

外流作用下管道流固耦合非线性动力学研究进展*

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摘要 管道广泛应用于海洋、核电以及航空航天等重大工程中,是采油平台、蒸汽发生器等重要工程装备的关键结构之一.当有外部流体经过时,管道会发生流固耦合振动行为,这是导致重大装备振动破坏和失效的重要原因之一,已成为重大工程设计必须解决的关键问题.本文针对外流作用下柔性管道流固耦合非线性动力学机理这一科学问题,梳理了国内外学者的重要研究成果,重点分析了柔性管道分别在横向外流和轴向外流作用下的流固耦合非线性振动行为.从实验研究、仿真分析和理论建模等方面进行了深入的探讨,揭示了外部流体对管道动力学行为的影响机制.最后,对国内外研究现状进行了简要的总结,并给出了这一研究仍存在的难点与挑战.

关键词 管道, 流固耦合振动, 屈曲, 颤振, 非线性动力学

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Research Progress on Fluid-Structure Interaction Vibrations of Pipes Subjected to External Flows*

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Abstract Pipes are widely employed in marine, nuclear power, aerospace and other important engineering applications. The pipe is one of the most key structures for engineering equipment such as the oil production platform and the steam generator. When the external fluid flows through the pipe, fluid-structure interaction vibration behavior of the pipe occurs, leading to vibration damage and fatigue failure of the engineering equipment. It has become a key problem that must be solved in engineering design. As to the scientific issues on nonlinear dynamical mechanism for fluid-structure interaction vibrations of flexible pipes subjected to external flows, this paper reviews the important research progress over the world scholars, focusing on discussing the nonlinear fluid-structure interaction vibrations of flexible pipes subjected to external cross flows and axial flows, respectively. The influence mechanism of external flows on dynamic behaviors of the pipe is revealed from aspects of the experimental research, computational fluid dynamics simulation and theoretical modeling. Finally, the current research status is briefly summarized and the research difficulties and challenges still exist in this field are proposed.

Key words pipe conveying fluid, buckling, flutter, nonlinear dynamics

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引言

管道在重大工程中应用非常广泛,比如,航空加油管、海洋采油立管、核电蒸发器传热管和微/纳尺度管等.当受到流体作用时,管道会发生流固耦合振动行为,这是导致工程结构振动破坏和失效的重要因素,成为重大工程设计必须解决的关键问题.管道动力学行为受多种因素的影响,比如结构和流体属性、边界条件和基础激励等^[1-4].由于管道流固耦合振动展现出丰富的动力学行为,其动力学特性和响应规律成了研究者关注的一个焦点.因此,在过去的60多年里,针对管道系统的稳定性、动力学行为和振动控制等问题,国内外学者开展了大量而深入的研究工作,取得了一系列重要研究成果^[5-10].

对于管道流固耦合振动特性的研究,一般从线性^[5,6]和非线性^[7,8]角度去表征动力学特性;根据管道内部流体流动状态的不同,可分为定常流和非定常流^[9,10].此外,根据边界条件的不同,可分为悬臂和两端支承边界.对于悬臂管道,在较大内流速下,会发生动态颤振失稳;对于两端支承管道,Holmes^[11]则指出,这类系统不会发生颤振,在内流速达到临界值时会发生静态屈曲失稳.另外,还有学者研究了复杂约束或边界条件下管道的流固耦合动力学特性,比如附加质量^[12,13]、运动约束^[14,15]、组合支撑^[16]以及旋转运动^[17,18]管道等,发现了一些丰富的动力学行为,为工程中管道结构设计提供了理论指导.

需要指出,上述研究大多探究的是内流作用下管道的非线性动力学问题.然而,工程中的管道除了受内流作用外,还会在外部流体力作用下产生流固耦合振动行为.比如,海洋工程中采油管线在洋流作用下发生涡激振动;核工程中传热管在二次侧流作用下经常发生湍流激振和流弹失稳等有害振动.因此,外流诱发细长柔性管道的失稳问题在工程中也愈发突出,通过探究这类动力学问题的内在机理,从而提出有效的管路设计方案和控制方法,已成为动力学与控制领域需要解决的一个重要科学问题.

当外部流体流动方向与管道轴线方向垂直时被称为横向外流,平行时则被称为轴向外流.在横向外流作用下,管道结构后方会出现周期性交替脱

落的旋涡.由于旋涡脱落,流体对结构产生升力和曳力,从而诱发结构振动;而结构振动反过来影响外流流动状态,此类现象称为“涡激振动”^[19](Vortex-Induced Vibration, VIV).涡激振动现象广泛存在于工程实际中,比如桥梁、输电导线、采油立管、系泊结构和各类水声结构等^[20].涡激振动行为具有自激、自限和锁频区域等非线性特性,它与轴向外流作用下结构的动力学机理完全不同.在轴向外流作用下,细长结构不仅受到离心力、科氏力和附加外流引起的惯性力作用,还会受到外流引起的法向和纵向黏性力作用.由轴向外流诱发的颤振、屈曲等失稳行为在工程中也经常发生,比如航空加油管、核工程中燃料棒等.下面本文分别从横向外流和轴向外流两个方面,总结国内外学者采用实验研究、仿真分析和理论建模这三种方法探究管道流固耦合动力学行为的重要研究成果,并提出这一研究仍存在的难点和挑战,研究框架如图1所示.

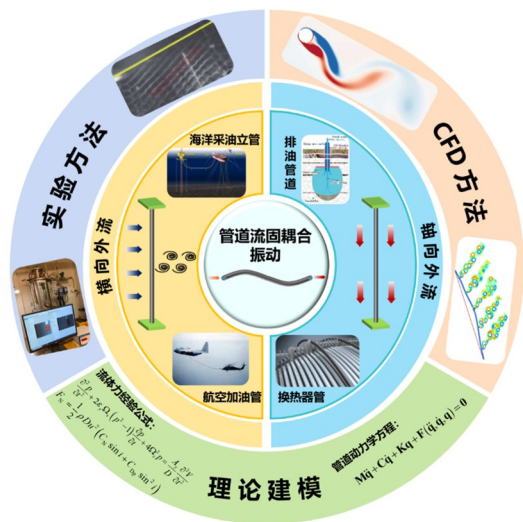


图1 外流作用下管道流固耦合振动研究框架

Fig.1 Research framework on fluid-structure interaction vibrations of pipes subjected to external flows

1 横向外流下管道动力学

由于细长圆柱体和管道的几何构型相似,因此许多涡激振动研究都是围绕这类结构展开的^[21-23].纵观管道涡激振动问题的研究文献,可以发现主要采用了以下三种研究方法:实验研究、数值方法和理论建模.

