sections and along the ship's lengthwise direction, ensuring accurate coupling between hydrodynamics and structural simulations.

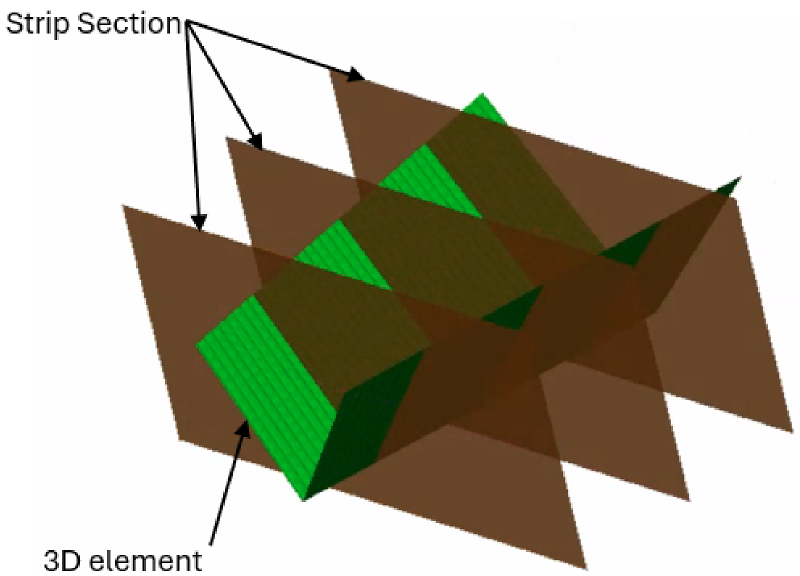

Figure 9. Two-dimensional element in hydrodynamics simulation.

The ship hull model in 3D hydrodynamics is identical to the one in structural analysis, allowing for the direct transfer of load pressures between the two simulations. However, differences in grid size and number between structural and hydrodynamics models need various methods to transfer loads from 3D hydrodynamics to 3D structural analysis. These methods include the following:

- Linear interpolation [53,84]:
  This method involves estimating and interpolating known node values. Small deformation hulls, which influence the small computational resources needed, favor the application of this method.
- Hybrid wetted surface [58,78]:
  This method employs a combination of multiple interpolation nodes to determine unknown node values. This method can be applied in a complex structure interface. However, it requires careful implementation.
- Inverse distance weighting [44,59,108]:
  This method interpolates an unknown value using a proportional distance calculation. This method yields smooth interpolating results, but it requires significant computational resources.
- Matching the closest node [60]:
  Unknown node results will be calculated based on the closest node in the original mesh. Unnecessary results will be shown in a non-uniform deformation. However, it is important to have a quick, simple, and efficient plan.
- Streamline upstream Petrov–Galerkin [61]:
  Suitable for structures with high deformations and moving boundaries.
- Non-trivial interpolation [86]:
  This approach is suitable for complex data transfer in FSI, an area where the standard method fails to capture. This approach has led to an increase in accuracy, albeit at the cost of requiring significant computational resources.
- Gluing method [34]:
  This method glues the mesh between the structural and fluid domains. Unnecessary results will be shown in the interpolation due to the complex implementation.
- Gauss integration [36,42]:
  The transferring interface is achieved by integrating a specific node. It is applicable to irregular geometry and non-matching meshes, but it requires high mesh quality and high computational resources.

Based on the transfer load method, it can be grouped into two main categories. Linear interpolation and matching the closest node are effective for low deformation which needs lower computational resources. However, for complex and high deformation hull inverse distance weighting, streamlined upstream Petrov–Galerkin and non-trivial interpolation are more suitable for complex and large deformation.

4.2.2. Structural Element

In structural simulations, two primary approaches for representing ship stiffness are beam elements and 3D elements. Studies have shown that both 1D (beam) and 3D elements can yield similar results in VBM [60]. However, each type of element has its own advantages and disadvantages. The choice between using 1D (beam) elements and 3D elements depends on multiple factors and considerations.

