

• 四川大学建校 130 周年特刊约稿 •

DOI:10.12454/j.jsuese.202600715



本刊网刊

# 液体晃荡及其工程应用

戚 岩<sup>1,2</sup>, 薛米安<sup>1,2</sup>, 林鹏智<sup>3\*</sup>

(1. 河海大学 海岸灾害及防护教育部重点实验室, 江苏 南京 210024; 2. 河海大学 港口海岸与近海工程学院, 江苏 南京 210024;  
3. 四川大学 山区河流保护与治理全国重点实验室, 四川 成都 610065)

**摘 要:**为解决液体晃荡在强非线性载荷预测、实用减晃技术、多物理场耦合机理与数据利用等方面面临的挑战,本文基于 220 余篇文献,从物理机制、工程应用和学科交叉前沿三大维度对液体晃荡研究进行了系统梳理。机制部分按解析、数值与实验 3 类研究手段的顺序,归纳了相应认识,应用部分按晃荡抑制与晃荡利用两条主线组织评述。结果表明:在机制层面,晃荡研究已由线性共振与自然模态,经非线性多模态耦合,发展至包含低温热力学、流固耦合与分层流的多物理场耦合,双层液体系统与强共振区间动力学成为当前机制研究前沿;在应用层面,减晃技术由刚性、穿孔、弹性挡板向浮动装置与主动控制持续演进,已应用于航天推进剂管理、液化天然气(LNG)运输安全与储罐抗震等场景,调谐液体阻尼器、充水浮式防波堤、海上可再生能源与深远海养殖等则把晃荡动力学转化为工程优势;在前沿层面,数据驱动建模、低温氢能、仿生表面减晃、非牛顿流体与尺度效应等交叉方向正重塑研究格局。液体晃荡研究正由传统水动力学向多学科交叉拓展,物理建模与数据驱动方法的融合、面向强非线性与多物理场的实时预测,以及跨尺度验证数据集的构建,是未来有待突破的关键问题。

**关键词:**液舱晃荡;多物理场耦合;晃荡抑制;晃荡利用

**中图分类号:**U661.7

**文献标志码:**A

**文章编号:**2096-3246(2026)05-0280-22

液体晃荡是指部分充液容器受外部激励时,内部液体自由液面产生的波动现象,其物理根源在于重力恢复力、容器运动惯性效应及壁面运动学约束三者之间的相互作用。晃荡的动力学谱系极为宽广:在低激励水平下表现为势流理论所描述的线性驻波<sup>[1]</sup>;随激励幅值增大,依次出现波浪破碎、飞溅和气液掺混,直至产生足以造成结构损伤的高幅值水动力冲击<sup>[2-3]</sup>。当外部激励频率趋近液舱耦合系统的固有频率时,自由液面振幅急剧增大,冲击压力可超过静水压力数个量级。控制这一过程的无量纲参数主要包括弗劳德数、邦德数、雷诺数和深长比,它们共同决定了不同动力学区间的转换条件及各区间内主导的物理机制。

液体晃荡研究的工程意义在于其兼具破坏性和可利用性。就破坏性而言,采用薄膜式围护系统的液化天然气(LNG)运输船在低温条件下极易受到晃荡冲击损伤,剧烈冲击集中在充液率 10% 至 70% 区间<sup>[4-6]</sup>,这一现

象长期制约着液货运输船的操作灵活性。在航天领域,液体推进剂晃荡产生的扰动力和力矩与柔性结构的振动发生耦合<sup>[7-8]</sup>,可导致结构固有频率发生显著偏移<sup>[9]</sup>;这些扰动同时作用于姿态控制系统,造成控制力矩的低估。液体储罐的抗震设计需同时考虑脉冲水动力分量和对流晃荡分量。1964 年阿拉斯加地震和 1999 年科贾埃利地震中储罐的破坏实例深刻说明了这一问题的严峻性<sup>[10-11]</sup>。正是这些危害事故,驱动着减晃技术从简单刚性挡板向穿孔挡板与多孔介质<sup>[12-13]</sup>、弹性挡板<sup>[14-15]</sup>、浮动装置<sup>[16]</sup>乃至主动控制装置持续演进。就利用而言,调谐液体阻尼器将晃荡动力学原理应用于结构振动控制<sup>[17-18]</sup>,通过自由液面耗散和相位调控等机制抑制高层建筑、桥塔及海上风力发电机等结构的振动或摇摆;浮式生产储卸装置、半潜式平台和浮式风机基础等海洋结构物在长期服役期间,持续利用晃荡与波浪运动的耦合效应实现运动控制<sup>[19-21]</sup>。

收稿日期:2026-08-03 修回日期:2026-08-25 网络出版日期:2026-09-04

基金项目:国家重点研发计划项目(2022YFB4200700);国家自然科学基金项目(52571289)

作者简介:戚 岩(1992—),男,博士后。研究方向:液体晃荡高效物理降阶模型开发与减晃机制。E-mail:yanqi7878@163.com

\* 通信作者:林鹏智,教授, E-mail:cvelinpz@scu.edu.cn

随着应用场景的不断拓展,液体晃荡研究呈现出高度的学科交叉性,覆盖应用数学、计算流体力学(CFD)、实验力学、结构工程和控制理论等多个领域<sup>[1]</sup>。在此背景下,当前研究面临的核心挑战可归纳为 4 个方面:1)强非线性工况下晃荡载荷的准确预测,此类工况涉及波浪破碎、气液夹带和剧烈流固耦合,线性势流理论和弱非线性多模态方法均难以应对,而面向工程参数化分析的高保真度计算流体力学成本依然高昂;2)开发在宽频激励、任意充液比和多样几何形状下均能可靠发挥作用的实用减晃技术,这一需求推动了从刚性挡板到浮动装置,直至主动控制装置的技术演进;3)多物理场耦合效应的识别与量化,包括低温液舱中晃荡引起的蒸发气体加速生成所涉及的热力学-水动力学耦合、北极航运中的冰-液耦合,以及水产养殖中的生物-流体相互作用;4)对日益丰富的实验与数值数据集的深度利用,亟需引入机器学习<sup>[22-23]</sup>、降阶建模<sup>[24]</sup>和新型数据分析等方法。

Zheng 等<sup>[25]</sup>系统评述了挡板减晃、分层液体晃荡、晃荡尺度效应和调谐液体阻尼器 4 个主题,为理解晃荡现象奠定了重要基础。然而,近年来液体晃荡研究出现了若干新的发展态势:以机器学习和人工智能为代表的驱动方法开始深度介入晃荡载荷预测、降阶建模与主动控制,低温氢能储运、仿生表面减晃、非牛顿流体晃荡等交叉方向相继兴起,晃荡研究的应用场景也从传统船舶与储罐拓展至深远海养殖和海上可再生能源等新领域。与 Zheng 等<sup>[25]</sup>的工作相比,本文

在组织框架上以从物理机制到工程应用再到研究前沿的递进式结构取代了主题并列的叙述方式,在应用层面将减晃技术与晃荡利用技术并列为两条主线,并纳入了 2021—2026 年的最新交叉进展。

围绕上述主题,本文的文献检索依托 ScienceDirect 与 Google Scholar 数据库,并辅以文献引文追溯。检索以 liquid sloshing、sloshing mitigation、sloshing utilization 等为核心关键词,分别结合解析与半解析方法、数值模拟、实验研究 3 类研究手段,以及航天推进剂管理、液化天然气运输、储罐抗震、浮式生产、结构振动控制、防波堤与海岸防护、海上可再生能源、深远海养殖等应用方向,和数据驱动建模、低温氢能、仿生表面、非牛顿流体等交叉前沿,分块展开检索。检索时间范围不设下限,以纳入 Faltinsen 等<sup>[1]</sup>奠基性经典工作;工程应用部分重点纳入近 5 年(2021—2026)发表的文献,以反映最新进展。经筛选,最终纳入与液体晃荡直接相关的同行评议期刊论文 220 余篇。

本文从物理机制、工程应用和研究前沿三大维度对液体晃荡研究进行系统梳理,整体研究脉络如图 1 所示。在物理机制层面,综合运用解析推导、数值计算和实验观测 3 种手段揭示关键机理,梳理出双层液体系统、强共振区间动力学和低温相变耦合等当前机制研究的前沿方向;在工程应用层面,以减晃和利用晃荡两条主线组织综述,于每一应用领域先阐明工程需求背后的物理逻辑,再以具体研究实例展开论述;立足机制认识与应用需求的交汇点,进一步从学科交叉

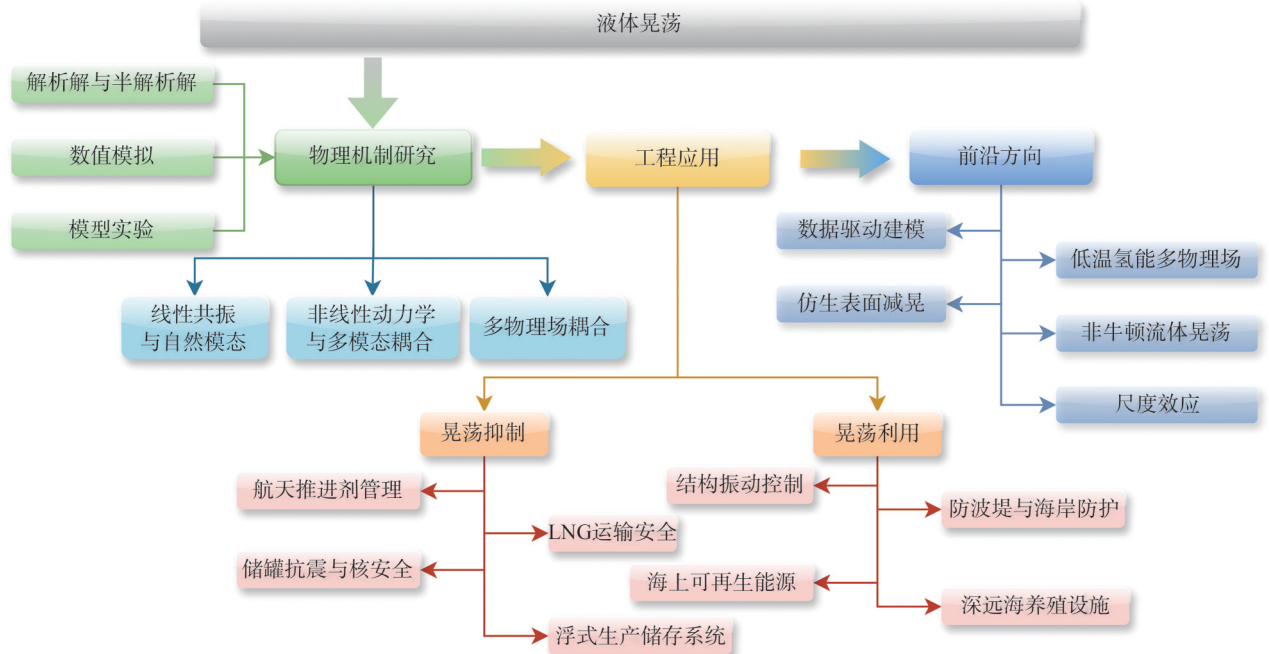


图1 液体晃荡研究脉络  
Fig. 1 Overview of liquid sloshing studies

视角讨论数据驱动建模、仿生表面减晃和非牛顿流体晃荡等有望重塑未来研究格局的前沿方向。

## 1 液体晃荡机制

理解液体晃荡的物理机制是发展减晃技术和利用晃荡的基础。晃荡问题涉及强非线性自由液面流动、多模态耦合和多物理场交互。本节以物理机制为主线,系统梳理从线性共振到多物理场耦合的机制图景,并在每类机制中总结已有认识的核心结论及其对工程实践的指导意义。

### 1.1 线性晃荡理论与自然模态

无黏无旋假设的线性波浪理论为液体晃荡分析提供了基础数学框架。以长度为 $L$ 、宽度为 $B$ 、静水深度为 $h$ 的矩形液舱为例,在该框架下,速度势在整个流体域内满足拉普拉斯方程。联立求解线性化的自由液面边界条件,可导出矩形液舱的色散关系和波数,分别表示如下:

$$\omega_{mn}^2 = gk_{mn} \tanh(k_{mn}h) \quad (1)$$

$$k_{mn} = \pi \sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{B}\right)^2} \quad (2)$$

式(1)~(2)中: $k_{mn}$ 为波数, $m, n=0, 1, 2, \dots$ ,且 $m$ 和 $n$ 不能同时为0, $m, n$ 分别为 $x$ 和 $y$ 方向的半波数,每一组 $(m, n)$ 定义了一种特定的自由液面空间振荡形态,称为晃荡模态; $\omega_{mn}$ 为该模态对应的固有圆频率; $g$ 为重力加速度。自然晃荡模态是固有频率对应的特征函数,构成描述自由液面运动的完备正交基。Faltinsen<sup>[1]</sup>和Lukovsky<sup>[26]</sup>等系统地建立了该理论体系。

线性理论最核心的工程启示在于:液舱的几何形状从根本上决定了其固有频谱特性,进而决定了在典型载荷条件下是否可能发生共振激励。具体而言,浅水条件下矩形液舱自然频率更易满足整数倍关系,一旦激励频率接近低阶固有频率,多个高阶模态可通过内共振被同步激发;而深水条件下频谱中高阶模态相对密集,但能量传递受限,响应倾向于呈现单模态主导的特征。这种水深依赖的动力学差异在车辆液舱中表现尤为突出。Kolaei等<sup>[27]</sup>对罐车动力学的评估表明,当横向加速度较低时,线性预测可满足工程估算精度,但在更高激励水平下非线性效应迅速占据主导。上述特性表明,减晃设计不能简单地采用通用方案,而必须针对目标液舱的固有频谱进行定制化匹配。

线性理论的应用范围已从标准矩形液舱延伸至带隔板液舱<sup>[28]</sup>、圆柱形与椭圆形液舱<sup>[29-33]</sup>、球形液舱<sup>[34]</sup>、环形圆柱液舱<sup>[35]</sup>、挡板类减晃装置<sup>[36-37]</sup>、三角形液舱<sup>[38]</sup>、渡槽<sup>[39]</sup>,以及“U”形容器<sup>[40]</sup>等多种工程几何构

型,其核心在于通过保角变换、分离变量、边界元与变分等解析手段求解各类构型的自然频率与模态,为减晃装置的定制化设计提供了频域依据。

除固有频谱的预测外,不同液舱几何形状下晃荡载荷的分布特征同样是机制研究和工程设计中需重点关注的问题。Xue等<sup>[41]</sup>对不同形状储液容器中的晃荡压力分布开展了流体动力学分析,揭示了容器几何特征对冲击压力幅值和空间分布的影响,为液舱选型和结构局部加强提供了直接的设计依据。针对球形液舱构型,Xue等<sup>[42]</sup>研究了液体晃荡的动力学特性,阐明了激励频率、充液比和激励幅值等关键参数对晃荡响应的影响规律,为航天和工业球形储罐中的推进剂管理和结构设计提供了重要的支撑。

总结而言,线性晃荡理论为工程师提供了一个基本框架,使其能够针对任意给定几何形状预测晃荡固有频率和模态结构,进而判断在预期运行激励下是否可能进入共振状态。这一判断依据对于液舱初始设计阶段的共振规避至关重要。然而,线性理论的前提假设限定了其适用范围。当激励幅值增大、非线性效应逐渐显现时,需借助更为精细的非线性分析工具。

