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评 述
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# 静水压下水声吸声材料研究进展

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**摘要** 随着声呐技术的快速发展, 潜艇等水下装备的声隐身要求变得越来越高. 水声吸声材料是实现水下装备声隐身的重要手段之一, 多年来持续受到广泛研究. 相比空气声, 水下声波传播更快、波长更长, 低频有效吸声更加困难. 此外, 水下装备的下潜深度逐步增大, 水声材料需要承受很大的静水压力. 已有研究表明, 静水压力对吸声材料的声学性能影响显著, 实现高静水压下低频宽带吸声的材料设计是该领域的技术难题, 需进一步深化吸声机理分析和优化设计工作. 本文首先介绍了当前水声吸声材料在静水压下的分析方法, 总结了材料的主流吸声机理以及静水压力对吸声的影响, 并从材料设计方面综述了抗静水压吸声材料的研究现状, 最后展望了静水压力下吸声材料的研究趋势和挑战, 以期推动静水压下水声吸声材料的发展.

**关键词** 水声吸声材料, 抗静水压, 吸声机理, 分析方法, 材料设计

声波是进行水下远距离探测、通讯的有效手段. 随着水下声呐技术的快速发展, 水下装备的声隐身性能变得越来越重要. 为了对抗声呐探测, 降低水下装备被发现的概率, 通过声隐身技术控制水下声场从而改变水下装备声目标特性, 是提高水下装备生存能力的重要手段[1]. 水下声呐探测主要包括被动声呐和主动声呐两方面[2]. 水下装备在航行过程中存在机械和水动力等噪声源, 被动声呐能够探测到水下装备噪声源向水中辐射的噪声, 从而对水下装备进行定位; 主动声呐则通过发射指向性强的声波并接收回波, 不仅能够对航行的水下装备进行精确定位, 对静止不动的水下装备同样有效, 弥补了被动声呐的不足. 针对主动声呐探测, 通常采用的方法是在水下装备壳体外表面贴覆水声吸声材料, 可以有效降低水下装备的声目标强度[3].

为了达到良好吸声性能, 水声吸声材料的表面声阻抗应与水的特性阻抗相匹配, 使得大部分声波能量顺利进入材料内部; 同时, 水声吸声材料应有高效的声波耗散能力, 能最大限度地耗散材料内部声能[4]. 为满足阻抗匹配要求, 橡胶材料[5,6]和聚氨酯材料[7,8]等高分子阻尼材料常作为水声吸声材料的基体材料. 均匀基体材料对低频声能的损耗低, 难以达到理想吸声效果, 常采用吸声结构提升其低频吸声性能. 科学家围绕声学结构低频吸声开展了大量研究工作. 第二次世界大战时期德国潜艇应用“Alberich”声学覆盖层[9], 通过空腔结构的共振和波形转换等思想, 在较小厚度限制下提升了低频吸声性能, 该结构成为多年来水声吸声材料的主流结构形式之一[10~15]. 在此基础上, 学者研究了柱形[12]、球形[13]、锥形[14]和组合型[15]等多种空腔构型的吸声机理及特性. 总体来说, 空腔共振频率与空腔体积、橡胶材料剪切波速度密切相关[16]. 空腔体积越大、剪切波速度越低, 则空腔共振频率越低, 低频吸声

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越好.

为了进一步提升材料的低频吸声性能，声学超材料技术被逐步引入到水声吸声材料设计中. 声学超材料是一种由人工微结构按一定方式排列而成、具有超常物理特性的人工复合材料或结构[17]. 2000年，Liu等人[18]提出了局域共振型声子晶体(locally resonant phononic crystal, LRPC)的概念, 它是由软硅橡胶包覆重质金属所组成的局域共振单元周期内嵌在树脂基体中构成的. LRPC能够在400 Hz的低频处产生带隙，晶格尺寸仅为带隙频率处弹性波波长的1/300，具有深亚波长特性，且LRPC在低频带隙频率处存在负的等效质量密度特性[19]. Zhao等人[20]将LRPC引入到水声吸声材料设计中, 分析表明, 局域共振单元在共振频率处产生纵横波波形转换效应, 实现了对水下声波的高效耗散. 局域共振水声超材料因具有良好的低频声波耗散性能，形成了一种新型的低频吸声机理[21~25]. 局域共振散射体的形状可影响共振频率，球形[20]、柱形[21]、椭球形[22]等局域共振构型的低频吸声特性均得到了深入研究.

水声吸声材料通常需工作在一定水深海洋环境中, 水下装备下潜深度每增加100 m，静水压力增加1 MPa. 在高静水压力下, 橡胶等高分子聚合物会变“硬”, 同时材料内部的声学结构也会发生变形，导致吸声材料对入射声波的损耗能力大大降低, 低频吸声变差. 现有的声学结构在高静水压下吸声性能明显下降[26,27]，在高静水压下实现低频宽带吸声一直是该领域的难题. 随着水下装备下潜深度的不断提升和声呐探测技术的不断发展，水声吸声材料在高静水压下的吸声性能要求逐步提高.

本文着重对静水压下吸声材料的研究进展进行综述，主要包括静水压下水声材料吸声特性的分析方法、主要吸声机理以及抗静水压吸声材料的设计现状, 最后总结当前静水压力下水声吸声材料所遇到的挑战.

## 1 静水压下水声材料吸声分析方法

与常压相比，静水压下水声吸声材料声学特性的分析更为困难. 利用水声声管[26,28]或压力水罐[29,30]可直接进行静水压下水声材料的吸声测试，但实验成本高昂, 难以应用于整个研究阶段. 建立准确、高效的建模分析方法, 对预测水声材料声学性能至关重要. 常见的水声吸声材料分析方法主要有等效介质法[31,32]、层多重散射法[33]和有限元法[34,35]. 这些分析方法均首先在常压下发展起来. 静水压力作用下水声吸声材料的声学特性分析本质上是静应力条件下基体材料/几何结构静态与声学动态激励耦合下的力声耦合建模问题. 由于水声吸声材料基体通常为弹性模量较小的橡胶类材料，预应力可引起材料内部声学结构变形及材料本征力学参数的变化.

等效介质法的基本思路是利用等效介质理论得到材料的等效参数(例如密度、声速、模量等), 进而通过等效参数计算材料的声学性能. 在静水压力条件下, Kim[36]采用等效介质理论建立了一种针对含中空玻璃微珠的多层复合黏弹性材料的水声性能分析模型. Gaunaurd等人[37]以多孔黏弹性材料为研究对象，通过均匀介质等效球体代替实际的多孔弹性介质球体，令等效均匀介质形成的散射波场与实际多孔散射体形成的散射波场相等, 建立相应的方程, 求解实际多孔弹性结构的等效参数. 通过静水压力下等效参数的计算, 分析外部静水压力对多孔黏弹性材料静、动态有效性能的影响. 数值结果表明，随着静水压力的增大，空腔共振产生的吸声峰向高频移动，吸声频带展宽. Zhang等人[38]针对一种含周期性柱形空腔和压电材料的半主动水声吸声材料，基于Neo-Hookean超弹性本构模型和唯象理论分析了橡胶层在静水压作用下的变形，然后结合等效介质法、分流阻尼技术和层状介质中的波传播理论建立了该材料的声学分析模型，分析了材料在0~6 MPa静水压力范围内的吸声性能. 为提高分析结果的可信度，该研究采用水声声管对自制样品进行声学测试, 测试结果与理论结果基本吻合.