In 1D elemental modeling, there are two main types: uniform beams and non-uniform beams. A uniform beam has a constant size and shape along the length of the ship. On the other hand, a non-uniform beam splits into multiple sections, each possessing unique dimensions and stiffness characteristics. Typically, 1D beam element modeling represents the ship hull using either dummy [41,58,66] or membrane [41,61,79,89] elements. This element is used to transfer loads from the ship hull to the beam elements. Dummy and membrane elements have minimal impact on structural stiffness, making the strength calculations for the beam elements relatively independent. Compared to 3D elements, 1D elements offer faster computation due to their simpler and fewer elements in the structural analysis. One of the key results produced by 1D elements is the vertical bending moment.

In 3D element modeling, there are two main types of structural representations: simplified and actual profile constructions. To reduce computational processing requirements, simplified structural analysis is used. However, simplified structures typically use more elements compared to a single beam element (1D element). Simplified 3D elements convert the ship's structure into a profile structure like a backbone experimental model while maintaining equivalent section properties of the ship. Most simplified structural models use single 3D elements [72,102,104,108], with additional bulkheads incorporated in some developments [48,59]. The bulkhead influences the effect of natural frequency in the torsional bending node.

A fully 3D model of a ship provides an accurate representation of the vessel's structure, whether at full scale or a scaled version. This approach offers significant advantages over simplified 3D models, especially in its ability to calculate stress accurately in specific areas of the ship. However, fully 3D models come with the drawback of requiring more computational resources due to their increased complexity and level of detail compared to simplified 3D models or 1D elements. On the other hand, 1D elements are more applicable for initial and rapid calculations. These simplified models allow for quicker assessments, though they may sacrifice accuracy in detailed stress analysis compared to fully 3D models.

4.2.3. Statistics of Hydrodynamics and Structural Elements

Table 5 illustrates the relationship between hydrodynamics and structural elements used in numerous studies. In hydrodynamics, most studies employ 3D hydrodynamics elements. Similarly, many structural element studies use 3D models. The most common combination in the literature consists of 3D hydrodynamics elements paired with fully 3D structural models. Another frequently used combination is 3D hydrodynamics elements with 1D non-uniform structural elements.

Table 5. Element statistics in hydroelasticity.

Structural Element \ Hydrodynamics Element	2D	3D
1D uniform	2	13
1D non-uniform	3	15
1D not stated	4	9
3D simplified	0	6
Fully 3D model	5	37

In two studies, 3D and 1D non-uniform simulations [51] and 3D and 1D non-stated simulations [84] were used to compare two different types of structural elements in simulations. The comparison between the 3D element and the 1D element reveals that the stress derived from the VBM calculation in 3D modeling is significantly higher than that of the 1D element [51,84]. However, the RAO pattern between the 1D and 3D elements is similar. This allows for the capture of comparable phenomena between 1D and 3D.

In summary, 1D structural simulation is preferable to using it as an initial analyzing study because it has a faster simulation process and limited data results. In 1D structural element results, the VBM can be used as an estimated ship strength modulus. However, 3D structural analysis not only results in VBM but also stress, strain, and local simulation.

The result can be an application for advanced structural calculation, including fatigue and sandwich structure.

4.3. Method of Computation

4.3.1. Method of Computation in Hydrodynamics

Potential flow theory and computational fluid dynamics (CFD) are the two main approaches used in ship hydrodynamics. The potential flow theory employs the Laplace equation to solve hydrodynamics problems, while CFD uses the nonlinear Navier–Stokes equations along with other supplementary equations. The potential flow theory assumes that the fluid is inviscid, incompressible, and irrotational, which significantly reduces computational resource requirements. However, the potential flow theory encounters challenges in accurately modeling viscosity effects such as ship roll and yaw [150]. To address this limitation, comparing CFD results with decay tests is necessary to capture viscous damping [151]. Consequently, the potential flow theory is more prevalent in the literature, with 52 articles, compared to CFD methods, which are covered in 33 articles, as shown in Table 6. Notably, eight articles in this table do not provide a detailed description of the hydrodynamics methods used. This shows that the potential theory is more popular compared to CFD because it requires fewer computational resources due to the simplified characteristics of fluid flow. However, achieving sufficient numerical accuracy is important. Therefore, the potential theory can be validated by comparing against the experimental results.

Table 6. Statistics of hydrodynamics and structural methods.