### 1.2 非线性动力学与多模态耦合

当激励幅值增大至线性理论失效的区域时,振幅依赖的频率漂移、内共振、模态能量级联和亚临界分岔等丰富的非线性现象开始主导系统行为。准确描述这些现象是预测极端工况下晃荡载荷的前提。Faltinsen<sup>[1]</sup>和Timokha<sup>[43]</sup>等发展的多模态方法为处理此类非线性问题提供了最重要的理论工具。该方法通过Galerkin投影将非线性自由液面条件映射到自然晃荡模态基上,以远低于CFD的计算成本捕捉关键非线性效应。多模态方法揭示的核心机理在于,非线性频率漂移的偏向取决于液舱长宽比和充液比,这意味着共振激励频率可能高于或低于线性理论给出的固有频率预估值。这一特性意味着工程中仅依赖线性固有频率进行共振规避是不可靠的,设计时须纳入非线性偏移的幅度和方向。该框架后续被推广至倾斜壁面液舱<sup>[43]</sup>和带格栅挡板的液舱<sup>[44-45]</sup>,其中,壁面倾角引起的不对称恢复力和挡板压降引入的非线性阻尼均显著改变了系统的动力学特性。

在强非线性区域,多模态方法揭示了一系列与工程安全直接相关的机制。Wei等<sup>[46]</sup>在带板条筛网液舱的砰击实验中发现,选取合适的筛网实度比可有效抑制自由面高程与垂直舱壁砰击压力。Saltari等<sup>[47]</sup>研究了垂向晃荡的耗散行为,发现频率接近法拉第波阈值时可激发参数共振。在旋转和轨道激励构型中,研究者进一步观察到超谐共振旋转波<sup>[48]</sup>、法拉第波和周期

三倍化<sup>[49]</sup>、晃荡驱动的自由容器周期振荡<sup>[50]</sup>,以及表面波从重力主导向表面张力主导的过渡<sup>[51]</sup>等丰富现象。Bardazzi等<sup>[52]</sup>在临界充液深度附近识别了不同晃荡流态及其转换机制。这些发现表明,在特定激励参数组合下,晃荡系统的动力学响应远超出简单单模态共振的预测范围。

在非线性晃荡研究的诸多分支中,近共振条件下的晃荡行为因其对初始条件和激励参数的高度敏感性而受到持续关注。Fang和Lin<sup>[53]</sup>针对纵荡激励下的近共振液体晃荡开展了系统的理论与实验研究;Bäuerlein等<sup>[54]</sup>通过实验相位滞后分析揭示了非线性响应最大值的预测判据;Constantin等<sup>[55]</sup>则对垂向激励下剧烈晃荡液体的非线性阻尼效应进行了系统表征,揭示了激励频率于系统固有频率附近微小偏离时晃荡响应的急剧变化特征。这类研究表明,在近共振区间内,线性理论预测与真实物理响应之间存在本质差异,非线性效应即使在小振幅激励下也可能产生显著影响,这意味着工程设计中仅依赖线性避共振准则难以保证结构安全,需引入更为精细的非线性分析手段来评估近共振风险。

总体而言,非线性多模态耦合研究的意义在于,它建立了从线性共振到强非线性冲击之间的过渡性理论框架,阐明了在依据线性理论判断为安全的设计区间内,非线性效应仍可能激发共振响应的物理机制,同时为减晃设计提供了更精细的调谐依据,使减晃装置在非线形效应显著的工作区间内仍能有效发挥作用。

### 1.3 多物理场耦合机制

实际工程中的晃荡往往超出纯水动力学非线性的范畴,涉及热力学、结构弹性和密度分层等多种物理过程的耦合。这些耦合效应不仅是机制研究的学术前沿,更直接关系到关键工程系统的安全性和经济性。

低温热力学与水动力学的耦合是最受关注的一类多物理场机制。晃荡引起的流体混合破坏了热分层结构,增大了参与热质交换的自由液面面积,从而加速液-气相变和蒸发气体(BOG)的生成。在LNG储运中,这意味着货物损失与BOG排放增加的双重经济与环境代价。该领域的研究从替代低温流体的实验入手,逐步建立了晃荡参数与传热增强之间的定量关联<sup>[56-57]</sup>,并进一步将CFD模拟与相变模型和隔热模型耦合,实现了工程可用的BOG生成量预测<sup>[58-60]</sup>。液氢作为新兴清洁能源载体,其极低的潜热和表面张力使这一问题在氢经济背景下被赋予了新的重要意义<sup>[61]</sup>。冲击事件中气垫气体可压缩性的影响<sup>[62-65]</sup>和LNG泵塔结构的水弹性效应<sup>[66]</sup>则进一步扩展了该方向的研究谱系。

流固耦合是另一类核心多物理场机制,直接关系到减晃装置的设计安全。弹性挡板因其结构柔性,能够在最低阶晃荡固有频率以下引入新的固有频率,这意味着弹性挡板可能在设计未预期的低频范围内产生新的共振风险<sup>[67-69]</sup>。Zhao等<sup>[70]</sup>建立了统一的光滑粒子流体动力学(SPH)框架用于模拟弹性液舱中的晃荡与挡板抑制;Meng<sup>[71]</sup>、Brietman<sup>[72]</sup>和Khouf<sup>[73]</sup>等分别研究了弹性挡板的变形特性、用于分离流固耦合响应的数字滤波方法,以及柔性液舱的耦合问题。在更复杂的非线性层面,二维橡胶膜与液体的非线性相互作用<sup>[74]</sup>已得到系统研究;弹性挡板与晃荡流动的SPH耦合分析<sup>[75-76]</sup>则揭示了柔性结构在晃荡激励下的动态响应机理。这类研究的工程意义在于指出不宜简单弹性挡板视为刚性挡板的柔性化替代,而须将其作为一个具有独立动力学特性的耦合子系统,进行系统性的分析与设计。

密度分层液体引入了浮力驱动的耦合,从根本上改变了系统的模态结构。分层晃荡研究表明,层间密度比控制着界面波激励强度,当密度比趋近于1时,内部界面振幅可与自由液面相当,三层系统还会产生均质或两层构型中不存在的拍击现象<sup>[77-82]</sup>。这类研究对FPSO湿式储存、化工容器等分层流体工况具有直接参考价值。已有实验获取的自由液面波与内部界面波同步演化图像(图2)进一步验证了上述分层液体理论。分层液体晃荡的相关评述可参考Zheng等<sup>[25]</sup>的综述。

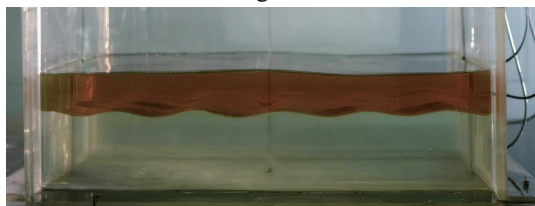


图2 分层流晃荡自由液面波与界面波

Fig. 2 Free surface and interface waves of stratified sloshing

总结而言,多物理场耦合构成了晃荡机制研究中最具工程相关性的核心议题。纯水动力学理论虽已相当成熟,但当实际工程系统涉及热力学、结构弹性和密度分层等多物理过程时,系统的动力学行为可能发生根本性改变。对这些耦合机制的深入理解不仅关系到预测精度的提升,更直接影响到减晃装置的设计策略和安全评估标准的制定。

### 1.4 机制研究的方法与前沿方向

上述机制认识从线性共振逐步延伸至多物理场耦合,每向前推进一步,都需要相应的研究手段提供支撑。解析方法从数学上锚定物理本质,但受无黏无旋假设限制,主要适用于规则域内的线性与弱非线性问题;数值模拟能够捕捉全非线性效应,将分析能力投向解析无法抵达的参数区间,却受计算成本与阻尼

精确表征的双重制约;实验观测始终是理论预测和数值结果不可绕过的检验环节,但也受尺度效应与传感器不确定性的影响。三者互为补充,共同支撑从基础机理到工程设计的完整认识链条。以下将沿解析与半解析、计算流体力学和实验研究 3 条脉络展开,并归纳若干前沿方向。

#### 1.4.1 解析与半解析方法

解析与半解析方法以无黏无旋势流假设为前提,通过求解速度势的解析表达式直接获得晃荡模态与共振频率等核心物理特征,为理解晃荡机制提供精确的数学基准。在简单规则流体域内,这类方法已为线性晃荡问题提供了完备的求解框架。当前方法演进的重心正从简单规则流体域向复杂几何构型和弱非线性工况延伸。

域分解与特征函数匹配是应用最为广泛的一类半解析策略,其基本思想是将复杂流体域划分为若干简单子域,在各子域内给出速度势的解析级数解,再根据交界面处压力与速度的连续性条件将各子域解匹配衔接起来。保角变换、匹配特征函数展开与变分域分解等半解析方法已广泛用于求解椭圆截面液舱、多孔挡板液舱、分层液体、超椭圆截面液舱与带挡板液舱的晃荡自然频率与模态<sup>[30,80,83-86]</sup>。

当激励幅值超出线性理论的适用范围后,将自由液面边界条件按小参数渐近展开是引入非线性效应的自然途径。Faltinsen<sup>[1]</sup>和 Timokha<sup>[43]</sup>等发展的多模态方法将这一思想系统化:通过 Galerkin 投影将非线性自由液面条件映射到自然晃荡模态基上,以远低于 CFD 的计算成本捕捉关键非线性效应,建立了从线性共振到强非线性冲击之间的过渡性理论框架。渐近方法在瞬变工况中的优势更为突出。Zhang 等<sup>[87]</sup>针对时变质量瞬态共振问题,将非线性渐近理论与 Bateman-Luke 变分原理相结合,将解按 1/3、2/3 和 1 阶渐近级数分解,成功捕捉了线性理论无法预测的自由液面包络非对称特征和非线性跳跃行为,拓展了理论模型的工程适用范围。

#### 1.4.2 计算流体力学方法

与解析方法不同,计算流体力学方法突破了无黏无旋势流假设的限制,通过直接离散控制方程捕捉全非线性效应。

有限差分与有限体积法结合流体体积法 (VOF) 界面捕捉是应用最广泛的欧拉方法。代表性的 NEWTANK 模型<sup>[88]</sup>以虚拟边界力模拟复杂挡板、以二阶 VOF 追踪自由液面;Qi 等<sup>[89-90]</sup>发展的三维线性频域有限差分方法则在非共振区域实现了高效的工程预测。

在无网格方法中,SPH 因无需网格而成为剧烈晃荡问题中最有效的方案, DualSPHysics<sup>[91]</sup>等框架在

LNG 运输船<sup>[92-93]</sup>、多相振荡水柱 (OWC)-防波堤<sup>[94]</sup>、浮式风机<sup>[95]</sup>与船舶运动耦合<sup>[96-97]</sup>等场景得到广泛应用;改进的 SPH 公式<sup>[98]</sup>和 SPH-有限元耦合<sup>[99-101]</sup>进一步扩展了其处理流固耦合问题的能力。移动粒子半隐式 (MPS) 方法<sup>[102-106]</sup>则在弹性液舱与水弹性晃荡问题中发挥了重要作用。有限容积法 (FVM) 结合 isoAdvector 与浮力修正湍流模型<sup>[107-111]</sup>被广泛应用于薄膜式 LNG 液舱、带挡板矩形液舱与分层液体晃荡。

此外,比例边界有限元法 (SBFEM) 及其等几何拓展<sup>[112-114]</sup>以边界离散降低了计算维度;船舶-液舱晃荡混合耦合框架<sup>[115-119]</sup>、FVM-VOF 隔板与液舱构型研究<sup>[120-123]</sup>、SPH 能量耗散分析<sup>[124]</sup>、SPH 波流数值水池<sup>[125-126]</sup>,以及大尺度 LNG 液舱晃荡研究<sup>[127]</sup>等工作共同构成了当前计算晃荡力学的方法论体系。基准测试<sup>[128]</sup>表明,阻尼的精确表示仍是所有计算方法面临的共同挑战。

#### 1.4.3 实验方法

数值模拟的精度和可靠性最终需通过物理实验检验。实验研究从 Pal<sup>[129]</sup>、Pal<sup>[130]</sup>等的先驱性工作起步,经 Souto-Iglesias 等<sup>[131-132]</sup>建立的基准问题系列逐步规范化, Panigrahy<sup>[133]</sup>与 Akyildiz<sup>[2]</sup>等提供了挡板和压力分布的基础数据,测量技术也从早期电容式探针演进到高速成像与粒子图像测速 (PIV) 同步表征、MAX-MIN 可视化和压力场快速重建<sup>[3,134-136]</sup>,使诊断能力从自由液面形态延伸至全场速度与压力信息。专题研究进一步围绕能量耗散、垂向阻尼、底部几何、燃料舱与低温相变等关键物理过程展开<sup>[137-143]</sup>,模型实验也日趋多样化<sup>[144-152]</sup>。

河海大学依托六自由度运动平台集成了 PIV 流场测试与多源异构传感器同步测试系统 (图 3),形成了自由液面、速度场与压力场的同步诊断能力,并据此开展了刚性、穿孔、弹性挡板及浮动式减晃装置的系列实验研究<sup>[153-156]</sup>,以及物理-数据混合主动控制<sup>[157]</sup>和多孔材料减晃等工作<sup>[12-13]</sup>。



图 3 液舱晃荡实验测试系统

Fig. 3 Experimental measurement system for tank sloshing

强共振区间的非线性动力学仍是实验研究的核心难题:晃荡响应激励参数与初始条件的微小偏差极为敏感,导致非线性跳跃和迟滞等瞬态行为难以通过常规扫掠实验完整捕捉。在多层液体系统方面,自由液面与内部界面的同步测量实验已揭示湿式储存系统中油水界面的旋转波动力学特征<sup>[158-159]</sup>,其耦合复杂程度超出了单层晃荡的理论框架。冰-液耦合<sup>[160]</sup>和纳米流体对流的实验<sup>[161]</sup>则将研究参数空间从常规工质拓展至物性变化驱动的动力学问题。总体而言,

随着测量技术、诊断能力与工程需求的同步提升,实验研究已从早期的单点验证逐步拓展至覆盖多物理场、多流体和多激励工况的系统化方法论。

纵观上述解析、数值与实验3类研究手段的演进,液体晃荡研究方法呈现出清晰的代际更替脉络。图4以解析方法、数值模拟与实验技术3条主线,梳理了从线性势流理论、VOF与粒子法到数据驱动方法,以及从电容探针、PIV到多源同步诊断的标志性进展,直观展示了该领域研究方法的发展趋势。