1.1 实验研究

由于涡激振动的复杂性,早期的研究大多是围

绕涡激振动实验展开的. 实验中, 一般采用线性可变量位移传感器测量位移, 同时使用非接触式位移传感器测量升力和阻力^[24], 也可在管柱上设置测点, 在测点上沿管柱的横向和流向布置应变片以采集振动信息^[25-27]. 其中, Feng^[28]、Sarpkaya^[29] 和 Khalak 等^[24] 在刚性圆柱体上进行了一系列实验研究, 阐明了涡激振动的主要特征, 这些实验是为众多涡激振动实验中的一小部分, 非常具有代表性.

在 Feng^[28] 的实验中, 研究对象为放置于空气中具有单自由度的柱体, 实验中的质量比(结构质量/附加流体质量)和雷诺数(Re)较大. 而 Khalak 和 Williamson^[24] 的另一项实验则是在水中进行的, 其实验模型如图 2(a) 所示, 质量比和雷诺数相对较小, 实验的漩涡脱落情况如图 2(b) 所示, 可以

看出每个周期形成了两个涡对, 并且得到了 Griffin 图(图 2(c)). Feng^[28] 的实验结果表明, 在较高雷诺数下, 柱体的响应幅值有两个分支(初始的和下面的), 而 Khalak 和 Williamson^[24] 的实验结果表明, 在较低雷诺数下, 涡激振动响应有三个分支(初始的、上面的和下面的), 而且具有更大的振幅和更宽的外流速锁频范围. 上述实验研究大多分析不同流动条件下细长圆柱体结构的涡激振动问题, 还有一些研究评估了涡激振动抑制方法的有效性^[25-27,30]. 最近, 贾杜平^[25] 等分析管柱在横向和流向的应变、频率、位移标准差以及模态特征如图 2(e)-(f), 其实验模型如图 2(d) 所示. 在这些实验研究中, 重点探究了涡激振动幅值、主导模态和频率、横流向(Cross-Flow, CF)和顺流向(In-Line, IL)响应的耦合疲劳损伤等问题.

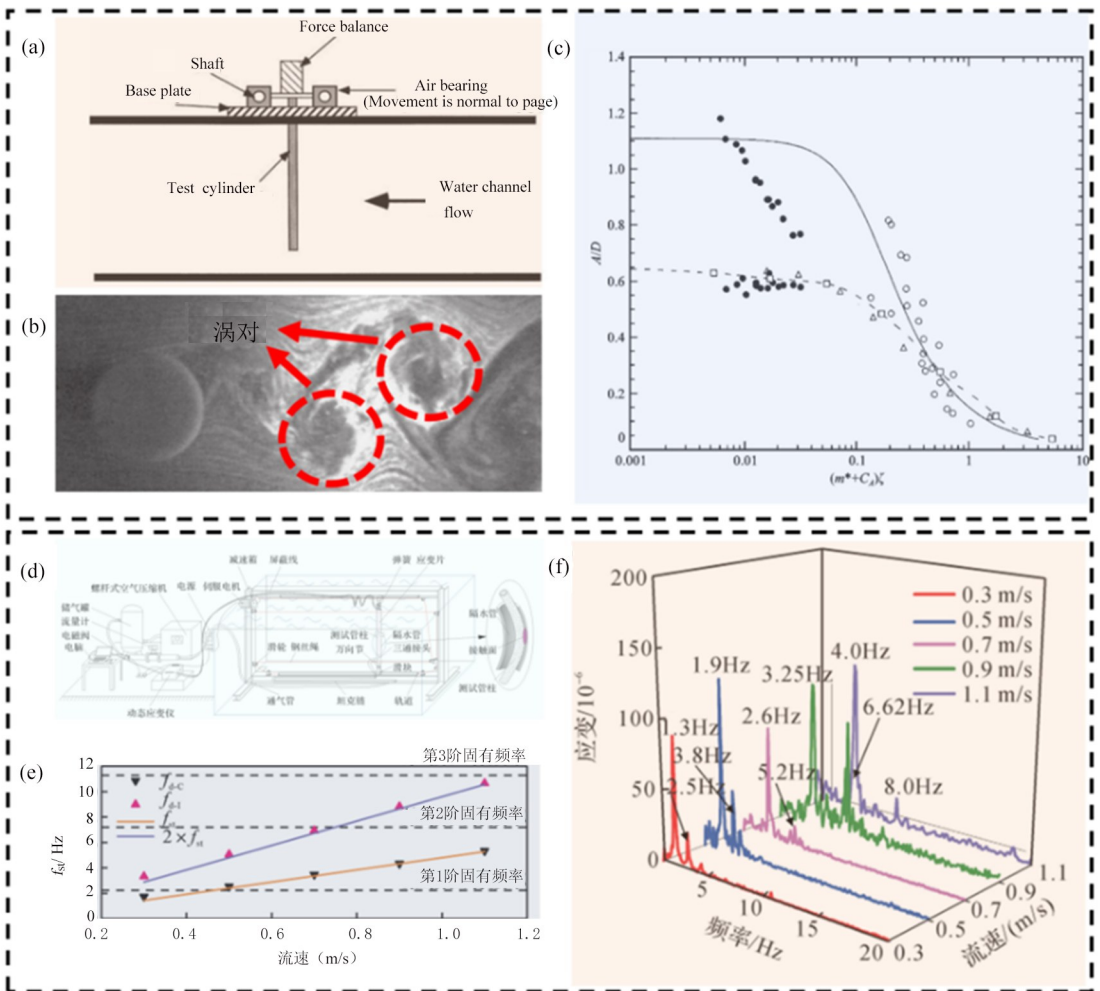


图 2 实验研究概况^[24,25]. (a, d) 实验模型; (b) 漩涡脱落情况; (c) Griffin 结果图; (e) 不同流速下振动响应频率; (f) 不同流速下漩涡脱落频率

Fig.2 Experimental researches^[24,25]. (a, d) Experimental setup; (b) Vortex shedding condition; (c) Griffin plot; (e) Response frequency of pipe at different flow velocities; (f) Vortex shedding frequency at different flow velocities

1.2 数值方法

除了实验研究外,还有许多文献使用数值模拟方法研究刚性或柔性立管的涡激振动^[31,32].在使用CFD方法计算涡激振动响应时,主要采用以下数值方法:准三维方法(Quasi-Three-Dimensional, Q-3-D)^[33]、离散涡方法(Discrete Vortex Method, DVM)^[34]、全三维有限元法(Finite Element Method, FEM)^[35]、有限体积法(Finite Volume Method, FVM)^[36]和有限解析纳维-斯托克斯法(Finite Analytic Navier-Stokes Method, FANS)^[37]等.

