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腔体气动噪声的研究现状及发展趋势

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摘 要 空腔流动在运输、航天等行业中广泛存在。当高速流体通过空腔时，在腔内产生自激振荡，流场和声场相互耦合产生的气动噪声会引起结构的振动和疲劳破坏，甚至影响结构的使用寿命，因此如何控制和降低腔体气动噪声已成为国内外学者研究的焦点问题。本文在阅读大量文献的基础上，概述了当前腔体气动噪声的研究现状，分析和归纳腔体气动噪声的预测理论、实验研究，数值模拟方法以及噪声控制技术，展望腔体气动噪声研究的未来发展趋势。

关键词 腔体 气动噪声 理论预测 实验研究 数值模拟 控制技术
中图法分类号 V211.3； **文献标志码** A

腔体流动多见于航天航空等领域[1]，当高速流体通过空腔时，会在腔内产生强烈的声辐射，因此空腔内的流动包括腔内气流的自激振荡以及其他复杂的流动，由此产生的气动噪声将引起结构的振动和疲劳破坏[2]。此类噪声限制了航天等领域的发展，需寻求有效的控制技术降低气动噪声。目前，腔体气动噪声已然成为许多国内外学者研究的重点[3—5]。

1 理论预测

理论预测方面很多学者多从格林函数入手，例如国外 Park 等[6]、Howe[7]、Durbin[8]，中国甘加业等[9]、王芳等[10]、庞川博等[11]、吕善伟[12]、宋亚辉等[13]。另外还有其他预测方法，如采用高精度紧致有限差分格式在频域内求解莱特希尔方程[14]。改进屈列夫斯(Trefftz)方法[15]，建立声固耦合方程，利用加权残数法算出声场的分析解，加有源控制获得消声模型。与二维驱动腔流动的其他数值解进行比较，发现格雷玻尔兹曼方法[16]在大范围雷诺数上误差和收敛速率方面能够给出精确的结果。

理论研究存在误差，误差较大，并且存在大量假设，真实性没有实验和仿真支撑。

2 实验研究

在研究腔体气动噪声前，早期研究的重点是腔体内部流动。Krishnamurty[17]首次研究空气通过矩形腔的亚、超音速流动，Roshko[18]通过压力和速度测量描述腔体底部的流动。Charwat[19]研究了腔内流动随几何形状长深比、边界层厚度等因素影响下的变化。赵小见等[20]通过离散点测量方法获得腔内流动在观测点的压力统计及功率谱密度函数。

随着技术的发展和实验设备的进步，发现腔体内流动产生振荡现象。使用恒温热线风速测定法[21]对流动振荡现象研究，发现在下游腔角处的涡流周期性脱落[22]。在亚、超音速空气流中出现空腔强烈声辐射，其振荡频率与空腔宽度成反比[23]。文献[24]对超声速空腔的非定常振荡特性进行了数值研究。Tam[25]提出二维腔的声模式频率的精确计算，发现长深比为 1 或更大的空腔，自然模式被高度阻尼。Rockwell 等[26]也发现了流体动力学振荡归因于空腔剪切层的不稳定性并且通过反馈机制增强。Ronneberger[27]将二维矩形切口的平板暴露于层流中和通过小孔的振荡流中，并将实验结果与解释水流对小孔声阻抗的模型预测进行比较。将腔外部流与腔流支撑剪切层分离，发现在高速下界面上形成单个大尺度涡流，在低速下同时存在两个涡流[28]。

近些年，学者的实验开始注重降低腔内噪声，Wang 等[29]研究亚音速流引起的噪声，特别关注开放天窗的汽车舱内低频压力振荡的问题。吴继飞等[30]采用剪切层扰流法研究亚、跨声速条件下开式流场的气动声学特性及气动噪声抑制效果。

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在航空业进行腔体实验研究有一定难度,试验设备的安装受环境影响大,自激振荡产生噪声与其他复杂流动噪声混合,同时增加了实验难度。