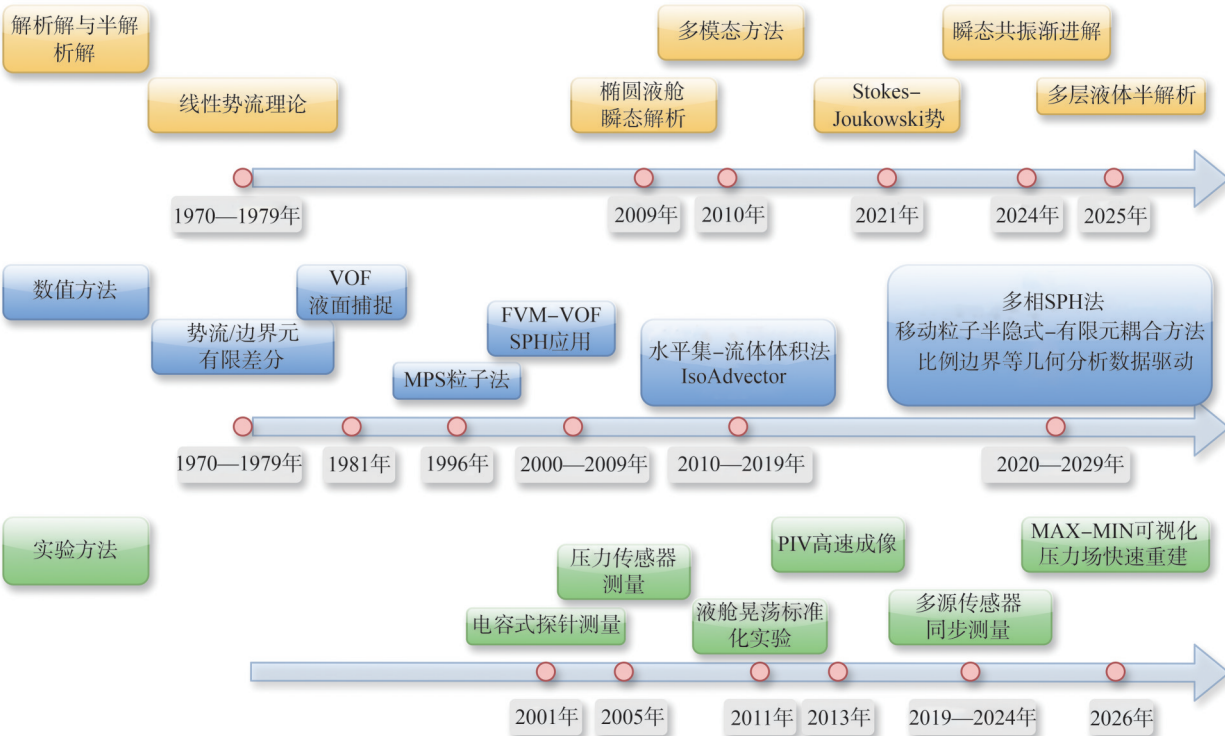


图4 液舱晃荡研究方法发展脉络

Fig. 4 Development of research methods for liquid sloshing

2 工程应用

液体晃荡兼具破坏性与可利用性,这一双重属性直接决定了其工程应用沿着晃荡抑制与晃荡利用两条主线展开。晃荡抑制着眼于控制液舱内自由液面的破坏性运动,其需求源自液化天然气运输、航天推进剂管理、储罐抗震安全等关键场景,一旦失效后果往往是灾难性的;晃荡利用则反其道而行之,将晃荡动力学转化为工程优势,覆盖结构振动控制、海岸防护、海上可再生能源与深远海养殖等领域。两条主线取向虽相反,却共享同一套物理机制认识,并且在充水浮式防波堤、养殖工船等场景中呈现出相互转化的交叉区间。表1从作用机制、典型装置、应用场景与代表性文献等方面,对两条主线下的代表性技术进行了横向比较<sup>[12-18,162-170]</sup>。

2.1 破坏性晃荡的抑制

在近共振激励条件下,晃荡冲击压力可达静水压力的数个数量级,直接威胁结构完整性。图5为减晃结构设计与工程应用场景。在这些安全系统中,减晃已从性能优化层面上升为安全底线。一旦晃荡载荷超出设计阈值,失效后果往往是灾难性的,且系统修复或改造的代价极其高昂。

针对以上工程场景,挡板是应用最为广泛的减晃手段,其作用机制在于挡板边缘的流动分离与涡脱落将有序波浪动能转化为湍流耗散。竖直挡板<sup>[153-154,162]</sup>、环形挡板<sup>[11,163]</sup>、曲面挡板<sup>[171]</sup>、穿孔挡板<sup>[172]</sup>、弹性挡板<sup>[14]</sup>、浮动挡板<sup>[16]</sup>,以及主动控制装置<sup>[15]</sup>等各类减晃手段的机理与效果已有系统总结,并可参见Zheng等<sup>[25]</sup>的综述。上述减晃手段的持续演进,从刚性到弹性、从固定到浮动、从被动到主动,为各具体工程应用场景提供了通用

表 1 晃荡抑制与晃荡利用技术对比

Tab. 1 Comparison of sloshing suppression and utilization technologies

| 技术主线 | 技术类型       | 典型装置       | 作用机制      | 应用场景       | 代表文献编号    |
|------|------------|------------|-----------|------------|-----------|
| 晃荡抑制 | 刚性挡板       | 竖直、环形、水平挡板 | 涡脱落耗散动能   | 各类储液容器     | [162–163] |
|      | 穿孔挡板, 多孔介质 | 穿孔板、多孔材料层  | 孔隙内动量耗散   | 液舱减晃       | [12–13]   |
|      | 弹性挡板       | 柔性挡板       | 结构柔性提供阻尼  | 液舱减晃       | [14–15]   |
|      | 浮动装置       | 浮板、浮动顶盖    | 随自由液面同步运动 | LNG 液舱     | [16]      |
|      | 主动控制       | PID 调控弹性挡板 | 调控有效刚度    | 宽频减晃       | [15]      |
| 晃荡利用 | 调谐液体阻尼器    | 部分充液液舱     | 频率调谐耗散能量  | 高层建筑、桥塔    | [17–18]   |
|      | 调谐液柱阻尼器    | “U”形液柱     | 液柱低频控制    | 海上光伏平台     | [164]     |
|      | 调谐多液柱阻尼器   | 多液柱        | 多液柱耦合     | 浮式风机俯仰减摇   | [165]     |
|      | 充水浮式防波堤    | 压载水防波堤     | 内部晃荡阻尼与共振 | 海岸防护、海上光伏场 | [166]     |
|      | 振荡水柱       | 气室水柱       | 水柱垂向晃荡    | 波浪能转换与防波堤  | [167–168] |
|      | 养殖工船液舱     | 双排液舱、过流式液舱 | 晃荡解耦      | 深远海养殖      | [169–170] |

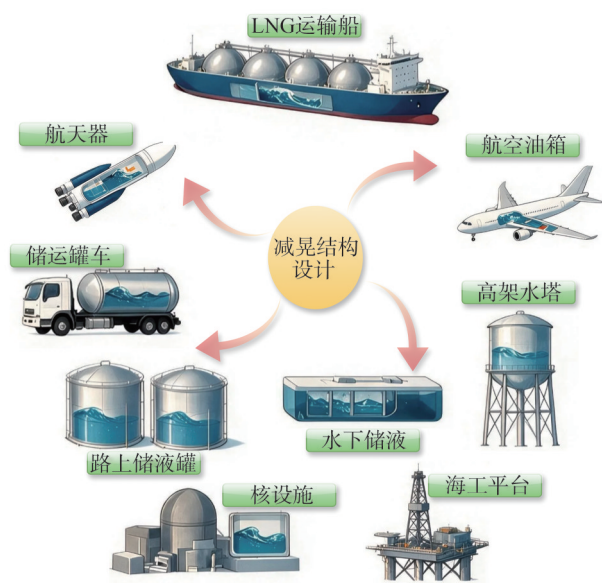


图 5 减晃结构设计与工程应用场景

Fig. 5 Structural design of sloshing reduction and its engineering application scenarios

技术基础。以下将从航天推进剂管理、LNG 运输安全、地震与核安全及浮式生产系统 4 个方面展开论述。

2.1.1 航天推进剂管理

在各类安全关键应用中,航天器推进剂管理对减晃技术的要求尤为严苛。航天器液体推进剂晃荡产生的扰动力和力矩须纳入姿态控制系统的设计考量。低频晃荡模态与航天器柔性附属结构之间存在强耦合效应, Wu 等<sup>[7]</sup>的耦合动力学分析表明,该耦合可导致结构固有频率发生显著偏移,在设计阶段忽略这一因素将造成控制力矩需求的系统性低估。Yang<sup>[173]</sup>与 Yan<sup>[174]</sup>等分别从姿态机动分析和解析稳定性的角度,为上述耦合机理提供了补充验证。

微重力环境使问题进一步复杂化。Dalmon 等<sup>[175]</sup>

通过空间实验数据与数值模拟的系统对比,确认接触线动力学与弯月面形态为控制晃荡的主导因素。Song<sup>[9]</sup>与 Chiba<sup>[176]</sup>等分别围绕姿态扰动控制和水弹性耦合理论开展了研究。微重力晃荡对邦德数高度敏感,导致基于弗劳德相似准则的地面实验无法直接再现微重力行为,成为了该领域的关键挑战。Deng 等<sup>[8]</sup>研究了柔性航天器在大幅值晃荡下的姿态跟踪控制, Wu 等<sup>[177]</sup>通过绝对节点坐标公式建立了刚-柔-液耦合卫星天线系统的动力学模型, Hunt<sup>[178]</sup>和 He<sup>[179]</sup>等在推进剂管理与低重力晃荡方面也开展了相关工作。

航天推进剂管理对减晃需求尤为迫切,其根源在于严苛的安全标准和巨大的系统失效代价。随着深空探测与可重复使用运载火箭技术的推进,推进剂晃荡管理已从传统的地面加注和入轨阶段延伸至在轨加注与长期空间驻留等更复杂的任务需求,要求减晃技术具备更高的自适应能力和可靠性。

2.1.2 液化天然气远洋运输安全

LNG 运输船普遍采用薄膜式围护系统,其中, NO96 型以厚度为 0.7 mm 殷瓦钢(Invar)为主膜, Mark III 型则以厚度为 1.2 mm 的 304L 不锈钢为主膜,在低温条件下实现货物围护的同时,于部分充装工况下极易遭受晃荡冲击损伤。充液比依赖性研究表明,剧烈冲击集中在约 50% 充液比附近<sup>[4–6]</sup>,棱形液舱的倒角则决定了冲击压力的空间分布特征。船舶运动与内部晃荡之间的双向耦合是核心动力学问题;当晃荡固有频率趋近船舶横摇固有频率时,耦合效应显著改变横摇响应。以水替代 LNG 的横摇耦合动力学等效性验证<sup>[180]</sup>为模型试验提供了支持。Cao 等<sup>[127]</sup>在大尺度 LNG 液舱晃荡方面的实验与数值研究为工程设计提供了直接验证数据。Barabadi 等<sup>[181]</sup>利用浮式泡沫材料

开展了矩形液舱减晃的数值研究,Odoom等<sup>[182]</sup>评估了高密度固体泡沫球在不同条件下的减晃效能。

低温热力学效应使LNG运输安全问题更为复杂。晃荡诱导的流体混合与自由液面面积增大加速了液-气相变,导致BOG生成量显著增加,这意味着货物损失与排放控制的双重压力。围绕BOG这一核心工程指标,通过替代低温流体开展的实验研究<sup>[56]</sup>与耦合传热计算分析<sup>[57]</sup>逐步建立了晃荡参数与BOG增强之间的定量关联,Wu<sup>[58-59]</sup>与Li<sup>[60]</sup>等工作则进一步将BOG生成量预测纳入工程设计流程。在结构安全层面,冲击事件中的气垫气体可压缩性效应<sup>[62-65]</sup>改变了局部压力响应,LNG泵塔的水弹性效应<sup>[66]</sup>引入了结构变形与晃荡流动的耦合机制,二者直接关系到围护系统的设计安全裕度。

LNG运输安全领域的研究还揭示了一个值得关注的现象:内部晃荡在特定条件下可降低船舶运动幅值和迎浪附加阻力<sup>[183]</sup>,表明减晃与利用之间并非绝对对立,存在可供工程利用的交叉区间。此外,通过改进液舱几何形状消除充装限制,为提升运输船操作灵活性和经济效率提供了可行路径。LNG晃荡模拟与大比尺模型实验研究也为后续拓展至液氢和液氨等新型低温介质的研究奠定了扎实的工作基础<sup>[113,127]</sup>。

### 2.1.3 地震与核安全

与航天和LNG运输的减晃需求不同,地震激励下的储液罐晃荡直接关系到基础设施的结构安全。液体储罐的抗震设计需同时考虑两种水动力分量:随罐壁刚性运动的脉冲压力及自由液面振荡产生的对流晃荡压力。Housner<sup>[184]</sup>在20世纪50年代建立的双分量模型为这一分析框架奠定了基础,并构成了美国石油学会(API)《650焊接钢制储油罐》和欧洲规范《结构抗震设计》(Eurocode 8)等国际标准的核心设计条文<sup>[10]</sup>。三维有限元分析与六自由度地震模拟器实验<sup>[185-186]</sup>验证了上述方法在多种储罐几何构型和多方向地震输入下的适用性。变分解法<sup>[187]</sup>的引入进一步将地震晃荡分析的适用范围从立式圆柱储罐拓展至卧式圆柱和球形工业压力容器等石化行业中的主流储罐<sup>[10]</sup>。

福岛核事故推动核乏燃料水池晃荡成为独立的安全专题。Chai等<sup>[188]</sup>针对事故工况下的溅出量估算提出了改进方案,Zhao等<sup>[144]</sup>发现独立式储存架虽通过流固耦合增强了系统阻尼,但同时引起的局部流动收缩使壁面压力增大,揭示了减晃与增载之间的工程权衡关系。Cheng<sup>[189]</sup>和Chen<sup>[190]</sup>等为上述分析提供了基准实验数据。在先进反应堆方向,土壤-结构相互作用、晃荡的耦合效应<sup>[191]</sup>,以及惯容器基底隔震系统<sup>[192]</sup>的引入,将抗震设计从单一的结构响应分析拓展至土-液-结构一体化动力学框架。Sacki等<sup>[193]</sup>记录的水

平注入射流自激晃荡现象与应急冷却注入场景直接对应,补充了晃荡激励源多样性方面的实验证据。

地震与核安全领域的晃荡研究因全球地震活跃带内液体储存基础设施的庞大存量与失效后果的严重性而长期受到关注。核安全维度还面临一项特殊挑战:大量现有设施的设计标准制定于晃荡动力学机制尚未被充分认识的时代,这意味着存在庞大的存量设施需要重新评估并进行抗震或减晃改造。

### 2.1.4 浮式生产与储存系统

与地震激励的突发性不同,浮式生产系统面临的是晃荡载荷在长服役周期中的持续累积效应。浮式生产储卸油装置(FPSO)坞修间隔可达数年,其间始终以部分充装的货油舱和压载舱运行,使晃荡成为贯穿结构全生命周期的设计要素。Igbadumhe等<sup>[19]</sup>通过FPSO纯横摇衰减实验发现,低充液比反而提供了更高的等效线性阻尼,其中立方阻尼项的贡献尤为突出,这一反直觉的结论对优化操作压载策略具有直接指导意义。Liu等<sup>[20]</sup>对干式与湿式储存方案进行了系统比较,结果表明:湿式储存技术在结构安全和动力稳定性方面均占优势,其油水界面展现出复杂的旋转波动力学特征<sup>[158]</sup>;自由衰减实验已测定了系统的黏性阻尼率,并确认了重力-毛细波在特定激励条件下的出现。Hu等<sup>[194]</sup>利用全非线性势流理论(FNPT)与CFD耦合方法分析了系泊FPSO在极端波浪下的动力响应,验证了数值工具在预测全海况下浮式生产系统运动特性方面的可靠性。