Q-3-D数值模拟法是指在三维空间中,沿圆柱体跨度放置多个二维计算平面,用一个无黏的非定常三维涡旋晶格进行流体动力学连接以表征三维

涡量场^[33].DVM是一种用于模拟二维不可压缩黏性流体流动的拉格朗日数值格式技术^[34].FEM和FVM对计算域复杂度适应性好,可以在模拟过程中改变整体网格形状,以适应管道的弯曲,但FVM数据结构较为简单,采用的形函数更为简单,计算效率更高^[35,36].FANS是完全三维的,没有省略任何纳维-斯托克斯方程中的项,能够以合理的精度预测管道的运动响应^[37].通过CFD方法得到柱体的运动轨迹,如图3(b)所示.从涡量图可以看出每个周期形成了两个涡对,呈现出2P模式,如图3(c)所示.然而,正如Wang等^[38]所指出的,对不同流动条件下的立管进行完整的三维流固耦合仿真仍有许多限制和挑战.因此,使用CFD方法研究立管的涡激振动有待进一步探索.

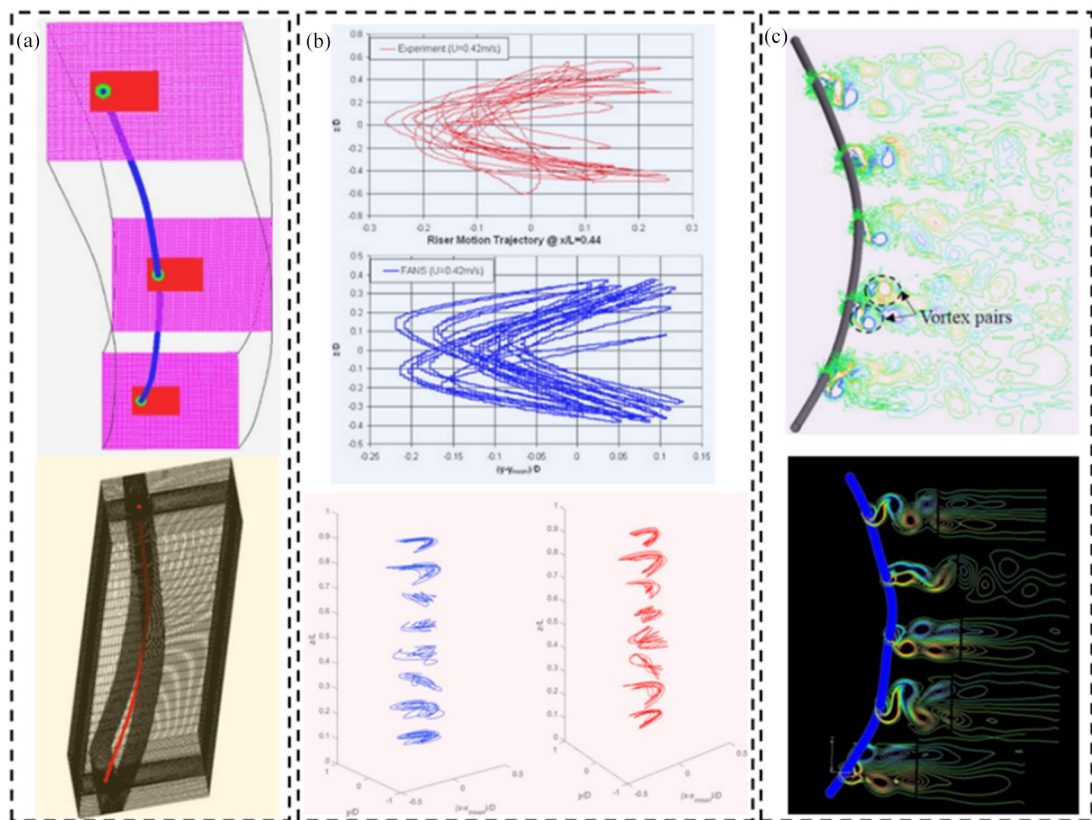


图3 计算流体动力学^[37,38]. (a) 仿真模型及网格; (b) 结构振动轨迹图; (c) 涡量图

Fig.3 Computational fluid dynamics (CFD) ^[37,38]. (a) Simulation model and mesh structure; (b) Phase trajectories; (c) Vortex contour

1.3 理论建模

预测管道涡激振动的第三种方法是利用理论模型,也称经验模型.这些经验模型本质上是基于静止或振动柱体旋涡脱落的实验数据总结归纳得出的,旨在预测直管或具有更加复杂三维构形管路

的涡激振动.比如,Liu等^[39]使用遗忘因子最小二乘法(Forgetting Factor Least Squares, FF-LS)识别多频涡激振动下柔性立管的时变水动力,他们发现考虑多频耦合效应的时变涡激力系数可以准确地重构立管所受涡激力,而多频率下的涡激力系数之和会产生过高估计的涡激力交叉项.Zhang等^[40]

推导了多频率下的涡激力,并采用水动力和系数识别方法,研究了带有浮力元件的柔性立管的水动力特性,还分析了横流向附加质量系数和激励系数的特性,发现裸管的附加质量系数比浮力元件大,但裸管和浮力元件的总质量沿管长是一致的。Qu

等^[41]提出了一种新的单个尾流振子模型,如图 4(a)、图 4(b)所示,其尾涡强度、升力和阻力由式(1)一式(3)计算得到,基于该尾流振子模型,他们预测了柔性圆柱体的三维涡激振动,如图 4(c)所示,发现该模型能满足柔性圆柱体涡激振动的大多数特征。