3 数值模拟方法

随着计算机技术和计算流体力学和气动声学的发展,腔体气动噪声研究开始以数值模拟方法为主,主要有直接数值模拟[31]大涡模拟[32]分离涡模拟[33]以及混合模拟方法等。

直接数值模拟领域,Fuglsang 等[34]研究纳维-斯托克斯(N-S)模型模拟非强制和强制腔体剪切层。Slimon 等[35]使用 EIF 方法,耦合黏性不可压缩流体动力学方程和无黏脉动方程,求解腔内流场压力和环境参量,发现模拟结果与湍流模型密切相关。Colonius 等[36]通过可压缩 N-S 方程计算空腔流体中的谐振不稳定性,解析辐射部分声场。Hamed 等[37]研究马赫数对开放空腔不稳定流动的影响,使用六阶空间差分与十阶隐式滤波器耦合的可压缩 N-S 方程获得隐式解。Abalakin 等[38]基于欧拉模型研究直接噪声计算(DNC)的精确性并且考虑模型完整性。

大涡模拟方面,Arunajatesan 等[39]利用大涡模拟计算表明微射流在抑制剪切层方面非常有效。Chen 等[40]采用大涡模拟和分离涡模拟两种方法分别研究了近、远压场三维湍流流动随时间的变化。Marsden 等[41]运用大涡模拟(LES)提供的声辐射在应用主动控制时显著减小,观察到剪切层中垂直速度波动和腔内的涡旋结构的强度也同时减小。Gloerfelt 等[42,43]研究高雷诺数空腔流的大涡模拟。温鑫等[44]对低速湍流流经带隔板长方形空腔时腔体内的流动进行数值模拟,使用大涡模拟模型,考查隔板几何参数对空腔流动特性的影响。

分离涡模拟方面,谭玉婷等[45]结合雷诺平均方法和大涡模拟两者的优点,基于 SA 模型的 DES 方法,数值求解 N-S 方程。欧阳绍修等[46]研究三维非定常雷诺平均 N-S 方程和分离涡模拟方法在空腔流动及空腔噪音问题上的应用。

由于计算机技术的发展,近几年数值模拟多采用混合数值模拟方法。Ashcroft 等[47]使用 N-S 方程计算由 k-ω 模型建模的近场湍流,研究自由流速度和边界层的厚度对腔内振荡频率和幅度影响。Gloerfelt[48]使用直接数值模拟与混合方法获得辐射噪声进行比较,使用在腔内计算的流场与积分公式组合以评估远场噪声。Reymen 等[49,50]发现不连续 Galerkin 方法(DGM)可以被看作有限体积法的扩展,通过增强时域阻抗边界条件创建一种新的公式。郝维等[51]用 k-ε 模型和大涡模拟方法分析涡流分布和脉动压力,使用 MATLAB 平台进行快速傅里叶变换。余培汛等[52]将分离涡模型计算流体力学(CFD)和空气动力学声学频域理论(FW-H 积分方程)用于模拟空腔噪声变化和剪切流流动特性。王芳等[53]基于格林函数和 Lighthill 的声学模拟理论,用二阶精度的拖延分离涡模型进行流场的数值模拟。张群峰等[54]研究分离涡模拟(DES)和非线性声学方法解决非线性波动方程的数值模拟。Roeck 等研究了流动与声场分离的混合 CAA 方法[55]。使用大涡模拟与 Ffowcs Williams-Hawkings 方程耦合的混合方法捕获流动噪声[56—58]。Bie 等[59]用混合方法研究二维空腔和三维射流上来自不稳定湍流的噪声产生和近场辐射。刘聪尉等[60]采用 LES-Lighthill 声类比混合方法,比较不同形状空腔噪声辐射特性。

其他数值模拟方法,例如通过从双方程 SST 湍流模型的尺度自适应模拟模型的计算流体动力学(CFD)技术喷射流的主动控制方法[61],模拟标准腔中流动特性,流场结构和噪声机制。对高雷诺数下不同结构的方腔的湍流数值模拟[62]以及内置发热源的方腔内双扩散混合对流现象的数值模拟等[63]。