浮式生产系统的减晃需求并非单一优化目标,而是与系泊设计、运动控制及作业窗口等多重约束深度耦合,须在考虑系统整体性能框架下完成综合权衡。

## 2.2 晃荡的工程利用

将晃荡的物理认识转化为可工程化的分析工具,等效力学模型扮演着关键角色。这类模型通过将复杂的晃荡动力学行为约化为机械系统参数,为姿态控制与振动抑制提供了可量化的设计输入。该框架已应用于飞艇气体晃荡、惯容器隔离储液罐,以及航天器耦合动力学等领域。在工程层面,这些方法指向一个共同的思路:主动利用晃荡动力学特性实现振动控制与能量耗散,而非单纯抑制其破坏性载荷。其核心策略在于,将液舱的晃荡固有频率调谐至目标结构的振动频率附近,使结构振动能量通过频率匹配转移至液体晃荡运动,再借助波浪破碎和壁面黏性耗散实现衰减。正是基于这一物理原理,晃荡利用已从陆地与海上结构的振动控制延伸至海岸防波堤消浪,从海上可再生资源装备拓展至深远海养殖设施,形成了一个一系列利用晃荡动力学的工程应用场景(图6)。

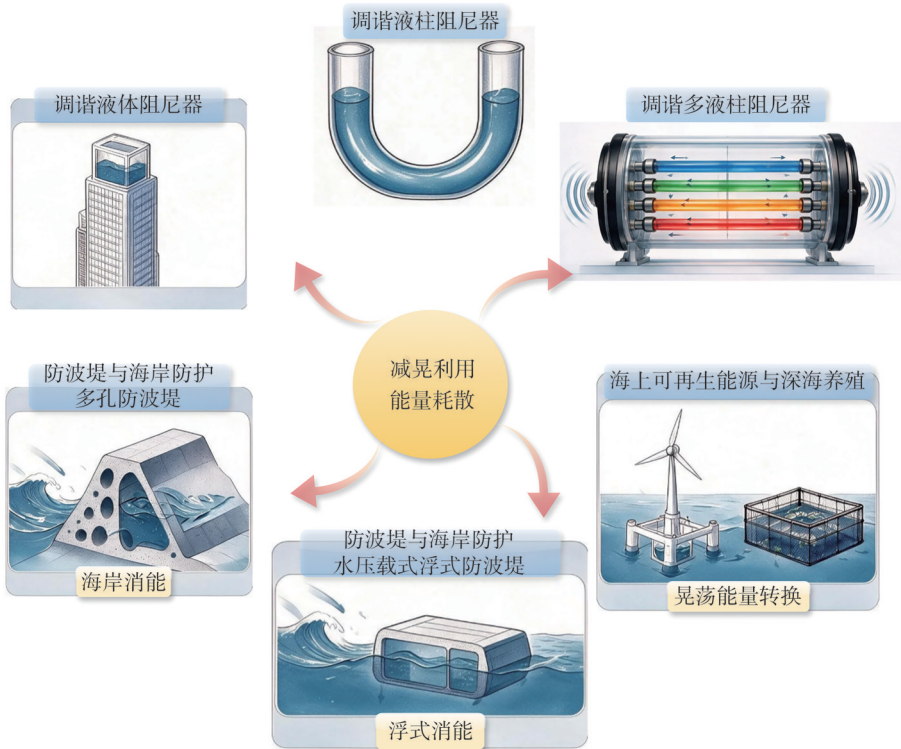


图 6 晃荡动力学的有益工程应用场景

Fig. 6 Beneficial engineering application scenarios of liquid sloshing dynamics

### 2.2.1 陆地与海上结构振动控制

前述减晃手段旨在抑制液舱内部的破坏性载荷,而另一类工程思路则主动将晃荡动力学转化为结构振动的控制机制,其中调谐液体阻尼器(TLD)是最成熟的实现方式,其原理是将液舱晃荡固有频率调谐至结构主振频率附近,使结构振动能量通过波浪破碎与壁面黏性耗散得以消散。TLD结构简单、无须外部能源,尤其适用于地震和风致振动等窄带激励场景;调谐液柱阻尼器(TLCD)与调谐多液柱阻尼器(TLMCD)则进一步将这一思路拓展至海上光伏支撑结构减振与浮式风机减摇<sup>[164-165]</sup>。TLD及其衍生装置的理论建模与工程应用已较为成熟<sup>[17-18,39-40]</sup>,可参见Zheng等<sup>[25]</sup>的综述。

### 2.2.2 防波堤与海岸防护

防波堤与海岸防护工程也可利用有晃荡提升其效能。与TLD通过液舱内部集中质量实现单点减振不同,充填压载水的浮式防波堤利用液舱内部的晃荡非线性阻尼和相位共振效应衰减入射波浪。Yuan等<sup>[166]</sup>开展了水槽实验,结果表明,与充填沙子的传统方案相比,充填压载水的设计使波浪透射系数最多降低21.1%,能量耗散系数提高达84.4%。这一工作揭示了内部晃荡动力学在浮式防波堤波浪衰减中的关键作用,为深水区域海上光伏场的防护提供了新的设计范式。Zhang等<sup>[195]</sup>进一步研究了压载浮式防波堤在波浪中的动力响应,水槽实验与小波变换分析表明,防波

堤在固有频率与入射波频率附近反应剧烈,纵摇运动比垂荡运动更易受充水率影响,为压载防波堤的充水率设计提供了依据。

在液舱内部防晃构型方面,Cho等<sup>[196]</sup>研究了水平多孔挡板在纵荡-横摇矩形液舱中的防晃效应,George等<sup>[197]</sup>通过解析与实验相结合的方法对类似构型进行了系统验证。这一技术路径的延伸推动了多功能海上结构物的发展,OWC与防波堤的一体化设计<sup>[168,198-199]</sup>使波浪能转换与海岸防护功能得以在同一结构中协同实现,其中,气室内水柱的垂向晃荡与气动阻尼的匹配决定了能量提取效率<sup>[200-201]</sup>。多相SPH模拟<sup>[94]</sup>、翼板数值方法<sup>[202]</sup>及波浪能转换器的数值建模与仿真<sup>[203-204]</sup>的进展,进一步将浮式防波堤、波浪能转换器和海上风机基础纳入全耦合分析框架。

防波堤领域的晃荡研究具有超越海岸工程自身的意义。随着海上可再生能源的扩张和海平面上升引起的海岸防护压力增加,对可靠且经济的消浪系统的需求日益增长。在此背景下,波浪能转换与海岸防护功能的一体化设计为同时满足消浪与发电双重需求提供了可行路径,有望在降低全寿命周期成本的同时提升海上结构的多功能复合效益。

### 2.2.3 海上可再生能源

海上可再生能源装备的运行不可避免地涉及液体晃荡问题。浮式海上风力发电机(FOWT)半潜式基

础立柱内的压载水在波浪激励下产生晃荡,直接影响平台的稳性和运动响应;OWC波能转换器气室内水柱的往复振荡,本质上是一种垂直方向的晃荡运动。Cheng<sup>[205]</sup>和Liu<sup>[206]</sup>等分别发展了FOWT全耦合气动-水动力数值模型;Chen等<sup>[207]</sup>将系泊动力学与CFD耦合,为分析浮式风机基础内部的液体晃荡效应提供了计算框架。在减摇方面,TLMCD将多液柱晃荡耦合机制引入FOWT俯仰控制<sup>[165]</sup>,TLCD则在弹性支撑结构减振中验证了晃荡被动阻尼对结构振动的抑制效果<sup>[164]</sup>。

波浪能转换器中的内部液体运动与晃荡动力学具有天然的物理联系。Zhang等<sup>[94]</sup>开发的多相SPH模型实现了OWC与防波堤集成系统的全耦合模拟,揭示了气室内水柱晃荡与外部波浪间的相位耦合机制。Cheng等<sup>[167]</sup>对混合OWC-振荡浮子系统的水动力分析表明,内部水柱的共振晃荡可显著增强波能提取效率。Penalba等<sup>[204]</sup>将数值波浪水槽与功率输出模型耦合,建立了从水动力晃荡到电力输出的全链路仿真能力。这些进展表明,晃荡动力学方法正从传统的液舱内部拓展至海上可再生能源装备的系统级水动力分析与优化设计。

#### 2.2.4 深远海养殖设施

深远海养殖设施是晃荡动力学与海洋生物学交叉的前沿领域,其核心在于利用晃荡的动力学认识主动调控液舱内部流场,而非单纯抑制。Tao等<sup>[169,208]</sup>针对双排液舱养殖工船开展了系统的试验与数值研究,发现当液舱横向晃荡的固有周期小于船体横摇固有周期的一半时,双排液舱布置可将内部晃荡与船体运动有效解耦,这一准则为养殖工船的液舱设计提供了基础依据。Bai等<sup>[170]</sup>研究了过流式养殖工船的双向耦合效应,船体侧开孔减小了排水体积与惯性矩,在衰减纵摇和垂荡响应的同时,开孔处形成的涡旋结构被动调控了舱内水流,实现了晃荡激励与水体交换的功能整合。Wiegerink等<sup>[209-210]</sup>提出的晃荡抑制块代表了一条不同的技术路径,该方案在自由液面位置设置物理屏障,以收缩有效自由液面面积,同时保持舱内作业体积不变,使晃荡动能被限制在抑制块上方耗散,为下部鱼群保留低流动能的栖息水体。在封闭式养殖网箱方面,Tsarau等<sup>[211]</sup>研究了网箱内带缓慢旋转液体的晃荡,发现旋转流动可分裂非旋转液体的固有频率并产生新的晃荡模态,足够高的旋转角速度还能部分抑制固有频率附近的剧烈晃荡,为循环水流与波浪诱导晃荡的相互作用提供了认识。

在生物响应层面,Dong等<sup>[212]</sup>首次系统研究了鱼类在晃荡暴露下的生理与代谢反应,发现皮质醇、乳酸和葡萄糖等生化指标随晃荡强度显著升高,脂质与

氨基酸代谢通路出现差异表达,从而确立了晃荡参数与鱼类应激响应之间的定量关联,为生物-流体-结构耦合分析框架的建立提供了关键实验数据。在微藻养殖方面,Chen等<sup>[213]</sup>提出了利用海洋波浪驱动液舱晃荡来混合微藻的被动式养殖方案,通过在液舱内设置水平挡板产生涡旋脱落增强颗粒混合,大幅降低传统机械搅动的电力消耗。集成FOWT-水产养殖求解器<sup>[214]</sup>则将上述晃荡动力学模块与海上风机气动模型耦合,为多功能海上结构物的协同设计提供了分析工具。

### 3 学科交叉与研究前沿

前文的梳理表明:晃荡研究在物理机制层面已建立起从线性共振、非线性多模态耦合到多物理场耦合的递进认识框架;在工程应用层面则以减晃和利用晃荡两条主线覆盖了航天推进剂管理、LNG运输安全、地震与核安全、浮式生产系统、陆地与海上结构振动控制、防波堤与海岸防护、海上可再生能源,以及深远海养殖设施等典型场景。这些进展在各自领域内已达到较高的成熟度,但也逐渐显露出传统水动力学框架在面对强非线性实时预测、极端温区多物理场耦合、新型材料减晃机制和多尺度跨介质问题时的内在局限。正是这些局限,催生了若干处于学科交叉地带的前沿方向。以下从数据驱动建模、低温氢能多物理场、仿生表面减晃、非牛顿流体晃荡和尺度效应5个方面展开论述。

将机器学习融入晃荡研究是当前最重要的方法学进展之一。从机制研究角度看,强共振条件下阻尼的准确定量描述和多物理场耦合带来的高昂计算成本,是传统方法面临的两项核心困难,而数据驱动方法恰好能够在这些方面发挥互补优势。Moya等<sup>[22]</sup>证明了通用晃荡动力学可直接从数据中学习,物理信息神经网络(PINN)则通过将控制方程嵌入网络损失函数实现了对晃荡问题的无网格求解。双PINN变体<sup>[23]</sup>和基于PINN的航天器晃荡分析<sup>[215]</sup>进一步将这一范式拓展至波型预测和参数推断。Liu等<sup>[24]</sup>基于数据增强方法建立了地震激励下晃荡高度的智能预测模型。算子学习框架,如DeepONet和傅里叶神经算子(FNO)在晃荡领域仍未被探索,代表了具有巨大潜力的方向。在主动控制层面,Konopka<sup>[216]</sup>与Le<sup>[217]</sup>等工作展示了从抑制容器内部晃荡到通过优化运动规划预防晃荡激发的思路转变,快速晃荡模型<sup>[218]</sup>则为数字孪生框架提供了支撑技术。从应用需求的角度审视,数据驱动方法最核心的贡献体现在实时预测能力的突破上。主动控制系统要求毫秒级响应,而高保真计

算流体力学模拟的典型耗时则高出数个数量级。物理-数据混合架构正是在这一精度与速度的结构性矛盾中可行的中间路线。

低温热力学与水动力学的耦合研究已在 LNG 晃荡中建立了从相变机理、传热增强到 BOG 生成量预测的定量分析框架,但其适用参数区间本质上受限于 LNG 的物性条件。液氢的出现将问题推向了全新的物理区间。液氢的邦德数较 LNG 低一个量级,潜热仅为其 1/6,晃荡行为处于重力与表面张力共同主导的过渡区间,传统弗劳德相似准则面临失效。晃荡动力学的特征时间在秒级,隔热系统的热扩散过程则跨越小时至天级的范围,两种尺度间的悬殊差距给多尺度建模带来了根本性困难。Liu 等<sup>[61]</sup>指出,晃荡诱导的混合对液氢储罐热分层的破坏效应不可忽视。面向这一挑战,数字孪生范式集成了实时传感器数据与纳入相变的降阶晃荡模型,为 LNG、氢和氨等多种低温介质提供运行决策支持,代表了从单一工况工程预测向多介质、多尺度、自适应运行决策跃迁的前沿方向。

在材料科学与晃荡的交叉前沿,仿生表面工程正在开辟无挡板被动减晃的新途径。受猪笼草液体稳定机制和睡莲冲击缓冲凹槽的双重启发,一种采用 3D 打印构建并辅以超疏水涂层的双仿生杯设计<sup>[219]</sup>,通过图案化亲水-超疏水边界与超疏水凹槽的协同效应,实现了自由液面的稳定与振荡能量的被动耗散。该设计在离心、振动及实际运输测试中均达到了近零溢溅水平,搭载该设计的车辆连续通过 50 个减速带后仍可近乎全部保留液体,而对照实验中的常规容器损失超过 40%。这一设计思路可向液舱减晃推广,其核心策略在于,通过调控内壁微纳结构与化学组成,来主动干预接触线动力学和壁面滑移条件,从而在不引入任何内部附加构件的前提下实现被动减晃。在航天微重力场景中,仿生表面的润湿梯度还可被动调控推进剂爬升形态与晃荡模态的能量分布。该方向的核心科学问题在于,阐明晃荡条件下动态接触角迟滞与自由液面大变形的耦合机制,以及评估表面微结构在长期浸没和冲击载荷下的耐久性。

非牛顿流体晃荡是具有广泛工程潜力的新兴方向。食品酱料储运、化工高分子溶液处理、钻井液晃动和医疗悬浮液输送等工业场景均涉及剪切变稀、剪切增稠、黏弹性及屈服应力等非牛顿流体在部分充装容器中的晃荡运动。与牛顿流体不同,非牛顿流体的有效黏度随剪切率和剪切历史动态变化,这一本构差异导致其阻尼机制、共振频率偏移及自由液面变形特性发生本质改变。初步研究表明<sup>[220]</sup>,采用非牛顿本构模型可更准确地刻画矿浆类流体的晃荡特性及其与挡