水声吸声材料常含有非规则的声学结构，在一定程度上限制了等效介质法的应用. 在分析静水压力对材料吸声性能的影响时，常采用有限元数值方法进行分析. 在静水压条件下的材料吸声分析中通常忽略基体材料的参数变化, 仅考虑材料(含声学结构)变形. Shi等人[39]采用有限元方法建立了内嵌空腔结构的复合材料在静水压力下的声学计算模型，数值计算结果表明复合材料的共振吸声峰会因静水压增大而向高频移动, 且低频吸声系数随静水压力的增大而减小. 姜闻文等人[40]利用有限元方法研究了静水压力下含不同空腔结构的水声吸声材料的变形及吸声性能，并采用水声声管进行了测试验证，结果表明，在4.5 MPa以内材料吸声频带随着静水压的增大向高频移动，理论分析与实验测试结果基本一致.

为了分析静水压力下材料参数与声学结构的耦合作用, Yang等人[26]提出了一种线性化分析理论, 分析了

吸声层的变形和基体增量本构张量，发现除腔体变形外，预应力和预变形同样会对吸声层声能耗散产生影响. Parnell[41]在不考虑橡胶阻尼效应的情况下，对含静压初始变形的橡胶介质中球形气腔的弹性波散射进行了理论研究. 结果表明, 基于橡胶的非线性弹性模型的理论分析, 可以准确预测空腔的压缩半径, 且模型的初始变形场对弹性波散射有很大影响. 邹明松等人[42]采用有限元方法计算了静水压作用下含锥形空腔的水声材料的受压变形，结合实验得到的不同静水压下基体材料的特性参数，分析了静水压对材料声阻抗的影响. 陈文炯等人[43]基于有限元方法，在考虑空腔变形和预应力对基体材料力学性能影响的条件下，分析了静水压力作用下含不同空腔的水声材料的吸声性能，发现材料的中高频(2~5 kHz)吸声都随静水压的增加而降低, 与不考虑预应力的材料吸声性能存在明显差异.

借助商业有限元软件，如ABAQUS[44]、ANSYS[45]和COMSOL[46]等，可进行静水压下的材料吸声建模分析. 在分析结构变形时，一种思路是先求解结构变形量，然后将变形量导出构建新有限元模型进行吸声性能分析[47,48]；另一种思路是直接将静水压下计算得到的变形后的模型应用到仿真分析中[49,50]. 陶猛和卓琳凯[47]基于含柱形空腔的二维水声吸声材料解析模型, 结合有限元软件ANSYS分析了材料在静水压力下的腔体单元变形量, 进而构建出新的有限元分析模型, 经分析发现, 静水压力会压缩空腔体积, 增加轴向波的相速度, 使得吸声峰向高频移动. 董文凯和陈美霞[48]利用有限元软件COMSOL计算了柱形空腔单胞结构的变形量，根据变形量构建了新的分析模型，分析结果表明, 在不考虑材料参数变化时，柱形空腔在静水压力作用下发生轴向和径向收缩, 吸声系数向高频移动. 由于声学结构的复杂性，直接在声学结构受压变形的基础上进行声学性能的计算，能有效避免依据变形量重新建模而产生的误差[49]. 杨立军等人[50]以含椭球形空腔的水声材料为研究对象，利用COMSOL软件分析了静水压下水声材料的变形，然后依靠“移动网格”模块直接将变形结果应用于声-固耦合计算中，有效地提高了计算精度. Fu等人[51]采用Nelder-Mead算法在COMSOL软件中建立了一种静水压力下的声-固全耦合有限元模型，在同一个模型中可分别进行静压变形分析和吸声性能分析, 提高了计算效率.

上述静水压下水声吸声材料的理论建模需要准确的基体动态力学参数[52]. 以橡胶、聚氨酯等高分子阻尼材料为代表的基体材料，其动态力学参数通常包括复弹性模量、复泊松比和损耗因子等，常通过实验测试获得. 材料的动态力学参数测试方法主要可分为力学方法和声学反演方法两类[53]. 力学方法主要是利用材料的振动特性来计算其动态力学参数，目前常用的有强迫非共振法、振动梁法、动态黏弹谱仪法[54]. 然而，这3种测试方法均难以进行静水压力条件下的动态力学参数测试. 为了获得材料受压后的动态力学参数, Guillot和Trivett[55]基于共振理论和波传播方法, 用激光测振仪测量了不同静压、温度条件下橡胶材料的复弹性模量，并在此基础上提出了一种测试橡胶材料复体积模量的方法. 声学反演方法通过对材料的声学参数进行测试，再根据所得声学参数反演获得材料的动态力学参数, 是一种间接测试方法. 黄修长等人[52]利用水声声管，分别对不含/含均匀圆柱空腔结构的橡胶材料进行静水压力条件下的声学测试，将获取的纵波波数和等效复波数联合求解反演出橡胶材料的动态力学参数，通过对比静水压力条件下吸声系数测试结果与采用实测橡胶材料参数进行的有限元分析结果，表明该方法具有较高的精度. 陶猛和江坤[56,57]基于水声声管开展声学参数测试，对静水压力下橡胶材料的动态力学参数声学反演方法进行了研究. 除水声声管外, 压力水罐同样可以应用于材料的材料参数反演[58].

## 2 水声材料吸声机理研究

### 2.1 常压下材料吸声机理研究

常见水声吸声材料的吸声机理包括阻尼耗散、阻抗匹配、散射、共振耗散[59]. 由于水声材料的基体材料多为高分子阻尼材料，通过材料内部高分子链的黏性内摩擦及弛豫过程产生的阻尼耗散效应，可将入射声能转化为热能进行耗散[60]. 阻抗匹配的目标是使声波能最大限度地进入材料内部，在选择合适基体材料的同时，通过设计多层阻抗梯度结构[61~63]或阻抗渐变空腔[64~66]等, 提高吸声效果. 声散射是在基体材料中嵌入气泡型填料[67]、玻璃微珠[68]以及金属微珠[69]等散射体, 通过散射体对入射声波形成的散射作用, 使得入射纵波转换为耗散效率高的横波, 增强声能耗散. 共振吸声机理主要是利用各种声学结构在特定频率处产生的共振效应, 使得材料发生局部剪切变形, 形成纵波向横波的转换以提高吸声[20,70]. 除空腔和局域共振结构外, 螺旋通道[71]、薄膜型共振结构[72]、微穿孔板[73~75]和

Fabry-Pérot共振[76,77]等也被用于共振型吸声结构设计中.

在实际水声材料的吸声设计中，为了提高低频吸声、拓宽吸声频段，通常是多种吸声机理综合应用. Liu等人[78]将不同尺寸的球形局域共振结构按一定空间规则嵌入到橡胶基体中，设计了一种新型水声吸声材料(图1(a))，通过多次局域共振耦合和散射作用将入射纵波转换为横波，在1077~10000 Hz频段内实现了吸声系数均大于0.8的宽频吸声. Jin等人[79]提出了一种基于空腔共振效应、局域共振效应、多振子耦合共振效应的多机理复合声学结构(图1(b))，有效拓宽了吸声频带. Gu等人[80]设计了一种二维水声吸声超材料，该材料利用钢支撑板与黏弹性体间相互作用产生的波形转换效应以及底部半椭圆空腔与黏弹性材料板间的耦合共振效应，实现了470~10000 Hz频段内的宽频吸声(吸声系数大于0.8). Jia等人[81]设计了一种由橡胶基体层、柱形空腔、五模超材料(pentamode metamaterial, PM)层和阻抗匹配层组成的复合水声吸声超材料. 该材料利用PM的特性，既保持了空腔共振带来的低频吸声性能，又增强了中高频吸声，在500~10000 Hz频段内的平均吸声达到了0.78. 总体来说，声学结构共振是水声吸声材料低频吸声的主流机理.