数值模拟方法在对于网格数量大网格质量要求高的腔体运算困难,需要计算机硬件运行速度的提升。但是对于多数腔体的噪声计算,数值模拟计算是主要手段。

4 噪声控制技术

腔体气动噪声的机理研究,奠定了噪声控制的理论基础。Zhang 等[64]对超音速腔内流动进行实验和计算研究,发现沿着腔的两个侧壁安装管对减少沿腔中心线的不利压力梯度是最有效的。Sellen 等[65]研究多孔材料性质和主动控制技术的混合声系统以减少流动管道应用中的宽带噪声谱。Sun 等[66]将网格布置在空腔中和空腔的前缘处,研究网格程序相对于洁净腔的噪声抑制效应和流场变化。Robert[67]修改现有的混合雷诺平均 N-S 和大涡模拟湍流模型来解释旋转和曲率效应,预测武器室中不稳定流动以及用于评估扰流器效率。Lackey 等[68]对高马赫数腔室流动的新型声抑制装置有效性进行计算流体动力学研究。高峰等[69]利用免疫遗传算法设计最佳压电片位置,进而降低腔体声压级。

在腔体上游加降噪扰流装置,利用圆柱销[70,71]进行腔体流动控制的实验发现抑制水平受到针形图案,密度和高度的影响。腔的前缘附加之字形扰流器[72],使用延迟分离涡模拟的 SAES 模型分析具有

固定马赫数和长宽比的矩形腔的噪声级。通过加致动器降噪,开发分布式压电致动器[73]、角型等离子体制动器[74]、压电陶瓷致动器片[75]等。

通过改变空腔形状观察衰减振荡情况进而选择噪声最小的空腔形状[76—78],白海涛[79]发现三角形空腔噪声明显小于矩形和椭圆形。研究具体前缘扰流激励技术[80]和高频纯音激励技术[81]降低空腔噪声。

腔体噪声抑制依赖于腔体流动及噪声产生机理进行研究,利用加降噪装置进行噪声抑制成为重要举措。

5 结语

综上所述,航天等领域对噪声控制及腔体气动力噪声的研究已变得越来越重要。在过去 50 年逐步推进和完善的噪声控制技术,可以预测在本世纪腔体的空气动力学噪声研究和控制将取得新的突破,下列领域将成为重点关注对象。

(1) 宽带噪声控制机制研究。随着腔流场到超声波和纵横比的发展,腔体的内部马赫数将增加,宽带噪声的影响将变得越来越明显。因此,宽带噪声的控制机制将是未来研究的重点。

(2) 噪声数值预测方法的工程应用。空腔气动噪声的数值模拟为腔的低噪声设计或实际降噪提供了理论基础。之前的研究仅限于噪声预测和计算,噪声数值分析方法的工程应用将成为研究的重点。

(3) 多学术领域、多研究方法的噪声控制技术。随着计算流体动力学,空气动力学声学,新的模拟方法和计算机硬件的快速发展,腔噪声控制效应将变得越来越明显,并且方法将更复杂和系统。腔结构优化,气动噪声分析,质量寿命计算等多学科领域的性能指标,多研究方法将逐步关注。

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Research Status and Development Trend of Cavity Aerodynamic Noise

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[**Abstract**] Cavity flow exists widely in transportation, aerospace and other industries, while the high speed fluid through the cavity, self-excited oscillation in the cavity, the flow field and sound field coupling of the aerodynamic noise will cause vibration and fatigue damage of the structure, and even affect the life of the structure, so as to control and reduce the cavity aerodynamic noise has become the focus of the problem of the scholars at home and abroad. Based on reading a lot of literature, an overview of the current research status of cavity aerodynamic noise, prediction theory, experimental analysis and induction cavity aerodynamic noise, numerical simulation method and noise control technology, the future development trend of gas cavity noise.

[**Key words**] cavity　aerodynamic noise　theoretical prediction　experimental study　numerical simulation　control technology