Hydrodynamics Method / Structural Method	TMM	DMB	FEM
Potential flow theory	3	1	48
CFD	0	2	31
Not Stated	0	0	8

In ship hydrodynamics, the CFD model describes a transient, incompressible, and viscous fluid. In an incompressible velocity field, the following Equation (1) applies. Therefore, we use the Reynolds-averaged Navier–Stokes (RANS) Equation (2). Potential flow methods assume the governing equation of the flow field to be inviscid, incompressible, and irrotational. The irrotational velocity potential is represented by Equation (3). The equation for potential flow employs the Euler momentum equation. F is an external body force, R is the Reynolds stress tensor, P is pressure, t is time, u is velocity, and ρ is fluid density.

$$\nabla.U = 0 \tag{1}$$

$$\frac{\partial \rho u}{dt} + \nabla.(\rho U.U) = -\nabla.\mathrm{p} + \nabla.(\mu\nabla \mathrm{u}) + \rho g + F + \nabla.R \tag{2}$$

$$\frac{\partial u}{dt} + (\nabla.U)u = -\frac{1}{\rho}\nabla \mathrm{p} + F \tag{3}$$

4.3.2. Method of Computation in Structural

The structural domain employs three main methods: the finite element method (FEM), the Transfer Matrix Method (TMM), and the Discrete Module Beam (DMB). FEM dominates hydroelasticity research, accounting for 88 articles, or approximately 94% of the literature. FEM offers significant advantages due to its versatility in modeling various elements, including beam, shell, and solid, among others. TMM and DMB, on the other hand, are not as flexible because they are mostly used for beam element modeling in the coupled simulation of ship hydrodynamics and structural dynamics. This means that they cannot be used on ships with more than one hull because they cannot create the geometry of the demi-hull. Self-developed codes are commonly used for DMB [45,55,77] and TMM [47,70,90]. Meanwhile, FEM analyses often employ both self-developed codes and commercial software, including Abaqus, Ansys, LS-DYNA, Dyana, Maestro, MBDyn, Calculix, and Mars. This availability of diverse commercial software contributes to the widespread adoption of FEM in hydroelasticity.

The comparison between DMB [55] and FEM [57] in hydroelasticity reveals similar values of vertical displacement in both rigid and elastic bodies. This comparison captured vertical displacement in the stern, midship, and bow of the ship. In another study, Yujia [77] reports that DMB yields similar results to FEA analysis [56,66] at high frequencies, but overestimates results at lower frequencies. However, the earlier study did not compare TMM and FEM; instead, it compared them to experimental methods.

In summary, FEM is better for structural calculations in coupled simulations because it has more support from code and software perspective. In addition, it can handle more complex models, and it is more useful and accurate.

4.4. Numerical Validation

To validate the coupled ship simulation in terms of hydrodynamics and structural dynamics, it is best to do some experiments with the backbone, joint stiffness, and fully elastic 3D. In this method, the interaction between the ship's hydrodynamics and structure manifests itself during the experiment. Therefore, during the experiment in the towing tank, the ship hull would be deformed. The most popular method for the verification of numerical analysis is the backbone model which was used in 31 articles. In the backbone model generally used for verifying VBM, ship motion is in either frequency- or time-domain. However, several studies have supplemented the backbone method to measure hull pressure [108], force [52,72], and damping coefficient [87,105]. On the other hand, Datta et al. used flexible joint experiments to validate ship simulation, which involved measuring the RAO of the VBM [80]. Compared to the backbone and flexible joint approaches, the elastic ship hull experiment offers a more variable way to validate ship simulation. We utilized the elastic hull experiment to validate 13 articles related to ship hydroelasticity simulation. Apart from measuring VBM, ship motion, force, and pressure, we found that an elastic body can capture hull deformation [62,89,120].

Several studies have validated only one aspect of ship structural or hydrodynamic analysis rather than in a coupled manner. Therefore, in these studies, there is no relationship or influence between ship hydrodynamics and ship structural behavior. Rigid-body motion is used to validate the hydrodynamics aspect of the simulation, modeling the ship as a rigid body in a towing tank. Researchers measured the ship's motion in frequency and time domains [53,95,100]. Another study measures the pressure of water on the ship hull [71,74,94]. Researchers compared the added resistance to the experimental data to confirm the fluid domain [53]. On the other hand, the hammer test was used for structural verification to validate the structural model [54]. We use this test to determine the structure's natural frequency. Natural frequency validation is only available for both 3D structural finite elements and experimental bodies. Therefore, the coupled system cannot be validated using this approach.