### 2.2 静水压下材料吸声机理研究

在空腔型水声材料设计中，增大声学空腔体积，虽然能够获得更低频的吸声，但是降低了吸声材料的整体刚度和强度. 在静水压力作用下声学空腔会发生大变形，空腔型水声吸声材料的低频吸声性能受静水压力的影响较大. 图2(a)给出了一种空腔型水声吸声材料在不同静水压环境下的实验测试结果[26]. 随着静水压力的增加，空腔型水声吸声材料的低频吸声性能显著下降. 这是由于随着静水压力升高，空腔体积逐渐减小，空腔共振频率会向高频偏移. 因此，传统空腔型水声吸声材料难以在高静水压力环境下实现高效的低频吸声. 局域共振型水声吸声材料受静水压力的影响同样不可忽视，图2(b)给出了一种局域共振型水声吸声超材料在不同静水压力环境下的实验测试结果[27]. 随着静水压力的增大，局域共振型水声吸声超材料共振效应减弱，低频吸声性能显著降低.

在静水压力下，吸声材料的内部结构会发生变形，空腔及局域共振结构产生的共振强度下降,共振频率升高. 同时，静水压力会降低橡胶等黏弹性高分子材料对声波的耗散能力[46,82]. 为分析静水压力对高分子结构吸声性能的影响，王清华[83]提出并验证了“自由体积吸声机理”. 该机理表明，高分子材料中自由体积的运动是导致材料吸声的关键，且自由体积运动与高分子链结构密切相关，链的柔性越大、分子间的作用力越小，则自由体积运动越容易，材料吸声性能越好. 高分子材料的弹性模量会因为外部压力而增加[2]，链结构被压缩，吸声能力降低. Yan等人[84,85]采用Yeoh超弹性本构模型分析了一种复合吸声结构在0~2 MPa静水压范围内吸声机理的变化，该结构具有阻尼耗散、波形转换和局域共振多种吸声机理. 分析结果表明，静水压力减弱了4.2~8.4 kHz频段内的局域共振和波形转换效应，静压下复合结构的吸声性能明显下降. 可见，在静水压力下的低频宽带水声吸声机理仍然需要突破.

## 3 抗压水声吸声材料设计现状

静水压力不仅会改变基体材料参数，还会导致其

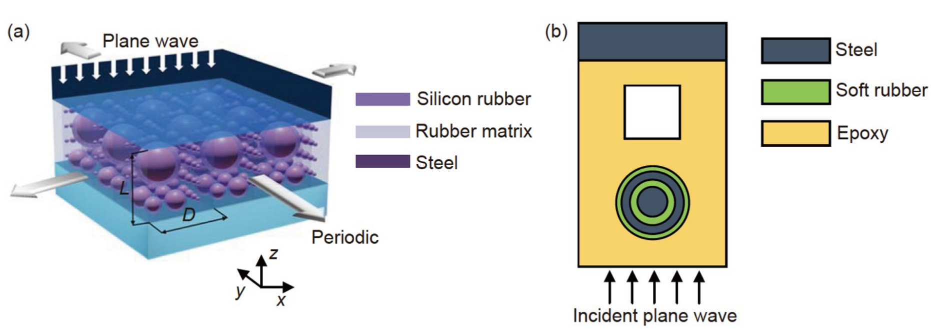


**图 1** (网络版彩色)多机理协同宽频水声吸声超材料. (a) 不同尺寸球形局域共振散射体组合[78]. Copyright © 2023, Acoustic Society of America. (b) 声学空腔与多层共振结构组合[79]

**Figure 1** (Color online) Multi-mechanism synergistic broadband hydroacoustic absorbing metamaterials. (a) Combinations of spherical local resonance scatterers of different sizes[78]. Copyright © 2023, Acoustic Society of America. (b) Acoustic cavity combined with multi-layer resonance structures[79]

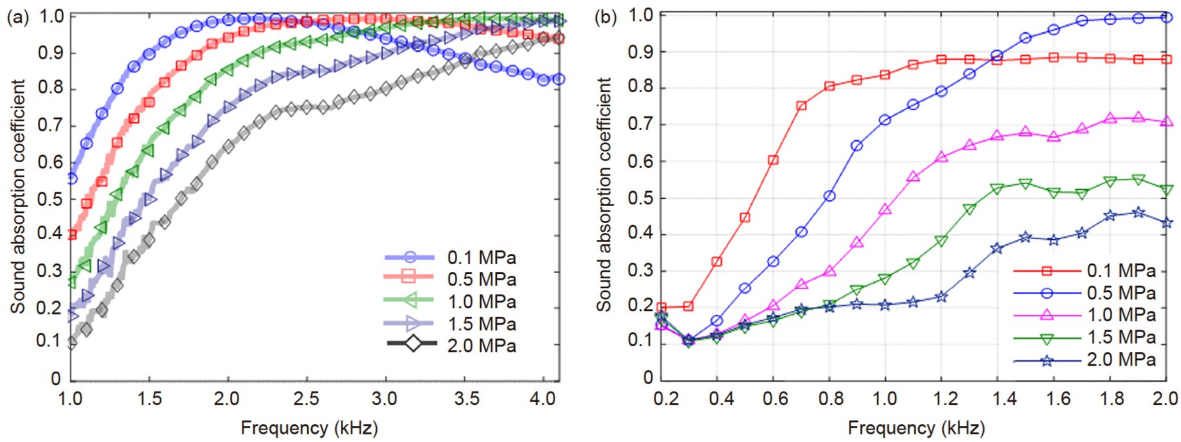


**图 2** (网络版彩色)静水压力对不同类型水声材料吸声性能的影响. (a) 空腔型[26]; (b) 局域共振型[27]
**Figure 2** (Color online) Influence of hydrostatic pressure on sound absorption properties of different types of hydroacoustic absorbing materials. (a) Air cavity type[26]; (b) local resonance type[27]

内部声学结构发生变化，这些都会影响水声材料的吸声性能. 为了增强水声吸声材料的抗静水压性能, 研究人员在材料和吸声结构设计两方面均开展了相关研究工作.

### 3.1 基体材料抗压设计

用于水声吸声材料设计的基体材料通常模量偏小，通过杂化等手段可以提高基体材料的抗压吸声性能. 为了提高聚二甲基硅氧烷(polydimethylsiloxane, PDMS)的抗压吸声性能，Fu等人[86,87]将碳纳米管混入PDMS中，采用水声声管对材料进行了声学测试，但效果并不明显. 随后, 该研究团队将石墨烯纳米片与碳纳米管同时混入PDMS中, 结果表明同时添加石墨烯纳米片和碳纳米管的PDMS明显优于仅含碳纳米管的材料的抗压吸声性能. 杜仲胶(*Eucommia ulmoides* gum, EUG)是一种天然橡胶, 由于其具有结晶和高模量特性, 可用于提高基体材料的抗压性能[88]. Dong等人[89]将EUG混合进聚氨酯制成复合材料, 通过实验分析, 表明EUG的加入提高了聚氨酯材料在4.5~8 kHz频段内的抗压吸声性能, 与纯聚氨酯相比, EUG/聚氨酯复合材料在常压下平均吸声系数提高了52.2%, 在4 MPa静水压下吸声性能提高了16.8%. Cao等人[90]将EUG与丁苯橡胶复合, 实验结果表明该复合材料在2.5 MPa静水压下, 3~8 kHz频段内的平均吸声比纯丁苯橡胶提高了24.23%. Su等人[91]和Zhang等人[92]利用EUG分别提高了纯丁腈橡胶和纯氯丁橡胶的抗压吸声性能.