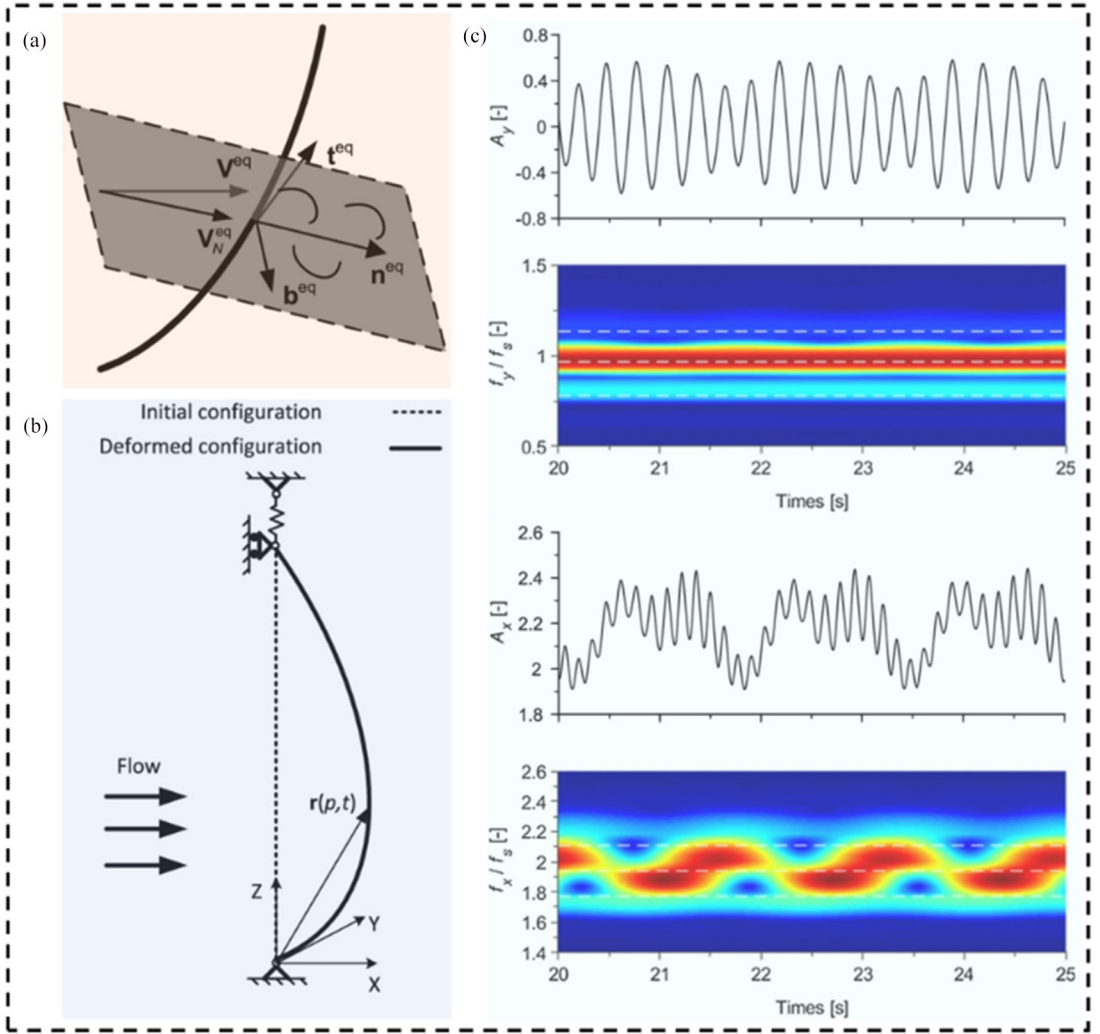


图 4 理论模型^[41]。(a) 建模分析示意图;(b) 模型示意图;(c) 位移及频率随时间的变化曲线
 Fig.4 Theoretical modelling ^[41]。(a) Schematic diagram for modelling; (b) Schematic diagram of the model
 (c) Displacement and frequency varying with time

$$\ddot{q} + \omega_s (q^2 - 1) \dot{q} + \omega_s^2 q - \kappa \frac{\omega_s^4 D \dot{\mathbf{r}}^T \mathbf{n}^{eq}}{\omega_s^4 D^2 + (\dot{\mathbf{r}}^T \mathbf{n}^{eq})^2} q = \frac{A}{D} \dot{\mathbf{r}}^T \mathbf{b}^{eq} \quad (1)$$

$$\mathbf{F}_{VL} = \frac{1}{2} \rho D \frac{C_{L0}}{2} q |\mathbf{U}_N|^2 \mathbf{D}_{VL} \quad (2)$$

$$\mathbf{F}_{VD} = \frac{1}{2} \rho DC_{VD} |\mathbf{U}_N| \mathbf{U}_N \quad (3)$$

1.4 工程应用模型研究

近些年来,针对轴向内流和横向外流作用下柔

性立管的涡激振动问题,学者们开展了广泛的研究,建立了各种各样的理论模型,并得到了丰富的结果,如图 5 所示。事实上,这类管道系统在海洋工程中具有重要的应用价值。流体建模大多采用尾流振子模型^[42-45]式(4)、式(5)。将尾流振子模型与结构控制方程进行联立求解,从而实现流固耦合计算。但尾流振子模型为半经验半理论模型,这个模型忽略了涡型和涡强度等细节。

早期,由于在横流向上经常观察到较大的响应幅值,因而管道涡激振动的研究大多局限于横流向

的响应^[20,46,47].例如,Keber等^[48]探讨了几何非线性对管道二维涡激振动响应的影响.Dai等^[49]分析了均匀横向外流中管道横流向的二维涡激振动响应,发现内流速对管道的非线性动态响应有很大的影响,特别是当内流速超过管道屈曲失稳的临界流速时.Meng等^[42]研究了轴向内流和横向外流对悬臂管道二维涡激振动响应的影响,他们利用线性振动理论建立了管道的振动控制方程.Guo和Lou^[50]是较早研究管道非平面涡激振动的学者,他们设计了实验来测量部分浸入波浪和水流中的两端固支

管道的非平面运动.他们考虑了内流、水波和外流的影响,观察到了管道弯曲变形的“8字形”运动轨迹.最近,Meng等^[43]和Yang等^[51]研究了均匀横向外流中两端简支管道的三维涡激振动.Liu等^[44]建立了碰撞约束下受横向外流作用的悬臂管道的三维理论模型,探究了内、外流体速度对悬臂管道涡激振动特性和分岔行为的影响.大量研究表明,由于双倍振动频率的关系,顺流向涡激振动可能与横流向的涡激振动一样,都可能造成结构的疲劳损伤^[52].