Considering a simple geometry is an alternative method to validate the simulation, which can approximately represent the complex ship hull geometry. The simplified validation method uses several simple geometries, including a cylinder [42] and box [45] to verify the simulation setting. However, Bakti [55] used a barge, which has a modest hull model, instead of the Wigley hull ship for experimental validation. The simplified models undergo comparison with elastic body experiments. The force is used to verify the simplified cylinder shape. However, in the box geometry, sloshing data are observed. This experiment replaces the barge geometry with a backbone model that can measure RAO in pitch, heave, and roll, as well as VBM in the time domain. Simplified geometry has several uncertainties to represent the complex hull geometry including mesh and scale uncertainties.

In summary, ship hydroelasticity is a coupled simulation of hydrodynamics and structural dynamics. Therefore, we can apply several methods to evaluate the simulation. There is a verification order that goes from moderate to high accuracy. The verification order includes simplified geometry, separate structural or hydrodynamics elements, a hydroelasticity backbone, a hydroelasticity stiffness joint, and a fully 3D elastic hydroelasticity system. High accuracy requires more complex and high-cost experiments.

5. Trends and Future Work

The application of coupled ship simulation in hydrodynamics and structural dynamics has been extensively developed over the past 15 years, as shown in Table 7. The most frequently studied topics include the application of 3D ship structures and structural mechanics. According to previous literature reviews, 3D modeling has been applied in approximately 46% of the studies. In structural mechanics applications, research over the past 15 years has primarily focused on fatigue, followed by sandwich structures, damage assessment, and fracture analysis. In hydroelasticity studies, fatigue analysis is used to estimate the lifespan of ship structures based on hydrodynamic effects. Fatigue simulations can be conducted at both local and global structural levels. Another notable application is the use of Proportional–Integral–Derivative (PID) control, which has potential implications in coupled ship simulation in hydrodynamics and structural dynamics.

Table 8 outlines future investigations into the coupled ship simulation in hydrodynamics and structural dynamics. Potential research areas are categorized into structural dynamics applications, computational resources, and other applications. In structural dynamics applications, future research may focus on optimizing ship structures, using high-strength materials, and studying the effects of corrosion and dented plates. Corrosion affects ship structures by reducing plate thickness and degrading material properties. Additionally, corrosion-related studies could extend to mooring systems and surface roughness. In computational research, efforts may be directed toward reducing computational costs and integrating artificial intelligence to enhance ship coupled analysis. Furthermore, biomedical engineering has made significant advancements in coupled fluid–structure interaction simulations. Potential applications in this field include real-time simulations and prestressing techniques.

Table 7. Trend of ship hydroelasticity.

	Definition	Result	References
Fatigue	Fatigue analysis extends hydroelasticity research, where structural results are used in fatigue simulations.	Key factors influencing fatigue in ship structures include springing, whipping, wave frequency, and spectral band.	[70,83,84,86,92,99,107,110,114,122,123]
Damage	Comparison of intact and damaged ship hull in ship hydroelasticity.	Comparisons between intact and damaged hulls reveal that damage increases the vertical bending moment (VBM) due to additional weight. In sagging conditions, the VBM may exceed permissible limits, while in hogging conditions, it remains below the limit.	[45]

Table 7. *Cont.*

	Definition	Result	References
Fracture	Comparing structural collapse in coupled CFD-FEM versus pure bending scenarios shows significant differences.	In four-point bending tests, the maximum bending moment is 9872 Nm, whereas in fluid–structure interaction (FSI) models, the ultimate strength is reduced by approximately half to 4080 Nm.	[103]
PID	Applying the effect of ship hydroelasticity in PID control	The effects of uncertainty in ship hydroelasticity, particularly vibrations, can be mitigated using PID autopilot systems. This approach helps in stabilizing the ship and improving control.	[65]
Sandwich Structure	Calculating ship hydroelasticity on the ship with a composite structure.	For ships with composite structures, results from non-FSI methods tend to overestimate performance compared to FSI methods. Comparing FSI models with towing tank experiments reveals an average error of about 25%.	[36,49]

Table 8. Potential future work.