### 3.2 吸声结构抗压设计

为了提升空腔型水声吸声材料的抗压性能, 汪慧铭[93]采用遗传算法对不同类型空腔结构的水声材料进行优化, 经过筛选得到在3 MPa静水压下吸声相对较好的抗压结构. Shi等人[39]利用功能梯度材料(functionally graded materials, FGMs)的特点, 从几何梯度和材料梯度两方面考虑, 将FGMs与几何梯度声学空腔结合, 设计了材料-材料复合梯度、材料-结构复合梯度、材料-结构-材料复合梯度3种复合梯度型水声吸声结构(图3). 数值计算结果表明, 复合结构的抗压性能得到了改善.

在吸声结构中加入抗压增强结构, 可改善静水压下的吸声性能. Feng等人[94]基于局域共振与声学空腔耦合原理, 设计了一种含铅质量块、空腔及钢隔板增强结构的二维水声吸声复合结构. 有限元分析结果显示, 与背衬相连的钢隔板增强结构减小了橡胶及空腔的变形量(图4(a)), 使该材料在4.5 MPa静水压力下仍能保持高效吸声, 但该工作尚未得到实验验证. Li等人[95]设计了一种包含漏斗形空腔与局域共振单元的复合结构, 将碳纤维柱作为增强材料加入到结构中, 结果表明碳纤维柱的加入提高了吸声结构的抗压性能. Yang等人[96]在柱形空腔周围嵌入铝制圆筒支撑(图4(b)), 仿真与实验分析结果均表明该复合结构在2 MPa静水压下的吸声性能得到了提高. 付宜风等人[97]设计了一种如图4(c)所示的抗压结构, 其由2 mm厚的环氧树脂硬壳、硅橡胶层和基体橡胶层构成. 实验分析表明, 与纯基体材料相比, 该结构在1.5 MPa静水压下、1.5~7 kHz

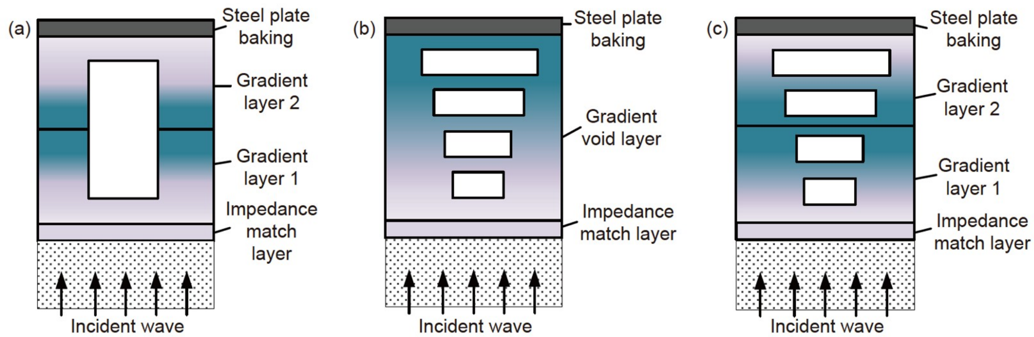


**图 3** (网络版彩色)3种功能梯度型声学结构[39]. (a) 两层FGMs复合; (b) 单层FGM与梯度空腔复合; (c) 两层FGMs与梯度空腔复合
**Figure 3** (Color online) Three functional gradient acoustic structures[39]. (a) Two-layer FGMs composite; (b) single-layer FGM is compounded with gradient cavities; (c) two-layer FGMs are compounded with gradient cavities

频段内的平均吸声从0.2提升到了0.7. Wang等人[98]设计了由碳纤维蜂窝(carbon fiber honeycomb, CFH)骨架和锥形空腔组成的复合吸声结构, 测试结果表明添加CFH增强结构能有效提高材料的抗压性能, 在1.5 MPa的静水压力下, 该复合结构在2.4~10 kHz频段内吸声系数均达到了0.9.

此外, 合理的超结构设计亦能改善材料的抗压性能. Zhong等人[99]通过在复合板中填充周期性圆柱振子, 设计了一种局域共振型水声超材料板, 实验分析表明, 该超材料在0.5 MPa静水压力下, 1.5~6 kHz频段内平均吸声达到了0.51. Baena等人[100]基于3D打印, 使用热塑性聚氨酯和热固性聚氨酯设计了一种具有周期性锥形腔的薄膜型声学超材料. 测试结果表明, 在1.5 MPa静水压力下, 该超材料在5625~7000 Hz频段内的平均吸声达到了0.9. 贾薪宇等人[101]为改善含球形空腔吸声材料的抗压性能, 在声波入射端插入周期性的金属孔板(图5(a)), 采用有限元方法进行了0~6 MPa静水压范围内的吸声特性分析, 结果表明金属孔板(材料为铅、铝或钢)的插入改善了该结构在中高频段(4~10 kHz)的抗压吸声性能. Lee等人[102]通过在铜板表面雕刻不同深度的周期性凹槽, 制成了一种可用于水下吸声的声学超表面, 该超表面在光学显微镜下的剖面图如图5(b)所示. 测试结果表明, 该超表面在0~5 MPa静水压范围内的吸声具有鲁棒性, 但吸声频段较高(2~5 MHz). Gao等人[103]通过在锥形多孔泡沫铝周

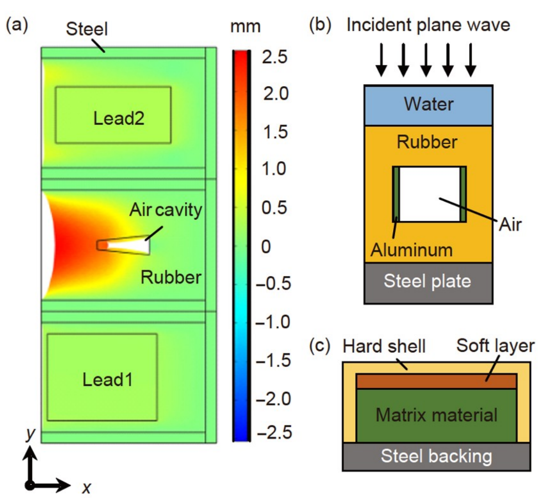


**图 4** (网络版彩色)具有增强结构的抗压水声吸声结构. (a) 含钢隔板增强结构的吸声材料在4.5 MPa下$x$方向的位移场图[94], Copyright © 2022, Acoustic Society of America; (b) 通过铝制圆筒增强柱形空腔抗压性能的吸声结构[96]; (c) 硬质壳体增强的吸声结构[97]
**Figure 4** (Color online) Pressure-resistant hydroacoustic absorbing structure with reinforced structures. (a) Displacement field diagram of the hydroacoustic absorbing material with steel diaphragm reinforced structures at 4.5 MPa in the $x$ direction[94], Copyright © 2022, Acoustic Society of America; (b) the hydroacoustic absorbing structure of the cylindrical cavity is enhanced by the aluminum cylinder[96]; (c) hard shell enhanced hydroacoustic absorbing structure[97]