板的相互作用。目前的瓶颈在于,黏弹性非牛顿流体中弹性应力与晃荡运动的双向耦合机理几乎未被触及,该领域仍缺乏系统的理论框架和基准实验数据。填补这些空白,是推动晃荡研究从理想牛顿流体向真实工业工质延伸的前提。

晃荡的尺度效应<sup>[25]</sup>是连接实验室机理研究与工程设计之间的长期悬置问题。基于弗劳德相似准则的传统缩尺模型实验在黏性耗散、表面张力和湍流特征等依赖雷诺数和韦伯数的物理过程上存在根本性不相似<sup>[221]</sup>,这一矛盾在低温 LNG 和液氢晃荡中尤为尖锐。

## 4 结论与展望

本文从物理机制、工程应用和前沿方向三大维度对液体晃荡研究进行了系统梳理。在机制层面,数十年来积累的线性共振与模态结构、非线性多模态耦合及多物理场耦合等认识,构成了发展晃荡抑制技术和晃荡利用技术的共同基础;双层液体系统、强共振区间动力学和低温多物理场耦合则是当前机制研究最为活跃的前沿方向。在应用层面,以减晃和晃荡利用两条主线组织的研究图景表明,航天推进剂管理、LNG 运输安全和地震与核安全是减晃需求最为迫切的安全关键领域,而调谐液体阻尼器、防波堤与海岸防护及海上可再生能源等方向则代表了利用晃荡动力学的典型工程范式。在方法层面,解析与半解析方法、计算流体力学方法和实验方法三者构成了互为补充的方法论工具箱,共同支撑着从基础机理到工程设计的完整认知链条。

基于本文分析,可提炼出若干跨领域研究趋势。基于物理的建模与数据驱动方法的融合代表了当前的主导方向,而晃荡研究向氢经济、深远海养殖等新场景的延伸,以及仿生表面工程、非牛顿流体力学等学科的渗透,正在从根本上重塑这一问题定义和研究范式。生物-流体-结构耦合、材料科学和实验相似理论等跨学科视角的引入,不仅带来了传统晃荡工程未曾面对的设计约束,也同时打开了新的减晃策略空间。可以预见,计算能力的持续进步与数据科学方法的深度介入将加速这一学科交叉进程。低温多物理场耦合的机器学习多保真度建模、面向瞬时载荷预测的算子学习框架、仿生表面减晃技术及跨尺度验证数据集的构建等议题,有望在未来几年内受到持续关注。将这些来自不同学科的方法学进展与日益丰富的工程应用场景相结合,可为液体晃荡研究注入持续的发展动力。

## 参考文献:

- [1] Faltinsen O M, Timokha A N. A multimodal method for liquid sloshing in a two-dimensional circular tank[J]. *Journal of Fluid Mechanics*, 2010, 665: 457–479.
- [2] Akyildiz H, Ünal E. Experimental investigation of pressure distribution on a rectangular tank due to the liquid sloshing[J]. *Ocean Engineering*, 2005, 32(11/12): 1503–1516.
- [3] Song Y K, Chang Kuangan, Ryu Y, et al. Experimental study on flow kinematics and impact pressure in liquid sloshing[J]. *Experiments in Fluids*, 2013, 54(9): 1592.
- [4] Lee S J, Kim M H, Lee D H, et al. The effects of LNG-tank sloshing on the global motions of LNG carriers[J]. *Ocean Engineering*, 2007, 34(1): 10–20.
- [5] Kim S Y, Kim Y, Park J J, et al. Experimental study of sloshing load on LNG tanks for unrestricted filling operation[J]. *Journal of Advanced Research in Ocean Engineering*, 2017, 3(1): 41–52.
- [6] Zhang Yali, Liang Hui, Chua K H, et al. Experimental and numerical analysis of resonant sloshing flow in a membrane tank of different filling levels[J]. *Ocean Engineering*, 2022, 263: 112337.
- [7] Wu Wenjun, Yue Baozeng, Huang Hua. Coupling dynamic analysis of spacecraft with multiple cylindrical tanks and flexible appendages[J]. *Acta Mechanica Sinica*, 2016, 32(1): 144–155.
- [8] Deng Mingle, Yue Baozeng. Attitude tracking control of flexible spacecraft with large amplitude slosh[J]. *Acta Mechanica Sinica*, 2017, 33(6): 1095–1102.
- [9] Song Xiaojuan, Yue Baozeng, Wu Wenjun. Investigation on attitude disturbance control and vibration suppression for fuel-filled flexible spacecraft[J]. *Acta Mechanica Sinica*, 2015, 31(4): 581–588.
- [10] Karamanos S A, Patkas L A, Platyrachos M A. Sloshing effects on the seismic design of horizontal-cylindrical and spherical industrial vessels[J]. *Journal of Pressure Vessel Technology*, 2006, 128(3): 328–340.
- [11] Maleki A, Ziyaeifar M. Sloshing damping in cylindrical liquid storage tanks with baffles[J]. *Journal of Sound and Vibration*, 2008, 311(1/2): 372–385.
- [12] Xue Mi'an, Jiang Zhouyu, Lin Pengzhi, et al. Sloshing dynamics in cylindrical tank with porous layer under harmonic and seismic excitations[J]. *Ocean Engineering*, 2021, 235: 109373.
- [13] Xue Mi'an, Jiang Zhouyu, Hu Ya'an, et al. Numerical study of porous material layer effects on mitigating sloshing in a membrane LNG tank[J]. *Ocean Engineering*, 2020, 218: 108240.
- [14] Ren Yaru, Xue Mi'an, Lin Pengzhi. Experimental study of sloshing characteristics in a rectangular tank with elastic baffles[J]. *Journal of Fluids and Structures*, 2023, 122: 103984.
- [15] Ren Yaru, Ye Mai, Lin Pengzhi. An effective sloshing mitigation method using a PID-controlled elastic baffle[J]. *Ocean Engineering*, 2025, 341: 122673.
- [16] Yu Yumin, Ma Ning, Fan Sheming, et al. Experimental and numerical studies on sloshing in a membrane-type LNG tank with two floating plates[J]. *Ocean Engineering*, 2017, 129: 217–227.
- [17] Love J S, Haskett T C. Nonlinear modelling of tuned sloshing dampers with large internal obstructions: Damping and frequency effects[J]. *Journal of Fluids and Structures*, 2018, 79: 1–13.
- [18] Tait M J, El Damatty A A, Isyumov N. An investigation of tuned liquid dampers equipped with damping screens under 2D excitation[J]. *Earthquake Engineering & Structural Dynamics*, 2005, 34(7): 719–735.
- [19] Igbadumhe J F, Sallam O, Fürth M, et al. Experimental determination of non-linear roll damping of an FPSO pure roll coupled with liquid sloshing in two-row tanks[J]. *Journal of Marine Science and Engineering*, 2020, 8(8): 582.
- [20] Liu Dongxi, Cai Wenjuan, Lu Tianze. Comparative assessment of liquid sloshing in dry and wet storage tank of floating offshore platform[J]. *Marine Structures*, 2023, 90: 103425.
- [21] Zhao Dongya, Hu Zhiqiang, Chen Gang, et al. Coupling analysis between vessel motion and internal nonlinear sloshing for FLNG applications[J]. *Journal of Fluids and Structures*, 2018, 76: 431–453.
- [22] Moya B, Gonzalez D, Alfaro I, et al. Learning slosh dynamics by means of data[J]. *Computational Mechanics*, 2019, 64(2): 511–523.
- [23] Huang Yinghao, Xu Zheng, Qian Yinghao, et al. Solving free-surface problems for non-shallow water using boundary and initial conditions-free physics-informed neural network (bif-PINN) [J]. *Journal of Computational Physics*, 2023, 479: 112003.
- [24] Liu Qinqin, Wang Zhiyu, Qin Yiyi, et al. Intelligent prediction of seismically-induced sloshing heights based on data augmentation[J]. *Ocean Engineering*, 2025, 339: 122130.
- [25] Zheng Jinhai, Xue Mi'an, Dou Peng, et al. A review on liquid sloshing hydrodynamics[J]. *Journal of Hydrodynamics*, 2021, 33(6): 1089–1104.
- [26] Lukovsky I A, Timokha A N. Multimodal method in sloshing[J]. *Journal of Mathematical Sciences*, 2017, 220(3): 239–253.
- [27] Kolaei A, Rakheja S, Richard M J. Range of applicability of the linear fluid slosh theory for predicting transient lateral slosh and roll stability of tank vehicles[J]. *Journal of Sound and Vibration*, 2014, 333(1): 263–282.

- [28] Sygulski R. Boundary element analysis of liquid sloshing in baffled tanks[J]. *Engineering Analysis with Boundary Elements*, 2011, 35(8): 978–983.
- [29] Hasheminejad S M, Mohammadi M M, Jarrahi M. Liquid sloshing in partly-filled laterally-excited circular tanks equipped with baffles[J]. *Journal of Fluids and Structures*, 2014, 44: 97–114.
- [30] Hasheminejad S M, Aghabeigi M. Liquid sloshing in half-full horizontal elliptical tanks[J]. *Journal of Sound and Vibration*, 2009, 324(1/2): 332–349.
- [31] Hasheminejad S M, Aghabeigi M. Transient sloshing in half-full horizontal elliptical tanks under lateral excitation[J]. *Journal of Sound and Vibration*, 2011, 330(14): 3507–3525.
- [32] Hasheminejad S M, Aghabeigi M. Sloshing characteristics in half-full horizontal elliptical tanks with vertical baffles[J]. *Applied Mathematical Modelling*, 2012, 36(1): 57–71.
- [33] Hasheminejad S M, Mohammadi M M. Effect of anti-slosh baffles on free liquid oscillations in partially filled horizontal circular tanks[J]. *Ocean Engineering*, 2011, 38(1): 49–62.
- [34] Lü Jing, Wang Shimin, Wang Tianshu. Coupling dynamic analysis of a liquid-filled spherical container subject to arbitrary excitation[J]. *Acta Mechanica Sinica*, 2012, 28(4): 1154–1162.
- [35] Takahara H, Kimura K. Frequency response of sloshing in an annular cylindrical tank subjected to pitching excitation[J]. *Journal of Sound and Vibration*, 2012, 331(13): 3199–3212.
- [36] Cho I H, Kim M H. Effect of dual vertical porous baffles on sloshing reduction in a swaying rectangular tank[J]. *Ocean Engineering*, 2016, 126: 364–373.
- [37] Goudarzi M A, Sabbagh-Yazdi S R. Analytical and experimental evaluation on the effectiveness of upper mounted baffles with respect to commonly used baffles[J]. *Ocean Engineering*, 2012, 42: 205–217.
- [38] Portela de Medeiros Oliveira Albuquerque F, Coutinho da Silva V, von Borries Lopes A. Sloshing in triangular basins[J]. *Wave Motion*, 2026, 146: 103754.
- [39] Li Yuchun, Wang Zhuang. An approximate analytical solution of sloshing frequencies for a liquid in various shape aqueducts[J]. *Shock and Vibration*, 2014, 2014(1): 672648.
- [40] Das A, Maity D, Bhattacharyya S K. Characterization of liquid sloshing in U-shaped containers as dampers in high-rise buildings[J]. *Ocean Engineering*, 2020, 210: 107462.
- [41] Xue Mi'an, Chen Yichao, Zheng Jinhai, et al. Fluid dynamics analysis of sloshing pressure distribution in storage vessels of different shapes[J]. *Ocean Engineering*, 2019, 192: 106582.
- [42] Xue Mi'an, Ye Zhanghan, Cao Zhanxue, et al. Dynamic characteristics of liquid sloshing in a spherical liquid tank[J]. *Physics of Fluids*, 2025, 37(7): 072123.
- [43] Timokha A N, Lukovsky I A. Modal modeling of nonlinear fluid sloshing in tanks with non-vertical walls. non-conformal mapping technique[J]. *International Journal of Fluid Mechanics Research*, 2002, 29(2): 27.
- [44] Faltinsen O M, Firoozkoobi R, Timokha A N. Analytical modeling of liquid sloshing in a two-dimensional rectangular tank with a slat screen[J]. *Journal of Engineering Mathematics*, 2011, 70(1): 93–109.
- [45] Faltinsen O M, Firoozkoobi R, Timokha A N. Steady-state liquid sloshing in a rectangular tank with a slat-type screen in the middle: Quasilinear modal analysis and experiments[J]. *Physics of Fluids*, 2011, 23(4): 042101.
- [46] Wei Zhijun, Faltinsen O M, Lugni C, et al. Sloshing-induced slamming in screen-equipped rectangular tanks in shallow-water conditions[J]. *Physics of Fluids*, 2015, 27(3): 032104.
- [47] Saltari F, Pizzoli M, Coppotelli G, et al. Experimental characterisation of sloshing tank dissipative behaviour in vertical harmonic excitation[J]. *Journal of Fluids and Structures*, 2022, 109: 103478.
- [48] Marcotte A, Gallaire F, Bongarzone A. Super-harmonically resonant swirling waves in longitudinally forced circular cylinders[J]. *Journal of Fluid Mechanics*, 2023, 966: A41.
- [49] Colville S W, Sclan Y M, Gambioli F, et al. Faraday waves and period tripling in a horizontal circular tank[J]. *Journal of Fluid Mechanics*, 2025, 1006: A4.
- [50] Herczyński A, Weidman P D. Experiments on the periodic oscillation of free containers driven by liquid sloshing[J]. *Journal of Fluid Mechanics*, 2012, 693: 216–242.
- [51] Reclari M, Dreyer M, Tissot S, et al. Surface wave dynamics in orbital Shaken cylindrical containers[J]. *Physics of Fluids*, 2014, 26(5): 052104.
- [52] Bardazzi A, Lugni C, Faltinsen O M, et al. Different scenarios in sloshing flows near the critical filling depth[J]. *Journal of Fluid Mechanics*, 2024, 984: A73.
- [53] Fang Haiqi, Lin Pengzhi. The near-resonance liquid sloshing under surge excitations: Theory and experiment[J]. *Proceedings of the Royal Society A (Mathematical, Physical and Engineering Sciences)*, 2025, 481(2312): 20240814.
- [54] Bäuerlein B, Avila K. Phase lag predicts nonlinear response maxima in liquid-sloshing experiments[J]. *Journal of Fluid Mechanics*, 2021, 925: A22.
- [55] Constantin L, De Courcy J, Titurus B, et al. Nonlinear damping effects in vertically vibrating systems with violently sloshing liquid[J]. *Journal of Sound and Vibration*, 2023, 544: 117405.
- [56] Jeon G M, Jeong S M, Park J C. Experimental and numerical investigation of the influences of sloshing motion on the change in boil-off gas/boil-off rate in a cryogenic liq-