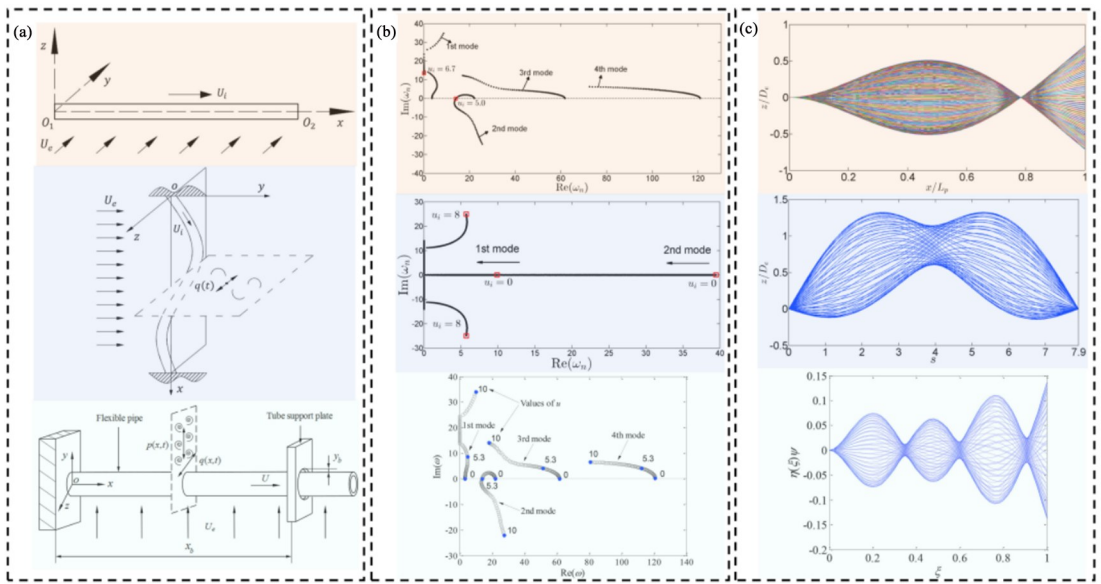


图5 工程应用模型^[42-44]. (a) 简化力学模型; (b) Argand图; (c) 振型图

Fig.5 Models devised from engineering applications^[42-44]. (a) Simplified mechanical model; (b) Argand diagram; (c) Oscillating shapes

$$\frac{\partial^2 q}{\partial t^2} + \varepsilon_z \Omega_s (q^2 - 1) \frac{\partial q}{\partial t} + \Omega_s^2 q = \frac{\Lambda_x}{D} \frac{\partial^2 W}{\partial t^2} \quad (4)$$

$$\frac{\partial^2 p}{\partial t^2} + 2\varepsilon_y \Omega_s (p^2 - 1) \frac{\partial p}{\partial t} + 4\Omega_s^2 p = \frac{\Lambda_y}{D} \frac{\partial^2 V}{\partial t^2} \quad (5)$$

然而,在海洋工程中,横向来流沿管长方向的速度分布不一定是均匀的,有可能是变化的.近些年来,剪切外流中柱体涡激振动问题引起了学者们的研究兴趣^[53,54].与均匀外流相比,在剪切外流中振动的刚性圆柱体,旋涡脱落发生在沿管长分布的有限长度的恒频单元^[55]中.Vandiver等^[56]研究了均匀和剪切外流中缆绳模态数的差异,发现在均匀外流中“锁频”现象可能发生在很高的模态数下,而这种情况在剪切外流中不会出现.Mathelin等^[57]研究了剪切外流下三种不同结构模型的涡激振动特性.此外,通过实验方法,许多学者研究了剪切外

流中圆柱体的涡激振动特性(Marcollo等^[58]和Vandiver等^[59]),如图6(a)-图6(c)所示.

除了理论和实验方法之外,还有文献利用数值模拟方法研究了剪切外流中柔性立管的涡激振动响应.Huang等^[60]使用CFD方法模拟了剪切外流中立管的涡激振动,他们考虑了两种横向外流情况,发现在剪切外流中尾流脱落模式为“2S”和“C”模式的混合,而在均匀外流中立管的运动和旋涡脱落模式通常是同步的.Bourguet等^[61]通过三维直接数值模拟(Three-Dimensional Direct Numerical Simulation, 3-D DNS)方法,研究了线性剪切横向外流中细长张紧圆柱体的三维涡激振动问题,得到了升力及阻力的时变图及运动轨迹图,如图6(d)、图6(e)所示,发现在剪切外流中横流向和顺流向的波形可能都包含了驻波和行波的混合模式.此

外, Bourguet 等^[61]重点探讨了横流向和顺流向运动的频率响应关系,还研究了旋涡脱落和结构振动的同步行为以及多频振动机理等问题. Jiang 等^[45]研究在横向剪切外流与轴向内流共同作用下管道的动力学行为,发现横向运动和直线运动的耦合频

率以及相应的耦合阻尼比会受到外部和内部流体速度的影响. 研究结果还表明,剪切参数对隔水管的动力响应有显著影响. 当横流剪切参数较大时,可以激发立管的多模态准周期响应,表现出均匀横流输送立管系统中未发现的新特征.