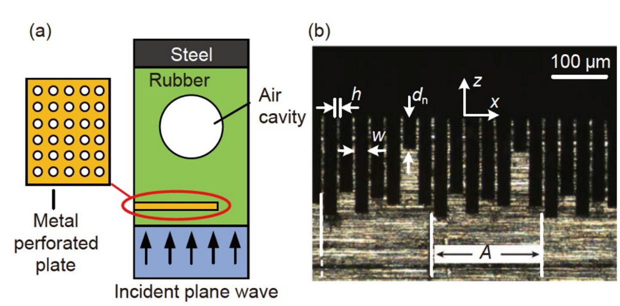


**图 5** (网络版彩色)抗压吸声型水声超材料. (a) 含空腔和金属孔板的超材料[101]; (b) 水声吸声超表面, 周期为$A$, 声波入射沿$z$轴负方向[102]. Copyright © 2018, Acoustic Society of America
**Figure 5** (Color online) Pressure-resistant hydroacoustic absorbing metamaterials. (a) Metamaterial containing cavity and metal perforated plate[101]; (b) hydroacoustic absorbing metasurface with a period of $A$, and the incident of the sound wave is negative along the $z$-axis[102]. Copyright © 2018, Acoustic Society of America

围浇筑聚脲, 设计了一种水声吸声超材料, 静水压下样品吸声性能测试结果表明, 与纯聚脲相比, 嵌入泡沫铝散射体提高了该材料在5 MPa静水压下的低频吸声性能.

## 4 结语

本文从分析方法、吸声机理、材料设计方面综述了静水压下水声吸声材料的研究现状. 由于水下装备下潜深度的不断增加, 高静水压条件下材料的低频宽带吸声研究仍然面临诸多挑战.

(1) 在吸声材料分析方法方面. 在静水压力条件下, 大多数理论研究只考虑材料(含内部声学结构)的几何变形而忽略基体材料参数变化, 或者对材料几何变形和基体参数变化分别进行研究, 再综合分析水声材料在不同静水压下的吸声性能. 实际上, 静水压下材料几何变形和基体参数变化相互耦合. 因此, 建立高静水压条件下更准确的材料声学分析模型和分析方法尚需进一步开展.

(2) 在水声材料吸声机理方面. 水声吸声材料的主要吸声机理包括阻抗匹配、阻尼耗散、散射、共振. 其中, 共振型水声材料通过声学空腔或局域共振单元等散射体产生的共振效应, 使得散射体周围的黏弹性材料或散射体内部产生剪切变形, 从而实现对声波能量的高效耗散. 随着静水压力的升高, 散射体低频共振效应逐渐减弱, 使得水声材料的低频吸声性能下降. 因此, 如何实现高静水压下材料的低频宽带高效吸声, 需要在借鉴新型声学超结构对低频声波调控研究的基础上, 提出新的低频吸声机理, 并综合现有机理研究, 通过多机理耦合设计, 拓展水声吸声频段.

(3) 在吸声材料设计方面. 大部分静水压力条件下的水声吸声材料设计工作均在4.5 MPa以下进行, 在4.5 MPa以上的高静水压力下水声材料往往低频(1 kHz以下)吸声性能不足[102]或仅局限于理论阶段[39,94,101], 实现高静水压力下低频宽带吸声的水声材料设计还需进一步深入研究. 通过设计更为抗压的基体材料和声学结构, 可以提升静水压力下水声材料的抗压吸声性能, 但如何兼顾材料的抗压性能和低频宽带吸声仍是该领域的瓶颈问题, 需要持续深入地开展相关研究工作.

## 参考文献


1 Shi Y X, Xi Z P, Tang H P, et al. Progress of underwater sound-absorbing materials (in Chinese). Mater Rep, 2010, 24: 49–52 [石云霞, 奚正平, 汤慧萍, 等. 水下吸声材料的研究进展. 材料导报, 2010, 24: 49–52]

2 Zhu B L, Huang X Z. Design of acoustic cover layer—A key technology of submarine stealth (in Chinese). Shanghai: Shanghai Jiao Tong University Press, 2012 [朱蓓丽, 黄修长. 潜艇隐身关键技术——声学覆盖层的设计. 上海: 上海交通大学出版社, 2012]

3 Zhang Y N, Chen K A, Hao X Y, et al. A review of underwater acoustic metamaterials (in Chinese). Chin Sci Bull, 2020, 65: 1395–1410 [张燕妮, 陈克安, 郝夏影, 等. 水声超材料研究进展. 科学通报, 2020, 65: 1395–1410]

4 Fu Y, Kabir I I, Yeoh G H, et al. A review on polymer-based materials for underwater sound absorption. Polym Test, 2021, 96: 107115

5 Calvo D C, Thangawng A L, Layman Jr C N, et al. Underwater sound transmission through arrays of disk cavities in a soft elastic medium. J Acoust Soc Am, 2015, 138: 2537–2547

6 Leroy V, Bretagne A, Fink M, et al. Design and characterization of bubble phononic crystals. Appl Phys Lett, 2009, 95: 171904

7 Gu B E, Huang C Y, Shen T H, et al. Effects of multiwall carbon nanotube addition on the corrosion resistance and underwater acoustic absorption properties of polyurethane coatings. Prog Org Coat, 2018, 121: 226–235

8 Weeratunge H, Shireen Z, Iyer S, et al. A machine learning accelerated inverse design of underwater acoustic polyurethane coatings. Struct Multidisc Optim, 2022, 65: 213

9 Richardson E G. Technical Aspects of Sound. New York: Elsevier, 1957

10 Meng Z, Wang L, Wang J. The extreme bulk-modulus contrast of bubbly soft matter for underwater acoustic modulation. Extreme Mech Lett, 2023, 61: 102023

11 Sun Y, Li Z, Chen J, et al. Variational autoencoder-based topological optimization of an anechoic coating: An efficient- and neural network-based design. Mater Today Commun, 2022, 32: 103901

12 Shankar Sharma G, Toyoda M, Skvortsov A, et al. Acoustic performance of a metascreen-based coating for maritime applications. J Vib Acoust, 2022, 144: 31015

13 Torquato P, Giusepponi D, Alisi A, et al. Nutritional and lipidomics biomarkers of docosahexaenoic acid-based multivitamin therapy in pediatric NASH. Sci Rep, 2019, 9: 2045–2322

14 Ye C, Liu X, Xin F, et al. Influence of hole shape on sound absorption of underwater anechoic layers. J Sound Vib, 2018, 426: 54–74