Variable	Research Gap	Reference	Potential Work
Artificial intelligence	A combination of CFD, FSI, cGAN, and CNN was used in cardiovascular.	[152]	Ship hydroelasticity has an opportunity to apply AI.
Environmental effect	Environmental and Ship Motion Forecasting (ESMF) was developed.	[153]	Developing environmental effects to ship hydroelasticity has a big opportunity.
Reducing computational resource	Hybrid CPU-GPU was reduced in CFD-DEM simulation.	[154]	Ship hydroelasticity needs huge resources; therefore, it needs more numerical acceleration.
Roughness	Surface roughness can significantly affect ship resistance and hull pressure.	[155]	Changes in hull resistance and the influence on ship structure can significantly affect ship motion. These effects are likely to impact ship hydroelasticity, as the interaction between resistance, structure, and motion plays a crucial role in the overall hydroelasticity behavior of the vessel.
Mooring and towing	Hydroelasticity principles have been applied to the mooring of floating structures.	[156]	Applying hydroelasticity principles to mooring systems is essential for accurately assessing ship hull interactions and the velocity of the ship. Effective mooring design must consider hydroelasticity effects to ensure stability and performance.
Structural optimization	Structural optimization techniques are employed to minimize the weight of ship structures.	[157]	Considering hydroelasticity in both structural design and motion analysis is crucial for achieving optimal results. Integrating hydroelasticity considerations helps balance structural integrity and performance, leading to improved ship design.

Table 8. *Cont.*

Variable	Research Gap	Reference	Potential Work
Effect of corrosion on plate thickness	Corrosion can lead to a reduction in ship strength over time.	[158]	A reduction in ship strength can affect ship stiffness, thereby altering ship behavior in hydroelasticity simulations. This impact must be accounted for to ensure accurate simulations and effective design solutions.
Dented plate	Dented plates reduce the structural strength of a ship.	[159]	They can arise from the fabrication process or occur due to unidentified incidents. This weakening effect is a critical factor in ship hull integrity and should be evaluated in ship hydroelastoplastic studies.
Advance material	The application of advanced materials is still being developed to enhance economic efficiency, operability, and safety.	[160]	Changes in material properties directly affect ship strength, making it essential to assess these effects in ship hydroelasticity studies.
Effect of weight distribution	The weight of a ship's structure has a direct influence on ship motion.	[161]	Weight distribution influences load distribution on the ship, affecting both structural strength and motion. Integrating these variables into hydroelasticity calculations is essential for a comprehensive analysis of ship performance.
Trimaran ship	In a catamaran ship, it shows a lateral effect.	[52]	A trimaran is a multiple-hulled ship, like a catamaran. Therefore, we need to calculate ship fluid structure interaction in a two-way coupled method to capture longitudinal and lateral effects.
Applying prestressing	Prestressing has been utilized in coupled simulations in biomedical engineering.	[162]	It significantly influences deformation in coupled simulations. In ship structures, prestressing originates from the fabrication process and should be considered in structural analysis.
Real-time FSI simulation	Real-time input has been applied in fluid–structure interaction (FSI) simulations of blood flow in arteries.	[163]	Similarly, real-time FSI can be implemented in ships by incorporating environmental factors during voyages to enhance ship hydroelasticity.

6. Conclusions

After rigorous screening and filtering, the PRISMA method for the systematic literature review identified a total of 93 key articles from an initial pool of 1440 articles. The bibliographic analysis reveals that China is a leader in hydroelasticity research, driven by strong support from the shipbuilding industry and funding. Additionally, the keyword analysis indicates that hydroelasticity, hydrodynamics, and the finite element method are the primary areas of focus within this field.

The literature suggests that a two-way coupling method combining potential flow for fluid dynamics and the finite element method (FEM) for structural analysis is commonly used in ship hydroelasticity simulations. This method is widely available in self-coded, open-source, and commercial software, and is particularly suited for multiple computational analyses. However, to ensure the accuracy of potential flow simulations, a decay test is necessary to validate the damping coefficient. In FEM, the use of 3D fluid and structural elements is recommended to achieve more precise results and enhance the overall quality of the analysis.

Furthermore, the review highlights several emerging areas of interest, including fatigue, damage, fracture, passive intelligent devices (PIDs), and sandwich structures. These topics serve as a foundation for further exploration and development. Future research in ship hydroelasticity should consider the inclusion of multiple variables, such as mooring, surface roughness, weight distribution, environmental influences, and structural optimization. Additionally, efforts to reduce computational costs and integrate artificial intelligence (AI) are critical areas for future advancement. Regarding ship types, trimarans present a promising opportunity for further exploration using two-way coupling methods.

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