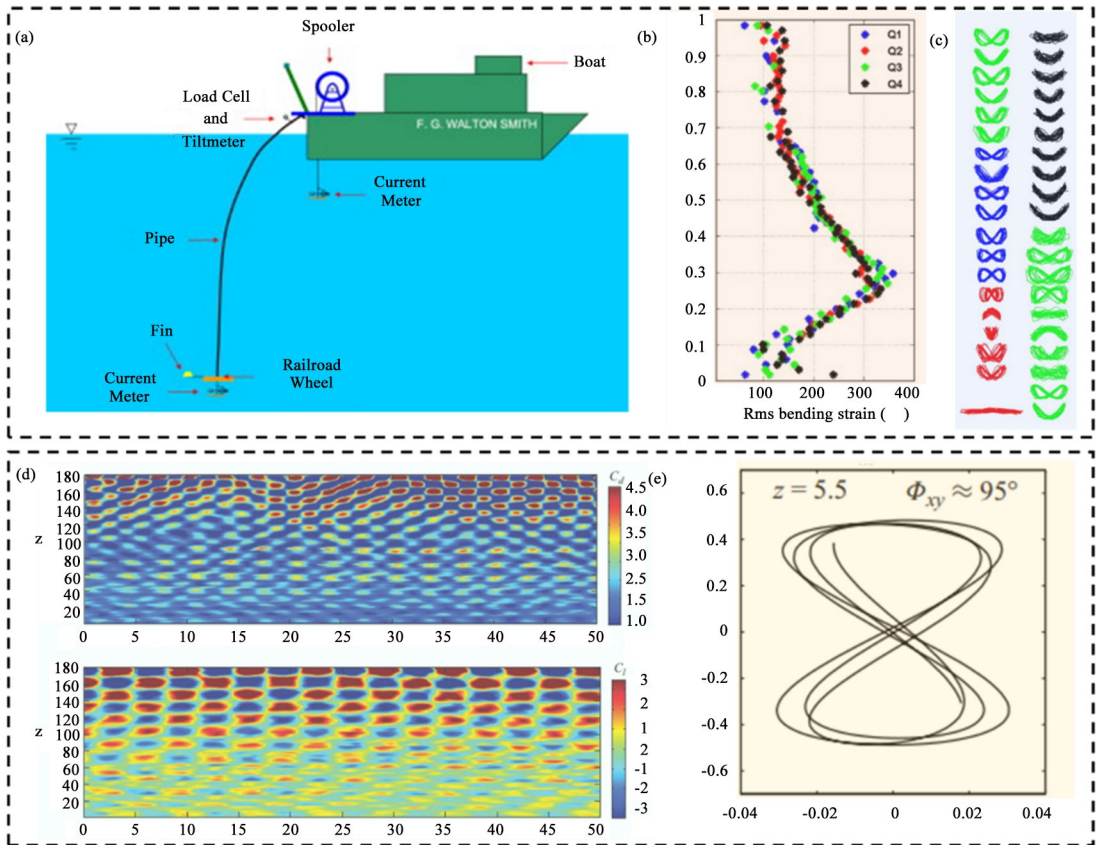


图6 剪切外流下管道涡激振动研究^[59,61]. (a) 模型示意图; (b, e) 运动轨迹; (c) RMS 弯曲应变; (d) 升/阻力系数变化
Fig.6 VIV of pipe in shear flows^[59,61]. (a) Schematic diagram; (b, e) Phase trajectories; (c) RMS bending strain; (d) Evolution of lift and drag coefficients

2 轴向外流下管道动力学

国内外关于轴向外流作用下管道流固耦合振动的研究大多集中在理论建模方面,通过建立流体力和管道结构的耦合动力学理论模型,研究细长管道的非线性动力学行为;对于实验和数值模拟方面的研究相对较少.下面将从理论研究、数值方法和实验研究三方面详细介绍国内外学者的研究进展.

2.1 理论建模

学者们进行了大量的理论研究,不断对轴向外流对管道作用的流体力模型进行修正,再将得到的流体力模型与结构控制方程相结合,从而对管道的动力学行为进行预测.通过对狭长动物游泳的研

究, Taylor^[62]首次提出了轴向外流作用在柱体结构上的黏性力的数学表达式见式(6)-式(8). Grigoriou^[63]、Paidoussis 和 Besancon^[64]以及 Wang 和 Bloom^[65]等学者对其进行了一系列的早期研究.值得指出的是,由于三维理论模型的复杂性,早期关于轴向外流中管道的动力学研究通常局限于平面振动情形.例如,基于线性理论, Hannyer 和 Paidoussis^[66]在 1978 年分析了轴向内流和轴向外流共同作用下圆管的稳定性和平面动力学行为式(7),发现两端支承和悬臂管道的稳定性特性有本质的区别.对于两端支承管,当内流速或外流速增大时,系统首先发生静态屈曲失稳,随后在较高外流速下发生颤振失稳.然而,对于悬臂管道,系统的稳定性则主要取决于内、外流速的绝对值和管道自

由端的形状.随后,Paidoussis等^[64]研究了轴向外流中管束的平面动力学和稳定性行为.

$$F_N = \frac{1}{2} \rho D u^2 (C_N \sin i + C_{Dp} \sin^2 i) \quad (6)$$

$$F_L = \frac{1}{2} \rho D u^2 C_T \cos i \quad (7)$$

$$\begin{aligned} & \left(1 + k \frac{\partial}{\partial t}\right) \left(EI \frac{\partial^4 y}{\partial x^4}\right) + \rho_i A_i \left(\frac{\partial}{\partial t} + U_i \frac{\partial}{\partial x}\right)^2 y + \\ & \rho_e A_e \left(\frac{\partial}{\partial t} + U_e^* \frac{\partial}{\partial x}\right) \left(\frac{\partial y}{\partial t} + U_e \frac{\partial y}{\partial x}\right) - \\ & (\rho_e A_e - \rho_i A_i - \rho A) g \frac{\partial y}{\partial x} - \\ & (T + A_e p_e + A_i p_i) \frac{\partial^2 y}{\partial x^2} + q_{bn} + \rho A \frac{\partial^2 y}{\partial t^2} = 0 \end{aligned} \quad (8)$$

1994年,基于理论和实验方法,Gagnon和Paidoussis^[67,68]研究了轴向外流中管束的流固耦合特性和湍流诱发的振动响应问题.此后,基于线性或非线性理论,学者们系统地研究了轴向外流中圆柱体的动力学行为.例如,2002年,Paidoussis、

Lopes和Semler等^[69-71]报道了由三篇文献组成的研究,探究了轴向外流中悬臂管道的动力学行为.在该研究的第一部分中,Paidoussis等^[70]分析了系统的稳定性和能量传递机制,发现实验结果和线性理论结果吻合得较好.在第二部分中,Lopes等^[69]利用Hamilton原理推导了轴向外流作用下悬臂圆柱体的非线性运动方程.在第三部分中,基于第二部分推导出的控制方程,Semler等^[71]通过分岔图、相图和Poincaré映射图分析了系统的线性和非线性动力学行为,并再次证实了理论结果和实验结果的高吻合度.此外,Modarres-Sadeghi等^[72]和Kheiri等^[73]研究了轴向外流中具有不同边界条件的细长圆柱体的动力学行为.除了上述研究外,还有许多文献探究了轴向外流作用下多种细长结构的稳定性和振动特性^[74,75].由于简支管的轴向位移通常比横向位移小一个数量级^[76],因此在许多轴向外流诱发的两端支撑管振动问题中,轴向位移通常是可以忽略的.