15 Wang Y, Zhao H, Yang H, et al. Inverse design of structured materials for broadband sound absorption. J Phys D-Appl Phys, 2021, 54: 265301
16 Sharma G S, Skvortsov A, MacGillivray I, et al. On superscattering of sound waves by a lattice of disk-shaped cavities in a soft material. Appl Phys Lett, 2020, 116: 41602
17 Cummer S A, Christensen J, Alù A. Controlling sound with acoustic metamaterials. Nat Rev Mater, 2016, 1: 16001
18 Liu Z, Zhang X, Mao Y, et al. Locally resonant sonic materials. Science, 2000, 289: 1734–1736
19 Liu Z, Chan C T, Sheng P. Analytic model of phononic crystals with local resonances. Phys Rev B, 2005, 71: 14103
20 Zhao H, Liu Y, Yu D, et al. Absorptive properties of three-dimensional phononic crystal. J Sound Vib, 2007, 303: 185–194
21 Jia X, Jin G, Shi K, et al. A hybrid acoustic structure for low-frequency and broadband underwater sound absorption. J Low Freq Noise Vib Act Control, 2022, 41: 1160–1177
22 Wen J, Zhao H, Lv L, et al. Effects of locally resonant modes on underwater sound absorption in viscoelastic materials. J Acoust Soc Am, 2011, 130: 1201–1208
23 Shi K, Jin G, Ye T, et al. Underwater sound absorption characteristics of metamaterials with steel plate backing. Appl Acoust, 2019, 153: 147–156
24 Meng H, Wen J, Zhao H, et al. Optimization of locally resonant acoustic metamaterials on underwater sound absorption characteristics. J Sound Vib, 2012, 331: 4406–4416
25 Jiang H, Wang Y, Zhang M, et al. Locally resonant phononic woodpile: A wide band anomalous underwater acoustic absorbing material. Appl Phys Lett, 2009, 95: 104101
26 Yang H, Zhao H, Wen J. Theory and numerical method for the effects of hydrostatic pressure on sound absorption of underwater acoustic coatings with air cavities. J Sound Vib, 2022, 533: 116985
27 Gu Y, Zhong H, Bao B, et al. Experimental investigation of underwater locally multi-resonant metamaterials under high hydrostatic pressure for low frequency sound absorption. Appl Acoust, 2021, 172: 107605
28 Fu Y. Measurement of underwater sound absorption coefficient at variable hydrostatic pressures using an improved transfer function method. J Test Eval, 2023, 51: 3237–3254
29 Humphrey V F, Robinson S P, Smith J D, et al. Acoustic characterization of panel materials under simulated ocean conditions using a parametric array source. J Acoust Soc Am, 2008, 124: 803–814
30 Tang J, Bai Y, Yan L, et al. GMA phased array for active echo control of underwater target. Appl Acoust, 2022, 190: 108646
31 Sharma G S, Skvortsov A, MacGillivray I, et al. Sound scattering by a bubble metasurface. Phys Rev B, 2020, 102: 214308
32 Skvortsov A, Sharma G S, MacGillivray I, et al. Sound absorption by a metasurface comprising hard spheres in a soft medium. J Acoust Soc Am, 2021, 150: 1448–1452
33 Ivansson S M. Anechoic coatings obtained from two- and three-dimensional monopole resonance diffraction gratings. J Acoust Soc Am, 2012, 131: 2622–2637
34 Hladky-Hennion A C, Decarpigny J N. Analysis of the scattering of a plane acoustic wave by a doubly periodic structure using the finite element method: Application to Alberich anechoic coatings. J Acoust Soc Am, 1991, 90: 3356–3367
35 Easwaran V, Munjal M L. Analysis of reflection characteristics of a normal incidence plane wave on resonant sound absorbers: A finite element approach. J Acoust Soc Am, 1993, 93: 1308–1318
36 Kim J H. Development of analysis model for underwater acoustic performance of multi-layered coatings containing visco-elastic composites. J KIMS Technol, 2018, 21: 25–39
37 Gaunaurd G, Callen E, Barlow J. Pressure effects on the dynamic effective properties of resonating perforated elastomers. J Acoust Soc Am, 1984, 76: 173–177
38 Zhang Z, Li S, Wang J, et al. Low-frequency broadband absorption of semi-active composite anechoic coating with subwavelength piezoelectric arrays in hydrostatic environments. Results Phys, 2021, 30: 104879
39 Shi K, Hu D, Li D, et al. Sound absorption behaviors of composite functionally graded acoustic structure under hydrostatic pressure. Appl Acoust, 2023, 211: 109474
40 Jiang W W, Chen G Y, Zhu Y. Computation and analysis of sound absorption performance of rubber structures under variable hydraulic pressure (in Chinese). Noise Vib Control, 2006, 26: 55–57, 73 [姜闻文, 陈光冶, 朱彦. 静水压变化下橡胶结构吸声性能的计算与分析. 噪声与振动控制, 2006, 26: 55–57, 73]
41 Parnell W J. Elastic wave scattering from a strained region. Master Dissertation. London: University of Oxford, 2000
42 Zou M S, Wu W W, Yu X L, et al. Calculation of acoustic coating's Impedance under hydrostatic pressure (in Chinese). Ship Sci Technol, 2013, 35: 57–60, 68 [邹明松, 吴文伟, 余晓丽, 等. 静水压下声学覆盖层声阻抗研究. 舰船科学技术, 2013, 35: 57–60, 68]
43 Chen W J, Lu C, Zhou X C. Analysis on the effect of hydrostatic pressure on the performance of acoustic coating (in Chinese). Ship Boat, 2023, 34: 25–34 [陈文炯, 卢辰, 周祥超. 静压作用对吸声覆盖层性能的影响与分析. 船舶, 2023, 34: 25–34]
44 Wei B. The deformation calculation and test study of anechoic tile under hydrostatic pressure (in Chinese). Master Dissertation. Wuhan:

Huazhong University of Science and Technology, 2012 [魏笔. 消声瓦静水压下变形计算及其试验研究. 硕士学位论文. 武汉: 华中科技大学, 2012]
45 Panigrahi S N, Jog C S, Munjal M L. Multi-focus design of underwater noise control linings based on finite element analysis. Appl Acoust, 2008, 69: 1141–1153
46 Jayakumari V G, Shamsudeen R K, Rajeswari R, et al. Viscoelastic and acoustic characterization of polyurethane-based acoustic absorber panels for underwater applications. J Appl Polym Sci, 2019, 136: 47165
47 Tao M, Zhuo L K. Effect of hydrostatic pressure on acoustic performance of sound absorption coating (in Chinese). J Shanghai Jiaotong Univ Sci, 2011, 45: 1340–1344, 1350 [陶猛, 卓琳凯. 静水压力下吸声覆盖层的声学性能分析. 上海交通大学学报, 2011, 45: 1340–1344, 1350]
48 Dong W K, Chen M X. Sound absorption performance analysis of anechoic coating under hydrostatic pressure considering cavity pressure (in Chinese). Chin J Ship Res, 2022, 17: 132–140 [董文凯, 陈美霞. 静压下考虑腔压的吸声覆盖层吸声性能分析. 中国舰船研究, 2022, 17: 132–140]
49 Zhang C, He S P, Yi S Q. Model and absorption performance of anechoic coating embedding sphere cavities (in Chinese). J Ship Mech, 2017, 21: 99–106 [张冲, 何世平, 易少强. 静压下球形空腔吸声覆盖层的建模与性能分析. 船舶力学, 2017, 21: 99–106]
50 Yang L J, Zhang C, Lou J J, et al. Absorption performance of the multi-layered material anechoic coating embedding spheroidicity cavities (in Chinese). Ship Sci Technol, 2017, 39: 54–57 [杨立军, 张冲, 楼京俊, 等. 静压下多层材料椭球形空腔吸声覆盖层的吸声性能分析. 舰船科学技术, 2017, 39: 54–57]
51 Fu Y, Wang H, Cao P. Numerical design and optimization of metamaterials for underwater sound absorption at various hydrostatic pressures. J Low Freq Noise Vib Act Control, 2023, 42: 1434–1450
52 Huang X Z, Zhu B L, Hu P, et al. Measurement of dynamic properties of rubber under hydrostatic pressure by water-filled acoustic tube (in Chinese). J Shanghai Jiaotong Univ Sci, 2013, 47: 1503–1508 [黄修长, 朱蓓丽, 胡碰, 等. 静水压力下橡胶动态力学参数的声管测量方法. 上海交通大学学报, 2013, 47: 1503–1508]
53 Yao L, Liu H W, Zhao H, et al. A hybrid method for measuring the low-frequency acoustic properties of polymer materials (in Chinese). Sci Sin Phys Mech Astron, 2008, 38: 546–554 [姚磊, 刘宏伟, 赵洪, 等. 一种测量高分子材料低频声学性能的混合方法. 中国科学G辑: 物理学 力学 天文学, 2008, 38: 546–554]
54 Tao M, Zhao Y. Identification method of viscoelastic material dynamic parameters based on acoustic-pipe measurement (in Chinese). J Vib Shock, 2014, (5): 97–101 [陶猛, 赵阳. 基于声管测量的黏弹性介质动态力学参数辨识方法. 振动与冲击, 2014, (5): 97–101]
55 Guillot F M, Trivett D H. Complete elastic characterization of viscoelastic materials by dynamic measurements of the complex bulk and Young's moduli as a function of temperature and hydrostatic pressure. J Sound Vib, 2011, 330: 3334–3351
56 Tao M. Measurement of viscoelastic dynamic parameters of polymer materials under hydrostatic pressure (in Chinese). J Shock Vib, 2016, 35: 59–63 [陶猛. 静水压力下高分子材料黏弹性动力学参数测量. 振动与冲击, 2016, 35: 59–63]
57 Tao M, Jiang K. Dynamic parameters measurement of damping materials under hydrostatic pressure based on a hybrid numerical-analytical method (in Chinese). J Vib Shock, 2016, 35: 96–101 [陶猛, 江坤. 基于数值-解析法测量静压条件下阻尼材料动态力学参数. 振动与冲击, 2016, 35: 96–101]
58 Wang M Q, Yan X W, Hu W Q. Theory and Method of Testing Dynamic Mechanical Parameters of Materials in Extreme Environments (in Chinese). Beijing: Science Press, 2022 [王敏庆, 闫孝伟, 胡卫强. 极端环境下材料动态力学参数测试理论与方法. 北京: 科学出版社, 2022]
59 Zhao H G. Research on the absorption properties of underwater acoustic absorption materials based on the theory of phononic Crystals (in Chinese). Doctor Dissertation. Changsha: National University of Defense Technology, 2008 [赵宏刚. 基于声子晶体理论的水声吸声材料吸声特性研究. 博士学位论文. 长沙: 国防科学技术大学, 2008]
60 Zhu J H, Wang Y S, Wen Q Z, et al. Development and application of underwater acoustic absorption polymer materials (in Chinese). Polym Mater Sci Eng, 2005, 21: 46–50 [朱金华, 王源升, 文庆珍, 等. 水声吸声高分子材料的发展及应用. 高分子材料科学与工程, 2005, 21: 46–50]
61 Feng Y, Qiao J, Li L. Acoustic behavior of composites with gradient impedance. Mater Des, 2020, 193: 108870
62 Liu C, Luo J, Liu X, et al. Hydroacoustic high absorption with broadband and wide-angle impedance matching. Phys Rev Appl, 2022, 18: 44008
63 Dong W, Zhou Z, Chen M, et al. Theoretical investigation on the underwater sound absorption of a functionally graded anechoic coating under the phased arc array incidence. Appl Math Model, 2023, 123: 373–391
64 Fang X, Yin X, Wu J, et al. Underwater metagratings for sub-kilohertz low frequency and broadband sound absorption. Int J Mech Sci, 2023, 260: 108630
65 Wang S, Hu B, Li S, et al. Acoustic performance of cavities with gradient changes of cavity numbers under low lattice constant in a soft elastic medium. Noise Cont Eng J, 2022, 70: 288–297
66 Wang S, Hu B, Du Y. Sound absorption of periodically cavities with gradient changes of radii and distances between cavities in a soft elastic medium. Appl Acoust, 2020, 170: 107501
67 Sun W H, Yan X. Review for influence of structure design and packings containing air bubble on underwater acoustic absorption materials (in

Chinese). China Synth Rubber Ind, 2012, 35: 239–244 [孙卫红, 晏欣. 结构设计及气泡型填料对水声吸声材料的影响综述. 合成橡胶工业, 2012, 35: 239–244]
68 Yu L G, Li C H, Wang R Q, et al. Analysis of underwater sound absorption of visco-elastic composites coating containing micro-spherical glass shell (in Chinese). Acta Phys Sin, 2013, 62: 64301 [于利刚, 李朝晖, 王仁乾, 等. 含玻璃微球的黏弹性复合材料覆盖层的水下吸声性能分析. 物理学报, 2013, 62: 64301]
69 Hinders M K, Rhodes B A, Fang T M. Particle-loaded composites for acoustic anechoic coatings. J Sound Vib, 1995, 185: 219–246
70 Yang H B, Li Y, Zhao H G, et al. Acoustic anechoic layers with singly periodic array of scatterers: Computational methods, absorption mechanisms, and optimal design. Chin Phys B, 2014, 23: 1056–1674
71 Zhou X, Duan M, Xin F. Low-frequency underwater sound absorption of hybrid metamaterials using dissipative slow-sound. Phys Lett A, 2022, 450: 128361
72 Sun Y, Yuan X, Jin Z, et al. An effective method to enhance the underwater sound absorption performance by constructing a membrane-type acoustic metamaterial. J Phys D-Appl Phys, 2022, 55: 435302
73 Kim H S, Ma P S, Kim B K, et al. Underwater sound absorption and insulation of elastic micro-perforated plates in impedance tubes. Appl Acoust, 2022, 197: 108935
74 Ke Y B, Li Z Y, Wu G H, et al. A foldable underwater acoustic meta-structure with broadband sound absorption at low frequency. Appl Phys Express, 2022, 15: 67001
75 Lin H C, Lu S C, Huang H H. Evaluation of a hybrid underwater sound-absorbing metastructure by using the transfer matrix method. Materials, 2023, 16: 1718
76 Qu S C, Gao N, Tinel A, et al. Underwater metamaterial absorber with impedance-matched composite. Sci Adv, 2022, 8: eabm4206
77 Liu J, Yang H, Zhao H, et al. A lightweight waterborne acoustic meta-absorber with low characteristic impedance rods. Int J Mech Sci, 2023, 255: 108469
78 Liu B, Huang S, Zheng B, et al. Tunable composite lattice structure for low-frequency and ultra-broadband underwater sound absorption. J Acoust Soc Am, 2023, 153: 415–422
79 Jin G, Shi K, Ye T, et al. Sound absorption behaviors of metamaterials with periodic multi-resonator and voids in water. Appl Acoust, 2020, 166: 107351
80 Gu J, Yan S, Zhang L, et al. Superior underwater sound-absorbing metasurface based on wave mode conversion and cavity-plate coupling resonance. Compos Struct, 2023, 323: 117459
81 Jia X Y, Jin G Y, Ye T G, et al. An efficient underwater absorber using pentamode metamaterials for broadband frequency. J Vib Control, 2023, 30: 1759–1771
82 Jiang H, Wang Y. Phononic glass: A robust acoustic-absorption material. J Acoust Soc Am, 2012, 132: 694–699
83 Wang Q H. The basic study on water acoustic absorption polymer materials (in Chinese). Doctor Dissertation. Changsha: National University of Defense Technology, 2009 [王清华. 高分子水声吸声材料的基础研究. 博士学位论文. 长沙: 国防科学技术大学, 2009]
84 Yan T, Wang K, Zhao X, et al. Underwater sound-absorbing performance of composite structure under hydrostatic pressure by considering constitutive models. Mater Today Commun, 2023, 37: 107172
85 Yan T, Zhao X, Wang K, et al. An optimization strategy of composite structure for underwater sound-absorbing via combining response surface method and quantum genetic algorithm. Arab J Sci Eng, 2023, 48: 10065–10078
86 Fu Y, Fischer J, Pan K, et al. Underwater sound absorption properties of polydimethylsiloxane/carbon nanotube composites with steel plate backing. Appl Acoust, 2021, 171: 107668
87 Fu Y F. Synergism of carbon nanotubes and graphene nanoplates in improving underwater sound absorption stability under high pressure. ChemistrySelect, 2022, 7: e202103222
88 Ni Q, Wu J, Kong P, et al. Inverse vulcanization polymer-modified *Eucommia ulmoides* gum with enhanced shape memory capability and sound absorption property. ACS Appl Polym Mater, 2022, 4: 4689–4698
89 Dong Y H, Yin D X, Deng L H, et al. Fabrication of millable polyurethane elastomer/*Eucommia ulmoides* rubber composites with superior sound absorption performance. Materials, 2021, 14: 7487
90 Cao R, Deng L, Feng Z, et al. Preparation of natural bio-based *Eucommia ulmoides* gum/styrene-butadiene rubber composites and the evaluation of their damping and sound absorption properties. Polymer, 2021, 213: 123292
91 Su L, Wang Q, Xiang P, et al. Development of nitrile rubber/*Eucommia ulmoides* gum composites for controllable dynamic damping and sound absorption performance. RSC Adv, 2022, 12: 21503–21511
92 Zhang Z, Liu Q, Zhang T, et al. Study on the phase structure and sound absorption properties of *Eucommia ulmoides* gum composites. Polymer, 2023, 272: 125801
93 Wang H M. Research on underwater sound absorption properties of membrane-cavity coupling acoustic metamaterial (in Chinese). Master