- uid tank[J].*Ocean Engineering*,2024,298:117173.
- [57] Chen Han,Xu Peng,Wan Zhong,et al.Analysis of convection and boil-off in multi-scale membrane LNG tanks under sloshing excitations[J].*Applied Thermal Engineering*,2025,259:124863.
- [58] Wu Sixian,Ju Yonglin.Numerical study of the boil-off gas (BOG) generation characteristics in a type C independent liquefied natural gas(LNG) tank under sloshing excitation[J].*Energy*,2021,223:120001.
- [59] Wu Sixian,Ju Yonglin.Numerical study on pressure drops and thermal response of cryogenic fuel storage tanks under sinusoidal sloshing excitation[J].*International Journal of Hydrogen Energy*,2023,48(93):36523–36540.
- [60] Li Cong,Zhao Zhongchao,Ding Jiahui,et al.Numerical study of thermodynamic and hydrodynamics in a type B LNG cargo tank during sloshing excitation[J].*Applied Thermal Engineering*,2024,247:123048.
- [61] Liu Zhan,Feng Yuyang,Lei Gang,et al.Fluid thermal stratification in a non-isothermal liquid hydrogen tank under sloshing excitation[J].*International Journal of Hydrogen Energy*,2018,43(50):22622–22635.
- [62] Peters A,el Moctar O.Effects of phase transition and fluid properties on sloshing-induced impact pressures[J].*Journal of Fluid Mechanics*,2025,1020:A27.
- [63] Storey J M,Kirk D R.Experimental investigation of spherical tank slosh dynamics with water and liquid nitrogen[J].*Journal of Spacecraft and Rockets*,2020,57(5):930–944.
- [64] Pistani F,Thiagarajan K.Experimental measurements and data analysis of the impact pressures in a sloshing experiment[J].*Ocean Engineering*,2012,52:60–74.
- [65] Bulian G,Botia–Vera E,Souto–Iglesias A.Experimental sloshing pressure impacts in ensemble domain: Transient and stationary statistical characteristics[J].*Physics of Fluids*,2014,26(3):032102.
- [66] Thome M,el Moctar O,Schellin T E.Hydroelastic effects on hydrodynamic loads on an LNG pump tower structure[J].*Ocean Engineering*,2024,307:118224.
- [67] Wang Jiadong,Zhou Ding,Liu Weiqing.Coupled response of liquid in a rigid cylindrical container equipped with an elastic annular baffle[J].*Meccanica*,2016,51(9):2045–2058.
- [68] Wang Jiadong,Liu Jinxing,Wang Dan.Coupled responses in a partially liquid-filled cylindrical tank with the single flexible baffle under pitching excitations[J].*Shock and Vibration*,2019,2019(1):9854187.
- [69] Wang Jiadong,Zhou Ding.Coupled responses of partially liquid-filled container with multielastic annular baffles under lateral excitations[J].*Journal of Aerospace Engineering*,2018,31(6):04018102.
- [70] Zhao Chenxi,Wu Yan, Yu Yongchuan,et al.A unified FSI framework for modeling liquid sloshing and baffle suppression in the elastic tank[J].*Applied Ocean Research*,2025,157:104498.
- [71] Meng Xun,Zhou Ding, Kim M K,et al.Free vibration and dynamic response analysis of liquid in a rectangular rigid container with an elastic baffle[J].*Ocean Engineering*,2020,216:108119.
- [72] Brietman N L,Suponitsky V,Bar–Yoseph P Z.Nonlinear liquid sloshing dynamics in upright circular cylindrical containers with FSI effects: Post-processing of conventional finite element solutions by digital filters[J].*Ocean Engineering*,2024,309:118510.
- [73] Khouf L,Benaouicha M,Seghir A,et al.Numerical modeling of liquid sloshing in flexible tank with FSI approach[J].*World Journal of Engineering*,2023,20(1):131–142.
- [74] Parasil W,Watanabe N.Nonlinear dynamic analysis of the interaction between a two-dimensional rubberlike membrane and a liquid in a rectangular tank[J].*Aerospace Science and Technology*,2016,56:212–222.
- [75] Ren Yaru,Khayyer A,Lin Pengzhi,et al.Numerical modeling of sloshing flow interaction with an elastic baffle using SPHinXsys[J].*Ocean Engineering*,2023,267:113110.
- [76] Park T,Park C J,Lee J,et al.Experimental observation on violent sloshing flows inside rectangular tank with flexible baffles[J].*Applied Ocean Research*,2025,154:104307.
- [77] Luo Maojun,Xue Mi'an,Yuan Xiaoli,et al.Experimental and numerical study of stratified sloshing in a tank under horizontal excitation[J].*Shock and Vibration*,2021,2021(1):6639223.
- [78] Liu Dongming,Wu Yang,Lin Pengzhi.An experimental study of two-layer liquid sloshing under pitch excitations[J].*Physics of Fluids*,2022,34(5):052112.
- [79] Liu Dongxi,Lu Tianze,Cai Wenjuan,et al.Experimental study on the sloshing of a three-layer liquid system with a free surface[J].*Ocean Engineering*,2023,279:114422.
- [80] Cao Zhanxue,Xue Mi'an,Zheng Jinhai,et al.Semi-analytical study on liquid sloshing in a two-dimensional rectangular tank with a vertical porous baffle[J].*Ocean Engineering*,2025,331:121377.
- [81] La Rocca M,Sciortino G,Adduce C,et al.Experimental and theoretical investigation on the sloshing of a two-liquid system with free surface[J].*Physics of Fluids*,2005,17(6):062101.
- [82] Kuznetsov N G.On direct and inverse spectral problems for sloshing of a two-layer fluid in an open container[J].*Nano-systems:Physics,Chemistry,Mathematics*,2016,7(5):854–864.
- [83] Cao Zhanxue,Xue Mi'an,Zheng Jinhai,et al.Semi-analytical

- solution on three-layer liquid sloshing in the rectangular tank with bed topography[J]. *Ocean Engineering*, 2025, 331: 121247.
- [84] Wang Jiadong, Gao Jiading, Sun Ying. Semi-analytical method for liquid sloshing in the rigid super-elliptical tank with the ring baffle[J]. *Ocean Engineering*, 2023, 281: 114718.
- [85] Shen Ruiyang, Lyu Jing, Wang Shimin. A variational domain decomposition scheme for the natural sloshing modes in the baffled tanks[J]. *Journal of Sound and Vibration*, 2021, 494: 115855.
- [86] Shen Ruiyang, Lyu Jing, Wang Shimin, et al. Variational domain decomposition scheme for linear Stokes–Joukowski potentials of fluid in baffled tanks[J]. *Acta Mechanica Sinica*, 2022, 38(4): 521387.
- [87] Zhang Chongwei, Li Donghai, Xie Zhigang, et al. Transient resonance of sloshing liquid with time-varying mass[J]. *Physics of Fluids*, 2024, 36(6): 067108.
- [88] Xue Mi'an, Lin Pengzhi. Numerical study of ring baffle effects on reducing violent liquid sloshing[J]. *Computers & Fluids*, 2011, 52: 116–129.
- [89] Qi Yan, Söding H, el Mactar O, et al. A three-dimensional fully linear finite difference approach to predict waves in tanks excited by ship motions[J]. *Ocean Engineering*, 2024, 302: 117391.
- [90] Qi Yan, Söding H, Stöcker J, et al. Prediction of waves in tanks excited by ship motion and moving walls with a three-dimensional fully linear finite difference approach[J]. *Ocean Engineering*, 2024, 310: 118648.
- [91] English A, Domínguez J M, Vacondio R, et al. Modified dynamic boundary conditions(mDBC) for general-purpose smoothed particle hydrodynamics(SPH): Application to tank sloshing, dam break and fish pass problems[J]. *Computational Particle Mechanics*, 2022, 9(5): 1–15.
- [92] Jiao Jialong, Zhao Mingming, Jia Guangyan, et al. SPH simulation of two side-by-side LNG ships' motions coupled with tank sloshing in regular waves[J]. *Ocean Engineering*, 2024, 297: 117022.
- [93] Jiao Jialong, Ding Shang, Zhao Mingming, et al. Simulation of LNG ship's motions coupled with tank sloshing in regular waves by DualSPHysics[J]. *Ocean Engineering*, 2024, 312: 119148.
- [94] Zhang Yifan, Pan Jiapeng, Song Mengxia, et al. A multi-phase SPH model for simulating the floating OWC-breakwater integrated systems[J]. *Coastal Engineering*, 2025, 197: 104658.
- [95] Wang Shengzhe, Chuang Weiliang. Dynamic analysis of breaking wave impact on a floating offshore wind turbine via smoothed particle hydrodynamics[J]. *Marine Structures*, 2025, 100: 103731.
- [96] Cao X Y, Ming F R, Zhang A M. Sloshing in a rectangular tank based on SPH simulation[J]. *Applied Ocean Research*, 2014, 47: 241–254.
- [97] Cao X Y, Tao L, Zhang A M, et al. Smoothed particle hydrodynamics(SPH) model for coupled analysis of a damaged ship with internal sloshing in beam seas[J]. *Physics of Fluids*, 2019, 31(3): 032103.
- [98] Shao J R, Li H Q, Liu G R, et al. An improved SPH method for modeling liquid sloshing dynamics[J]. *Computers & Structures*, 2012, 100: 18–26.
- [99] He Kunpeng, Zhu Huiling, Ye Jianhong. An integrated model for fluid-structure-seabed interaction based on SPH–FEM: Validation and a practical engineering application[J]. *Ocean Engineering*, 2024, 313: 119636.
- [100] Zhang Z L, Khalid M S U, Long T, et al. Investigations on sloshing mitigation using elastic baffles by coupling smoothed finite element method and decoupled finite particle method[J]. *Journal of Fluids and Structures*, 2020, 94: 102942.
- [101] Zhang Z L, Khalid M S U, Long T, et al. Improved element-particle coupling strategy with  $\delta$ -SPH and particle shifting for modeling sloshing with rigid or deformable structures[J]. *Applied Ocean Research*, 2021, 114: 102774.
- [102] Khayyer A, Tsuruta N, Shimizu Y, et al. Multi-resolution MPS for incompressible fluid-elastic structure interactions in ocean engineering[J]. *Applied Ocean Research*, 2019, 82: 397–414.
- [103] Zha Ruosi, Peng Heather, Qiu Wei. An improved higher-order moving particle semi-implicit method for simulations of two-dimensional hydroelastic slamming[J]. *Physics of Fluids*, 2021, 33(3): 037104.
- [104] Zhang Youlin, Wan Decheng. MPS-FEM coupled method for sloshing flows in an elastic tank[J]. *Ocean Engineering*, 2018, 152: 416–427.
- [105] Zhang Guiyong, Wu Jinxin, Sun Zhe, et al. Numerically simulated flooding of a freely-floating two-dimensional damaged ship section using an improved MPS method[J]. *Applied Ocean Research*, 2020, 101: 102207.
- [106] Sun Z, Zhang G Y, Zong Z, et al. Numerical analysis of violent hydroelastic problems based on a mixed MPS-mode superposition method[J]. *Ocean Engineering*, 2019, 179: 285–297.
- [107] Li Jinlong, You Yunxiang, Chen Ke, et al. Numerical computations of resonant sloshing using the modified isoAd-vector method and the buoyancy-modified turbulence closure model[J]. *Applied Ocean Research*, 2019, 93: 101829.
- [108] Devolder B, Rauwoens P, Troch P. Application of a buoyancy-modified  $k$ - $\omega$  SST turbulence model to simulate wave run-up around a monopile subjected to regular waves using

- OpenFOAM®[J].Coastal Engineering,2017,125:81–94.
- [109]Zhao Yucheng,Chen Hamn–ching.Numerical simulation of 3D sloshing flow in partially filled LNG tank using a coupled level-set and volume-of-fluid method[J].Ocean Engineering,2015,104:10–30.
- [110]Huang Peng.A comprehensive investigation on liquid sloshing of rectangular water tank with vertical baffles[J].Ocean Engineering,2023,288:116126.
- [111]Akyildiz H,Erdem Ünal N.Sloshing in a three-dimensional rectangular tank: Numerical simulation and experimental validation[J].Ocean Engineering,2006,33(16):2135–2149.
- [112]Zang Quansheng,Zhang Bei,Zhong Yanhui,et al.Nonlinear analysis of liquid sloshing in containers under pitching load with scaled boundary finite element method[J].Computers & Structures,2025,315:107791.
- [113]Zang Quansheng,Zhong Yanhui,Ye Wenbin,et al.A NURBS-enhanced semi-analytical method for nonlinear liquid sloshing analysis in liquid storage structures with various baffles[J].Engineering Analysis with Boundary Elements,2025,173:106155.
- [114]Liu Jun,Zang Quansheng,Yang Fan,et al.Performance assessment of internal porous structures on liquid sloshing in various 3D tanks by multi-domain IGABEM[J].Applied Mathematics and Computation,2023,438:127621.
- [115]Lyu Wenjing,Riesner M,Peters A,et al.A hybrid method for ship response coupled with sloshing in partially filled tanks[J].Marine Structures,2019,67:102643.
- [116]Lyu Wenjing,el Moctar O,Schellin T E.Ship motion-sloshing interaction using a field method[J].Marine Structures,2021,76:102923.
- [117]Jiang Shengchao,Teng Bin,Bai Wei,et al.Numerical simulation of coupling effect between ship motion and liquid sloshing under wave action[J].Ocean Engineering,2015,108:140–154.
- [118]Jiao Jialong,Huang Songxing,Wang Shan,et al.A CFD-FEA two-way coupling method for predicting ship wave loads and hydroelastic responses[J].Applied Ocean Research,2021,117:102919.
- [119]Tabri K,Matusiak J,Varsta P.Sloshing interaction in ship collisions—An experimental and numerical study[J].Ocean Engineering,2009,36(17/18):1366–1376.
- [120]Rubesh Raja V,Ponnusamy P.Numerical modelling of nonlinear baffles on sloshing suppression of rectangular tanks under horizontal excitation[J].Ocean Engineering,2023,267:113277.
- [121]Akyildiz H.A numerical study of the effects of the vertical baffle on liquid sloshing in two-dimensional rectangular tank[J].Journal of Sound and Vibration,2012,331(1):41–52.
- [122]Sanapala V S,Selvaraj T,Ananthasivan K,et al.Numerical simulation of wave impact and high pressure characteristics due to violent sloshing in a rectangular tank[J].Ships and Offshore Structures,2024,19(5):625–643.
- [123]Saghi R,Saghi H.Numerical simulation of half-full cylindrical and bi-lobed storage tanks against the sloshing phenomenon[J].Ocean Engineering,2022,266:112896.
- [124]Lu Tianze,Cao Deping.SPH study of sloshing dynamics and energy dissipation characteristics in baffled tanks with varying baffle quantities[J].Ocean Engineering,2025,340:122378.
- [125]Capasso S,Tagliafierro B,Martínez–Estévez I,et al.Development of an SPH-based numerical wave-current tank and application to wave energy converters[J].Applied Energy,2025,377:124508.
- [126]Capasso S,Shahroozi Z,Göteman M,et al.SPH-based modeling of a direct-drive WEC in extreme waves and currents[J].Applied Ocean Research,2025,165:104808.
- [127]Cao Zhanxue,Xue Mi'an,Xu Guohui,et al.Experimental and numerical study on effects of different excitations and liquid levels on sloshing in a large-scale LNG tank[J].Ocean Engineering,2024,308:118343.
- [128]Brown S A,Colville S W,Francis V,et al.A blind comparative study on isothermal sloshing in a circular tank(CCP-WSI Blind Test Series 5)[J].Ocean Engineering,2026,362:126290.
- [129]Pal N C,Bhattacharyya S K,Sinha P K.Experimental investigation of slosh dynamics of liquid-filled containers[J].Experimental Mechanics,2001,41(1):63–69.
- [130]Pal P,Bhattacharyya S K.Sloshing in partially filled liquid containers—Numerical and experimental study for 2-D problems[J].Journal of Sound and Vibration,2010,329(21):4466–4485.
- [131]Souto–Iglesias A,Botia–Vera E,Martín A,et al.A set of canonical problems in sloshing.Part 0:Experimental setup and data processing[J].Ocean Engineering,2011,38(16):1823–1830.
- [132]Souto–Iglesias A,Bulian G,Botia–Vera E.A set of canonical problems in sloshing.Part 2:Influence of tank width on impact pressure statistics in regular forced angular motion[J].Ocean Engineering,2015,105:136–159.
- [133]Panigrahy P K,Saha U K,Maiti D.Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks[J].Ocean Engineering,2009,36(3/4):213–222.
- [134]He Yihang,Tang Lian,Lin Pengzhi.PIV study of turbu-