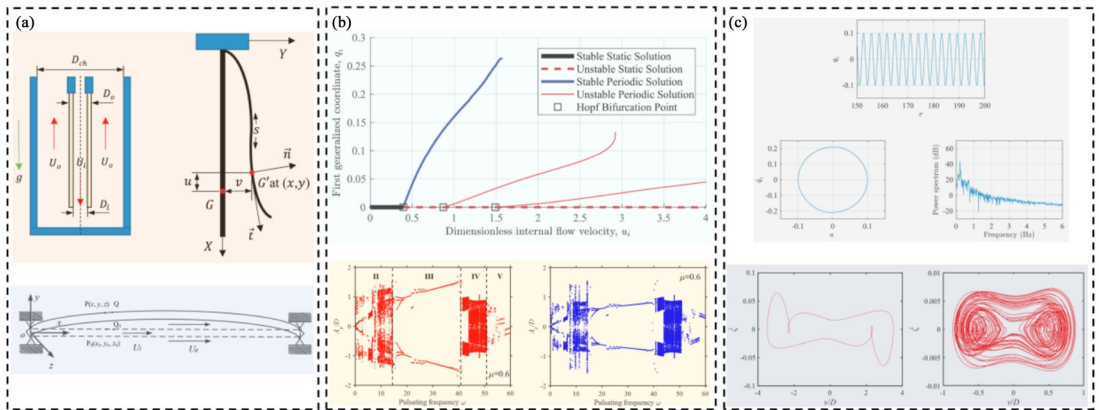


图7 理论模型研究^[78,81]. (a) 模型示意图; (b) 管道动力学分岔图; (c) 时间历程、相轨迹和PSD图

Fig.7 Theoretical modeling^[78,81]. (a) Schematic diagrams; (b) Bifurcation diagrams; (c) Time history, phase portraits and PSD diagrams

针对环形通道中受轴向内流和轴向外流作用的竖直悬臂管道,研究人员得到了丰富的管道动力学行为,如图7所示.Qian等^[77]建立了其平面振动理论模型,Abdelbaki等^[78]推导了轴向内流和轴向外流作用下悬臂管道的非线性理论模型,系统中内流和外流相互影响,且两者流向相反.通过与已发表的研究结果^[79]对比,Abdelbaki等^[78]验证了建立的理论模型的可靠性.然而,关于同时受轴向内流和轴向外流作用的管道三维动力学方面的研究文献还非常有限.迄今为止,Liang等^[80]进行的可

能是少有的利用三维非线性理论模型预测这类管道系统动力学行为的研究,他们建立了同时受轴向内流和轴向外流作用的旋转钻柱的三维理论模型,并综合分析了该系统的频率、能量、振型和时域响应.研究表明:黏性外流、流体速度、转速、重力和轴向预拉力对管道系统的动力学行为有显著的影响,且该旋转系统的动力学与无旋转悬臂管道的动力学有很大的不同.2020年,Jiang等^[81]分析了轴向外流作用下两端简支管道的线性稳定性以及三维非线性动力学响应.

2.2 实验研究

在过去的数十年里,学者们也相继开展了实验研究,观察到了丰富的动力学现象.实验中,主要通过位移跟踪器来跟踪管道自由端附近点的运动^[82,83].跟踪器有单向位移跟踪器、双向位移跟踪器两类,将跟踪器捕获的运动视频进行识别处理从而进行数据分析.比如,Kuiper 等^[84]设计了一种实验装置,其中管子的自由开口一端在水里,而固定的一端在水面以上.实验结果表明,悬臂管道吸水速度超过临界流速时,悬臂管道失稳.管道失稳时表现出由两个交替相组成的复杂运动.Moditis 等^[85]将悬臂管道悬挂在一个大直径的刚性外管内,研究了系统长度的影响.增加长度会导致渐近

稳定行为,管道的临界流速和相关频率都达到了极限值.当管道足够长时,系统通过 Pitch 分岔而不是颤振发生失稳行为.

Butt 等^[82]进行了流速比实验,实验模型和示意图如图 8(a)、图 8(b)所示,内管和外管是同心且为悬臂边界,管道的顶部固定在一个大的装满水的圆柱形罐中,实验获得了悬臂管道的相平面图,如图 8(c)所示,并发现当流速增加时,均方根振幅与曲线呈现急剧增加的趋势,如图 8(d)所示.还有一些实验研究发现了重要的动力学现象,比如,Chehrehghani 等^[83]研究了在部分受限外轴流作用下,悬臂输流管道的动力学特性;Minas 等^[86]发现轴向排油管道存在颤振现象,并且环形流动对排油管有很强的失稳作用.