Dissertation. Harbin: Harbin Institute of Technology, 2020 [汪慧铭. 膜腔耦合型声学超材料水下吸声性能研究. 硕士学位论文. 哈尔滨: 哈尔滨工业大学, 2020]
94 Feng J, Liang Q, Dou Y, et al. Ultrathin underwater sound-absorbing metasurface by coupling local resonance with cavity resonance. Phys Rev Appl, 2022, 18: 34054
95 Li K, Zhou Z, Huang Z, et al. Underwater sound absorption characteristic of the rubber core sandwich structure with funnel-shaped cavities reinforced by carbon fiber columns. Appl Acoust, 2023, 208: 109375
96 Yang L, Zhao X, Wang K, et al. Influence of deformation on sound-absorbing performance under hydrostatic pressure. Int J Acoustics Vib, 2022, 27: 344–353
97 Fu Y F, Wang H M, Cao P. Thin shell structure enhanced nanocomposite coating for deep-sea high pressure sound absorption (in Chinese). China Mech Eng, 2022, 33: 1444–1451 [付宜风, 王虎鸣, 曹攀. 薄壁结构加强的纳米复合涂层深海高压吸声性能. 中国机械工程, 2022, 33: 1444–1451]
98 Wang Z, Huang Y, Zhang X, et al. Broadband underwater sound absorbing structure with gradient cavity shaped polyurethane composite array supported by carbon fiber honeycomb. J Sound Vib, 2020, 479: 115375
99 Zhong H, Gu Y, Bao B, et al. 2D underwater acoustic metamaterials incorporating a combination of particle-filled polyurethane and spiral-based local resonance mechanisms. Compos Struct, 2019, 220: 1–10
100 Baena J C, Wang C, Fu Y, et al. A new fabrication method of designed metamaterial based on a 3D-printed structure for underwater sound absorption applications. Appl Acoust, 2023, 203: 109221
101 Jia X Y, Jin G Y, Ye T G, et al. Characteristics of pressure resistance and sound absorption onanechoic coating with metal perforated plate under hydrostatic pressure (in Chinese). J Vib Eng, 2023, https://zdxb.nuaa.edu.cn/zdgcxb/article/abstract/202210001 [贾薪宇, 靳国永, 叶天贵, 等. 静压下带金属孔板声学覆盖层的耐压与吸声特性. 振动工程学报, 2023, https://zdxb.nuaa.edu.cn/zdgcxb/article/abstract/202210001]
102 Lee H, Jung M, Kim M, et al. Acoustically sticky topographic metasurfaces for underwater sound absorption. J Acoust Soc Am, 2018, 143: 1534–1547
103 Gao N, Yu H, Liu J, et al. Experimental investigation of composite metamaterial for underwater sound absorption. Appl Acoust, 2023, 211: 109466

Summary for “静水压下水声吸声材料研究进展”

# A review of hydroacoustic absorbing materials under hydrostatic pressure

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With the rapid technological advancements, sonar technology has made remarkable progress in recent years. This advancement not only facilitates the advancement of sonar technology, but also imposes stricter requirements on the stealth performance of underwater equipment, such as submarines. Consequently, hydroacoustic absorbing materials (HAMs) have emerged as indispensable tools for achieving acoustic stealth in such equipment. Extensive research has been conducted on HAMs in recent years. However, due to the faster propagation speed and longer wavelength of underwater sound waves compared to airborne sound, effective sound absorption becomes increasingly challenging. Additionally, considering the higher density of water, sound absorbing materials must be able to withstand high-level pressure, particularly in deep-water environments. These factors pose significant challenges in designing efficient HAMs.

Previous studies have demonstrated that hydrostatic pressure has a significant impact on the acoustic properties of HAMs. Under hydrostatic pressure, the matrix parameters of HAMs undergo changes, and the internal acoustic structure is squeezed and deformed. This specifically leads to reduced sound absorption in low frequencies. Currently, the design of low-frequency and wideband HAMs under high hydrostatic pressure remains a challenging task in this field. Therefore, further investigation is needed to analyze and optimize sound absorption.

This review provides an extensive overview of the current research status on analysis methods for acoustic absorption in HAMs under hydrostatic pressure. The focus is primarily on theoretical and experimental analysis methods. Additionally, this review summarizes the sound absorption mechanisms of HAMs and examines how hydrostatic pressure impacts these mechanisms. Specifically, under hydrostatic pressure, the damping dissipation effects caused by internal friction and relaxation processes within the matrix material of HAMs are diminished. Furthermore, compression deformation weakens resonance effects in acoustic structures, such as cavities or local resonances, ultimately leading to a decrease in the sound absorption performance of HAMs.

This review further summarizes the design considerations for existing HAMs. Regarding the matrix material, enhanced pressure resistance and sound absorption performance can be achieved through a combination of diverse materials and specialized structures. In terms of acoustic structure, superior pressure resistance and sound absorption capabilities can be achieved by incorporating reinforced structures that exhibit increased resistance to hydrostatic pressure or by employing innovative metamaterial designs.

Finally, the review presents a forward-looking perspective on the research trends in HAMs under hydrostatic pressure. Currently, a significant challenge remains in balancing hydrostatic pressure resistance and low-frequency broadband sound absorption. There is a pressing need for more meticulous designs of acoustic models suitable for high-pressure conditions exceeding 4.5 MPa. These unresolved questions represent crucial areas for future investigations. It is anticipated that this review will provide novel insights into the design of materials with sound absorption capabilities under hydrostatic pressure, paving the way for future advancements in this field.

**hydroacoustic absorbing material, hydrostatic pressure-resistance, sound absorption mechanism, analysis method, material design**

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