- lence characteristics in resonant sloshing within a rectangular tank with a vertical perforated baffle[J]. *Ocean Engineering*, 2026, 343: 123529.
- [135] Erdogan B, Kocaman S. A novel MAX-MIN image-based measurement approach for experimental analysis of passive sloshing control[J]. *Ocean Engineering*, 2026, 364: 126946.
- [136] Yuan Bo, Du Xiangyu, Liang Shuya, et al. A rapid reconstruction method for pressure loads in nonlinear liquid sloshing[J]. *Ocean Engineering*, 2026, 355: 125102.
- [137] Cavallagli N, Biscarini C, Facci A L, et al. Experimental and numerical analysis of energy dissipation in a sloshing absorber[J]. *Journal of Fluids and Structures*, 2017, 68: 466–481.
- [138] Constantin L, Titurus B, Rendall T C S, et al. Experimental analysis of liquid vertical slosh damping at vacuum and atmospheric pressures[J]. *Journal of Sound and Vibration*, 2024, 574: 118228.
- [139] Agresta A, Cavallagli N, Biscarini C, et al. Effect of bottom geometry on the natural sloshing motion of water inside tanks: An experimental analysis[J]. *Applied Sciences*, 2021, 11(2): 605.
- [140] Frosina E, Senatore A, Andreozzi A, et al. Experimental and numerical analyses of the sloshing in a fuel tank[J]. *Energies*, 2018, 11(3): 682.
- [141] Lee J, Ahn Y, Kim Y. Experimental study on effect of density ratio and phase transition during sloshing impact in rectangular tank[J]. *Ocean Engineering*, 2021, 242: 110105.
- [142] Ning Dezhi, Su Peng, Zhang Chongwei. Experimental study on a sloshing mitigation concept using floating layers of solid foam elements[J]. *China Ocean Engineering*, 2019, 33(1): 34–43.
- [143] Shen Limin, Liu Peng, Feng Jiamin, et al. Experimental investigation of multi-floating structures for suppressing hydroelastic slamming in a shallow-water sloshing tank[J]. *Physics of Fluids*, 2026, 38: 012103.
- [144] Zhao Fei, Liu Yu, Zhu Yuxuan, et al. Experimental investigation on liquid sloshing in a water tank containing free-standing structures[J]. *Ocean Engineering*, 2024, 303: 117740.
- [145] Park T, Hwang J, Kim Y, et al. Experimental study on sloshing flow in cylindrical tanks with internal structures[J]. *Journal of Hydrodynamics*, 2026, 38(2): 285–296.
- [146] Xie Fei, Liu Yu, Zhu Yuxuan, et al. Experimental, theoretical, and numerical investigation on sloshing behavior in annular sector containers[J]. *Physics of Fluids*, 2024, 36(10): 102109.
- [147] Li Yiran, Liu Dongxi, Wang Jin. Experimental investigation on the sloshing dynamics of first- and super-harmonic resonances in a rectangular tank with and without a vertical baffle[J]. *Applied Ocean Research*, 2024, 153: 104315.
- [148] Liu Dongxi, Cai Qiyang, Li Yiran, et al. Experimental study of primary- and higher-mode resonant sloshing in a horizontally excited square-base tank[J]. *Applied Ocean Research*, 2025, 156: 104482.
- [149] Liu Dongxi, Chang Fangyuan, Chen Yujiao. Experimental study of vertical baffle height on sloshing reduction effects in the rectangular tank[J]. *Ocean Engineering*, 2025, 335: 121674.
- [150] Liu Dongxi, Zhu Hui, Wang Jin. Experimental study on the influence of vertical baffles on liquid sloshing in a horizontal cylindrical tank[J]. *Aerospace Science and Technology*, 2026, 172: 111665.
- [151] Peng Peng, Gao Zhenguo, Li Xianshu, et al. Experimental study of sloshing flows in a rectangular tank under coupled pitch and heave excitations[J]. *Ocean Engineering*, 2024, 309: 118544.
- [152] Zhang Zhen, Wu Qiaorui, Xie Yonghe, et al. Experimental and numerical investigations on the liquid tank sloshing in regular waves[J]. *Ocean Engineering*, 2023, 271: 113668.
- [153] Xue Mi'an, Zheng Jinhai, Lin Pengzhi, et al. Experimental study on vertical baffles of different configurations in suppressing sloshing pressure[J]. *Ocean Engineering*, 2017, 136: 178–189.
- [154] Yu Liting, Xue Mi'an, Jiang Zhouyu. Experimental investigation of parametric sloshing in a tank with vertical baffles[J]. *Ocean Engineering*, 2020, 213: 107783.
- [155] Yu Liting, Xue Mi'an, Zheng Jinhai. Experimental study of vertical slat screens effects on reducing shallow water sloshing in a tank under horizontal excitation with a wide frequency range[J]. *Ocean Engineering*, 2019, 173: 131–141.
- [156] Lu Jintao, Jin Heng, Xue Mi'an, et al. Experimental investigation of the effect of the floating damping baffle on liquid tank sloshing under vertical excitation[J]. *Applied Ocean Research*, 2024, 147: 103976.
- [157] Qi Yan, La Ferlita A, Neugebauer J, et al. A physics- and data-based method for sloshing active control[J]. *Physics of Fluids*, 2025, 37(9): 095113.
- [158] Liu Dongxi, Wang Xiaoying, Chen Yujiao. An experimental study of three-dimensional separation surface sloshing in the wet storage tank of a floating offshore platform[J]. *Journal of Marine Science and Engineering*, 2024, 12(4): 558.
- [159] Liu Dongxi, Li Yiran, Cai Wenjuan, et al. Experimental investigation on the three-dimensional liquid sloshing behavior in an offshore circular cylindrical container[J]. *Ocean Engineering*, 2024, 313: 119426.
- [160] Shi Y Y, Yuan S L, Li Z F. Fluid sloshing in a partially ice-covered rectangular tank[J]. *Ocean Engineering*, 2026, 364:

- 126947.
- [161] Aly A M, Raizah Z A S, Sheikholeslami M. Analysis of mixed convection in a sloshing porous cavity filled with a nanofluid using ISPH method[J]. *Journal of Thermal Analysis and Calorimetry*, 2020, 139(3): 1977–1991.
- [162] Jung J H, Yoon H S, Lee C Y, et al. Effect of the vertical baffle height on the liquid sloshing in a three-dimensional rectangular tank[J]. *Ocean Engineering*, 2012, 44: 79–89.
- [163] Akyıldız H, Erdem Ünal N, Aksoy H. An experimental investigation of the effects of the ring baffles on liquid sloshing in a rigid cylindrical tank[J]. *Ocean Engineering*, 2013, 59: 190–197.
- [164] Xue Mi'an, Hu Xiaoping, Hu Ya'an, et al. Experimental and numerical study on dynamic response of a photovoltaic support structural platform with a U-shaped tuned liquid column damper[J]. *Ocean Engineering*, 2024, 311: 118908.
- [165] Xue Mi'an, Dou Peng, Zheng Jinhai, et al. Pitch motion reduction of semisubmersible floating offshore wind turbine substructure using a tuned liquid multicolumn damper[J]. *Marine Structures*, 2022, 84: 103237.
- [166] Yuan Xiaoli, Cao Zhanxue, Xue Mi'an, et al. Experimental study on effects of floating breakwater filled with ballast water on wave attenuation[J]. *Ocean Engineering*, 2025, 341: 122720.
- [167] Cheng Yong, Du Weiming, Dai Saishuai, et al. Hydrodynamic characteristics of a hybrid oscillating water column-oscillating buoy wave energy converter integrated into a  $\pi$ -type floating breakwater[J]. *Renewable and Sustainable Energy Reviews*, 2022, 161: 112299.
- [168] Cheng Yong, Du Weiming, Dai Saishuai, et al. Wave energy conversion by an array of oscillating water columns deployed along a long-flexible floating breakwater[J]. *Renewable and Sustainable Energy Reviews*, 2024, 192: 114206.
- [169] Tao Yanwu, Zhu Renqing, Gu Jiayang, et al. Experimental and numerical investigation of the hydrodynamic response of an aquaculture vessel[J]. *Ocean Engineering*, 2023, 279: 114505.
- [170] Bai Chenguang, Zhang Jianing, Peng Zekun, et al. Bidirectionally coupled sloshing of a flow-through aquaculture vessel with side openings in waves[J]. *Ocean Engineering*, 2026, 351: 124287.
- [171] Zhu Aimeng, Xue Mi'an, Yuan Xiaoli, et al. Effect of double-side curved baffle on reducing sloshing in tanks under surge and pitch excitations[J]. *Shock and Vibration*, 2021, 2021(1): 6647604.
- [172] Jin Heng, Liu Yong, Li Huajun. Experimental study on sloshing in a tank with an inner horizontal perforated plate[J]. *Ocean Engineering*, 2014, 82: 75–84.
- [173] Yang Dandan, Yue Baozeng, Wu Wenjun, et al. Attitude maneuver of liquid-filled spacecraft with a flexible appendage by momentum wheel[J]. *Acta Mechanica Sinica*, 2012, 28(2): 543–550.
- [174] Yan Yulong, Yue Baozeng. Analytical method for the attitude stability of partially liquid filled spacecraft with flexible appendage[J]. *Acta Mechanica Sinica*, 2017, 33(1): 208–218.
- [175] Dalmon A, Lepilliez M, Tanguy S, et al. Comparison between the FLUIDICS experiment and direct numerical simulations of fluid sloshing in spherical tanks under microgravity conditions[J]. *Microgravity Science and Technology*, 2019, 31(1): 123–138.
- [176] Chiba M, Shigematsu S, Motoyama N. Theoretical and experimental study on the effect of plane diaphragm tension on hydroelastic coupled vibrations in a hemispherical tank[J]. *Journal of Fluids and Structures*, 2022, 113: 103632.
- [177] Wu Ji, Zhang Dingguo, Li Liang, et al. Dynamics analysis of a rigid-flexible-liquid coupled satellite antenna system via absolute nodal coordinate formulation curvature continuity constraints[J]. *Aerospace Science and Technology*, 2024, 144: 108814.
- [178] Hunt A, Foster–Turner R, Drury R. Propellant slosh force and mass measurement[J]. *International Journal of Aerospace Engineering*, 2018, 2018(1): 3026872.
- [179] He Yuanjun, Ma Xingrui, Wang Pingping, et al. Low-gravity liquid nonlinear sloshing analysis in a tank under pitching excitation[J]. *Journal of Sound and Vibration*, 2007, 299(1/2): 164–177.
- [180] Wang Zihao, Wang Yunhe, Jiang Shengchao. Coupling actions between ship roll motion and internal sloshing with water and LNG inside[J]. *Journal of Marine Science and Application*, 2025, 24(6): 1194–1207.
- [181] Barabadi S, Iranmanesh A, Passandideh–Fard M, et al. A numerical study on mitigation of sloshing in a rectangular tank using floating foams[J]. *Ocean Engineering*, 2023, 277: 114267.
- [182] Odoom J K, Xue Mi'an, Otoo E. Mitigation of liquid sloshing in tanks using high-density solid foam spheres: A numerical modeling approach[J]. *European Journal of Mechanics-B/Fluids*, 2025, 114: 204331.
- [183] Zheng Miaozi, Ni Yang, Wu Chengsheng, et al. Experimental investigation on effect of sloshing on ship added resistance in head waves[J]. *Ocean Engineering*, 2021, 235: 109362.
- [184] Housner G W. Dynamic pressures on accelerated fluid containers. *Bulletin of the seismological society of America*, 1957, 47(1), 15–35.

- [185] Rawat A, Mittal V, Chakraborty T, et al. Earthquake induced sloshing and hydrodynamic pressures in rigid liquid storage tanks analyzed by coupled acoustic-structural and Euler-Lagrange methods[J]. *Thin-Walled Structures*, 2019, 134:333–346.
- [186] Mir F U H, Yu C C, Whittaker A S. Experimental and numerical studies of seismic fluid-structure interaction in a base-supported cylindrical vessel[J]. *Earthquake Engineering & Structural Dynamics*, 2021, 50(5):1395–1413.
- [187] Patkas L A, Karamanos S A. Variational solutions for externally induced sloshing in horizontal-cylindrical and spherical vessels[J]. *Journal of Engineering Mechanics*, 2007, 133(6): 641–655.
- [188] Chai J F, Lin Fanru, Hsu W H, et al. Experimental study on seismic sloshing of storage water for spent fuel pool in NPPs[J]. *Nuclear Engineering and Design*, 2025, 445:114531.
- [189] Cheng Songbai, Li Shuo, Li Kejia, et al. A two-dimensional experimental investigation on the sloshing behavior in a water pool[J]. *Annals of Nuclear Energy*, 2018, 114:66–73.
- [190] Chen Y H, Hwang W S, Ko C H. Sloshing behaviours of rectangular and cylindrical liquid tanks subjected to harmonic and seismic excitations[J]. *Earthquake Engineering & Structural Dynamics*, 2007, 36(12):1701–1717.
- [191] Yin Xunqiang, Chen Xu, Xu Shutong. Seismic performance analysis of suspended storage structure in lead-based reactor considering the coupled effects of liquid sloshing and soil condition[J]. *Nuclear Engineering and Design*, 2025, 435: 113935.
- [192] Jiang Yiyao, Zhao Zhipeng, Zhang Ruifu, et al. Optimal design based on analytical solution for storage tank with interter isolation system[J]. *Soil Dynamics and Earthquake Engineering*, 2020, 129:105924.
- [193] Sacki S, Madarame H, Okamoto K. Self-induced sloshing excited by a horizontally injected plane jet[J]. *Journal of Fluid Mechanics*, 2001, 448:81–114.
- [194] Hu Zhengzheng, Yan Shiqiang, Greaves D, et al. Investigation of interaction between extreme waves and a moored FPSO using FNPT and CFD solvers[J]. *Ocean Engineering*, 2020, 206:107353.
- [195] Zhang Zhen, Tao Aifeng, Wu Qiaorui, et al. Wave to the dynamic response of the ballast floating breakwater[J]. *Ocean Engineering*, 2024, 305:117915.
- [196] Cho I H, Choi J S, Kim M H. Sloshing reduction in a swaying rectangular tank by an horizontal porous baffle[J]. *Ocean Engineering*, 2017, 138:23–34.
- [197] George A, Cho I H. Anti-slosh effect of a horizontal porous baffle in a swaying/rolling rectangular tank: Analytical and experimental approaches[J]. *International Journal of Naval Architecture and Ocean Engineering*, 2021, 13:833–847.
- [198] Cheng Yong, Xi Chen, Dai Saishuai, et al. Wave energy extraction and hydroelastic response reduction of modular floating breakwaters as array wave energy converters integrated into a very large floating structure[J]. *Applied Energy*, 2022, 306:117953.
- [199] Zhang Hengming, Zhou Binzhen, Vogel C, et al. Hydrodynamic performance of a dual-floater hybrid system combining a floating breakwater and an oscillating-buoy type wave energy converter[J]. *Applied Energy*, 2020, 259:114212.
- [200] Zhou Yu, Ning Dezhi, Shi Wei, et al. Hydrodynamic investigation on an OWC wave energy converter integrated into an offshore wind turbine monopile[J]. *Coastal Engineering*, 2020, 162:103731.
- [201] Elhanafi A, MacFarlane G, Fleming A, et al. Investigations on 3D effects and correlation between wave height and lip submergence of an offshore stationary OWC wave energy converter[J]. *Applied Ocean Research*, 2017, 64:203–216.
- [202] Yuan Hongsheng, Zhang Hongzhou, Wang Guanyu, et al. A numerical study on a winglet floating breakwater: Enhancing wave dissipation performance[J]. *Ocean Engineering*, 2024, 309:118532.
- [203] Finnegan W, Rosa-Santos P, Taveira-Pinto F, et al. Development of a numerical model of the CECO wave energy converter using computational fluid dynamics[J]. *Ocean Engineering*, 2021, 219:108416.
- [204] Penalba M, Davidson J, Windt C, et al. A high-fidelity wave-to-wire simulation platform for wave energy converters: Coupled numerical wave tank and power take-off models[J]. *Applied Energy*, 2018, 226:655–669.
- [205] Cheng Ping, Huang Yang, Wan Decheng. A numerical model for fully coupled aero-hydrodynamic analysis of floating offshore wind turbine[J]. *Ocean Engineering*, 2019, 173:183–196.
- [206] Liu Yuanchuan, Xiao Qing, Incecik A, et al. Establishing a fully coupled CFD analysis tool for floating offshore wind turbines[J]. *Renewable Energy*, 2017, 112:280–301.
- [207] Chen Haifei, Hall M. CFD simulation of floating body motion with mooring dynamics: Coupling MoorDyn with OpenFOAM[J]. *Applied Ocean Research*, 2022, 124:103210.
- [208] Tao Yanwu, Zhu Renqing, Gu Jiayang, et al. Sloshing response of an aquaculture vessel: An experimental study[J]. *Journal of Marine Science and Engineering*, 2023, 11(11): 2122.
- [209] Wiegerink J J, Baldock T E, Callaghan D P, et al. Slosh Suppression Blocks—A concept for mitigating fluid motions in floating closed containment fish pen in high energy en-

- vironments[J]. *Applied Ocean Research*, 2022, 120: 103068.
- [210] Wiegerink J J, Baldock T E, Callaghan D P, et al. Experimental study on hydrodynamic response of a floating rigid fish tank model with slosh suppression blocks[J]. *Ocean Engineering*, 2023, 273: 113772.
- [211] Tsarau A, Lugni C, Lucarelli A, et al. Sloshing in a rotating liquid inside a closed sea cage for fish farming[J]. *Physics of Fluids*, 2021, 33(3): 037114.
- [212] Dong Ruiguang, Song Xiefa, Chang Zongyu, et al. Physiology and metabolomics characteristic of rainbow trout juveniles (*Oncorhynchus mykiss*) response to fish cabin sloshing[J]. *Aquaculture*, 2026, 625: 744269.
- [213] Chen B F, Yang H K, Wu C H, et al. Numerical study of liquid mixing in microalgae-farming tanks with baffles[J]. *Ocean Engineering*, 2018, 161: 168–186.
- [214] Cai Yefeng, Zhao Haisheng, Li Xin, et al. Developing an OpenFOAM solver for coupled aero-hydrodynamic analysis of integrated structure with floating offshore wind turbine and aquaculture net cage[J]. *Coastal Engineering*, 2025, 198: 104720.
- [215] Huo Jiawei, Yue Chengfei, Wang Tianshu, et al. Analysis of liquid sloshing in liquid-filled spacecraft by physics-informed neural network[J]. *IFAC-PapersOnLine*, 2025, 59(20): 1515–1520.
- [216] Konopka M, De Rose F, Strauch H, et al. Active slosh control and damping—Simulation and experiment[J]. *Acta Astronautica*, 2019, 158: 89–102.
- [217] Le D T, Dao Q T. ACO-optimized S-curve trajectory and HTSMC-PPC-ESO control for robust sloshing suppression in liquid transportation using a biglide parallel robot[J]. *European Journal of Control*, 2026, 91: 101555.
- [218] Godderidge B. A phenomenological rapid sloshing model for use as an operator guidance system on liquefied natural gas carriers[D]. Southampton: University of Southampton, 2009.
- [219] Ma Jie, Zhan Zidong, Zhang Zihao, et al. Bioinspired wettability boundary stabilizes water sloshing[J]. *Science Advances*, 2025, 11(46): eadz7099.
- [220] Zhang Jianwei, Wu Wanqing, Hu Junquan. A numerical study of the effects of the longitudinal baffle on nickel ore slurry sloshing in a prismatic cargo hold[J]. *Marine Structures*, 2016, 46: 149–166.
- [221] Kim S Y, Kim K H, Kim Y. Comparative study on model-scale sloshing tests[J]. *Journal of Marine Science and Technology*, 2012, 17(1): 47–58.

### 【校友简介】



林鹏智, 四川大学教授, 欧洲科学与艺术学院院士, 国家杰出青年科学基金获得者, 教育部高层次人才奖励计划特聘教授, 天府杰出科学家。现任山区河流保护与治理全国重点实验室副主任, *Applied Ocean Research* 主编。长期从事计算流体动力学(CFD)及其在水利、海岸与海洋工程中的应用研究, 如水灾害模拟与防治、基于自然解决方案的海岸韧性提升、海洋可再生能源评估、极端环境下水工结构安全等。发表SCI收录论文200余篇, 出版中英文专著3部, 引用11 000余次。研究成果获教育部自然科学奖一等奖1项、广西自然科学奖二等奖1项。2016至今连续入选Elsevier水利工程与海洋工程“中国高被引学者”。

## Liquid Sloshing and Its Engineering Applications

QI Yan<sup>1,2</sup>, XUE Mi'an<sup>1,2</sup>, LIN Pengzhi<sup>3\*</sup>

(1. Key Laboratory of Coastal Disaster and Protection of Ministry of Education, Hohai University, Nanjing 210024, China;

2. College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing 210024, China;

3. State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China)

### Abstract:

**Significance** Liquid sloshing refers to the free surface oscillation of a liquid within a partially filled container subjected to external excitation. Its dynamics range from linear standing waves governed by potential flow theory to weakly nonlinear multimodal interactions and violent, strongly nonlinear motions accompanied by wave breaking, spray, and gas–liquid entrainment. Under near-resonant conditions, impact pressures can exceed hydrostatic pressures by several orders of magnitude. This spectrum is governed by dimensionless parameters, including the Froude, Bond, and Reynolds numbers and the depth-to-length ratio, which collectively influence the transitions between distinct flow regimes. Because partially filled containers are ubiquitous in aerospace, marine, mechanical, and chemical engineering, liquid sloshing has destructive and exploitable implications. On the destructive side, membrane-type liquefied natural gas (LNG) carriers are susceptible to sloshing-induced impact damage near 50% filling under cryogenic conditions; propellant sloshing can couple with flexible spacecraft structures, alter natural frequencies, and lead to underestimation of the control torque required by attitude con-

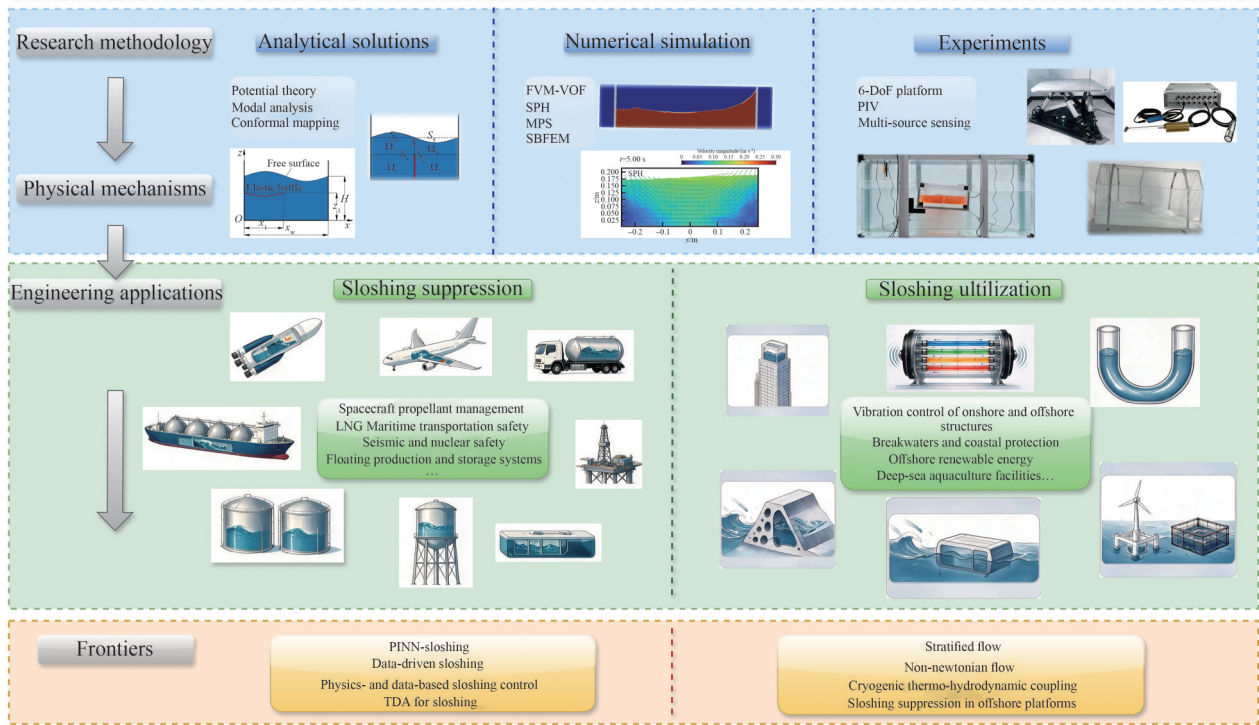
trol systems; and liquid storage tanks must withstand impulsive hydrodynamic and convective sloshing components, as illustrated by tank failures during the 1964 Alaska and 1999 Kocaeli earthquakes. On the exploitable side, tuned liquid dampers (TLDs) utilize sloshing to control structural vibrations, while phase coupling among waves, floating bodies, and internal sloshing has been exploited to control the motions of floating production, storage, and offloading units, semisubmersible platforms, and floating wind turbine foundations. These dual implications underscore the engineering significance of liquid sloshing research.

**Progress** Drawing upon 220 publications, this review summarizes the progress of liquid sloshing research along three complementary lines. Mechanistically, the linear potential flow framework provides the dispersion relation and natural modal structure of partially filled tanks, which form an orthogonal basis for describing free surface motion and predicting resonance in preliminary design. This framework has been extended from simple rectangular tanks to elliptical, spherical, annular, and aqueduct-shaped geometries. Nonlinear multimodal methods further capture amplitude-dependent frequency shifts, internal resonance, modal energy transfer, subcritical bifurcations, and parametric resonance phenomena such as Faraday waves. These studies demonstrate that resonance can occur within parameter ranges considered safe by linear theory and that impact regimes can emerge abruptly through subcritical bifurcation without obvious precursors. Multiphysics coupling effects have also been progressively clarified. Cryogenic thermodynamics influences the generation of boil-off gas (BOG) through sloshing-enhanced mixing and heat transfer; fluid-structure interaction with elastic baffles can introduce additional natural frequencies below the lowest sloshing mode, creating potential resonance risks; and density stratification in layered liquids substantially alters the modal structure through buoyancy-driven coupling. In two-layer and multilayer systems, the density ratio governs the intensity of interfacial wave excitation, while internal interfaces can attain amplitudes comparable to those of the free surface and exhibit beating phenomena absent in homogeneous liquids. Methodologically, analytical and semi-analytical approaches based on potential flow assumptions, computational fluid dynamics (CFD) techniques, including the volume-of-fluid (VOF), smoothed particle hydrodynamics (SPH), and moving particle semi-implicit (MPS) methods, and model experiments employing particle image velocimetry (PIV) and multisource synchronous sensing have evolved into a complementary toolbox. Nevertheless, accurate representation of damping remains a common challenge across these approaches. In engineering practice, sloshing suppression has been pursued using rigid, perforated, porous, elastic, and floating baffles, as well as active control, with applications in spacecraft propellant management, LNG maritime transportation safety, seismic and nuclear safety, including nuclear spent fuel pools, and floating production and storage systems. In parallel, sloshing utilization has been developed through TLDs, tuned liquid column dampers (TLCDs), and tuned multi-liquid-column dampers (TLMCDs) for structural vibration control; ballast water-filled floating breakwaters that exploit nonlinear damping and phase resonance associated with internal sloshing to reduce wave transmission; oscillating water column (OWC) wave energy converters, in which the internal water column undergoes oscillatory motion analogous to vertical sloshing; and aquaculture vessels, in which sloshing dynamics are regulated to decouple internal liquid motion from hull motion. At the interdisciplinary frontier, data-driven modeling using physics-informed neural networks and operator learning frameworks, such as DeepONet and Fourier neural operators, together with extensions to liquid hydrogen and ammonia supported by digital twin paradigms, bio-inspired surface suppression strategies, non-Newtonian fluid sloshing, and sloshing scale effects, has emerged as a set of research directions with the potential to reshape the field.

**Conclusions and Prospects** The accumulated understanding of linear resonance, nonlinear multimodal coupling, and multiphysics interactions provides a common foundation for sloshing suppression and utilization, with analytical methods, computational fluid dynamics, and model experiments forming an interdependent methodological toolbox. Nevertheless, several challenges remain unresolved, including the accurate prediction of sloshing loads under strongly nonlinear conditions involving wave breaking and gas-liquid entrainment; the development of mitigation techniques that remain effective across broadband excitation, a wide range of filling levels, and diverse tank geometries; and the establishment of comprehensive cross-scale validation datasets linking laboratory experiments with full-scale design conditions. Sloshing suppression and utilization are also not strictly opposed: Under certain conditions, internal sloshing can reduce ship motion amplitudes and added resistance, suggesting the existence of an exploitable intermediate regime. Future research should focus on integrating physics-based modeling with data-driven methods, developing multifidelity models for cryogenic multiphysics coupling, applying operator learning frameworks for real-time load prediction, developing bio-inspired baffle-free suppression strategies, and establishing robust cross-scale validation. Interdisciplinary perspectives, including bio-fluid-structure interaction, materials science, and experimental similarity theory, may provide new strategies for sloshing suppression and accelerate the translation of fundamental sloshing research into safe, economical, and sustainable engineering solutions.

**Key words:** liquid sloshing; multi-physics coupling; sloshing suppression; sloshing utilization

Graphical abstract:



(编辑 张 琼)

引用格式: Qi Yan, Xue Mi'an, Lin Pengzhi. Liquid sloshing and its engineering applications[J]. Advanced Engineering Sciences, 2026, 58(5): 280–301. [戚岩, 薛米安, 林鹏智. 液体晃荡及其工程应用[J]. 工程科学与技术, 2026, 58(5): 280–301.]