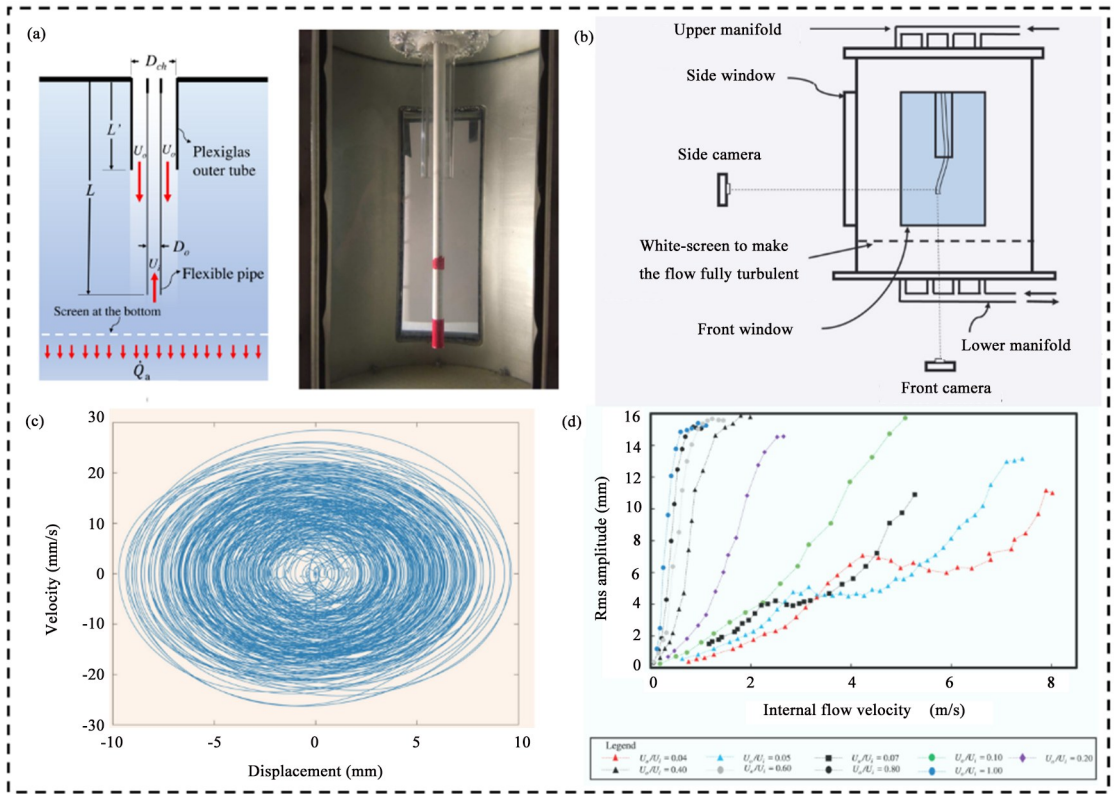


图 8 实验研究^[82]. (a) 实验模型; (b) 实验示意图; (c) 相平面图; (d) RMS 幅值
 Fig.8 Experimental research^[82]. (a) Experimental model; (b) Schematic diagram of the experimental apparatus; (c) Phase portraits; (d) RMS amplitudes

2.3 数值方法

除了实验研究和理论研究外,在近十年里,学者们尝试通过数值方法求解轴向外流作用下管道的动力学行为.对于轴向外流作用下的管道,相较于实验与理论建模的复杂性,数值方法建模较为简

单,仿真模型及网格如图 9(a)所示,但存在计算需求量大及计算时间长的问题.现有研究大多基于 CFD 与 CSM (Computational Fluid Dynamics - Computational Structure Mechanics) 方法耦合计算^[87-91],得到了周围流场及管道的变形情况如图 9 (b)所示.

早期, Giacobbi 等^[87] 针对悬臂吸流管道结构建立了 CFD 和 CSM 的完全耦合模型, 通过数值计算结果对牛顿解析法推导的描述系统的线性运动方程进行了修正, 考虑了进气处所包含的两部分流体降压的影响. Kontzialis 等^[88] 对部分受限悬臂管在内外反方向同时流作用下的动力响应和稳定性进行了数值研究. 结果表明, 随着约束程度的增加, 系统对不稳定性的敏感性增加. De Ridder 等^[89] 利

用 CFD-CSM 耦合模拟计算了圆柱束的模态特性. 近年来, De Santis 等^[90] 使用商业代码 STAR-CCM+ 进行流固耦合模拟来研究核燃料棒的流动诱导振动, 重点研究速度脉动对棒材振动的影响. 此外, Daneshmand 等^[91] 研究了一根细长的柔性垂直悬臂管在刚性管内同心悬挂形成环空的模型, 并进行了双向流固耦合仿真分析, 重点探究了仿真模型预测系统开始发生颤振失稳的能力.

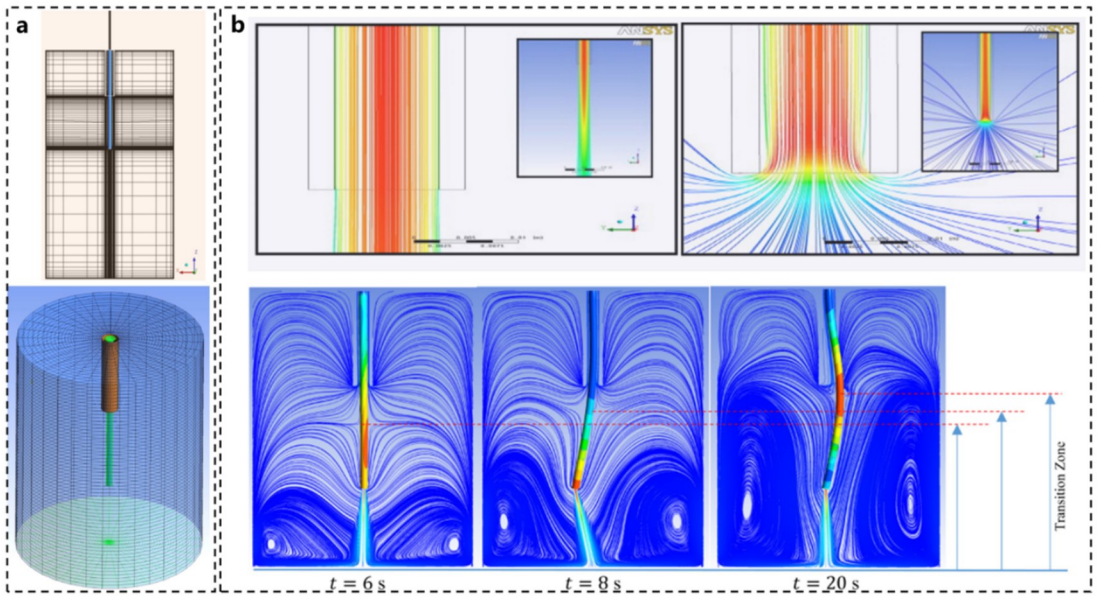


图9 计算流体动力学^[87,91] (a) 仿真模型及网格; (b) 流场及管道变形

Fig.9 Experimental research^[87,91] (a) Simulation model and grid; (b) Fluid field and pipe deformation

3 结论与挑战

本文对外流作用下管道流固耦合动力学研究进行了详细的概述, 从文中可以看出, 关于管路系统流固耦合振动的理论分析和实验研究非常丰富, 众多文献从频率、模态、分岔行为和动态响应等多个方面对外流作用下各类管道结构的动力学特性进行了深入而系统的探究. 本文分别针对横向外流和轴向外流作用下管道流固耦合振动问题, 介绍了国内外学者所采用的研究方法, 并详细探讨了各研究方法所取得的研究进展, 同时也回顾了国内外学者针对工程应用问题建立的管道流固耦合振动理论模型, 得到了重要的研究成果.

根据以上研究现状, 关于外流作用下管道流固耦合非线性动力学问题的研究已取得了一些重要成果, 为解决工程实际问题提供了理论指导和实验数据. 然而, 需要指出的是, 目前国际上关于内外流

共同作用下管道非平面非线性动力学的研究报道还比较少见, 仍存在许多关键性的基础科学问题有待解决, 主要包括以下几个方面:

(1) 对于同时受内流和外流作用的管道系统, 目前大多局限于平面动力学问题的研究, 很少有文献系统地分析管道的非平面振动问题, 尤其是对于管道内流速较高的情况, 此时管道会发生失稳导致外流作用下振动行为更加复杂. 此外, 现有研究在采用实验或 CFD 仿真方法研究该类问题时, 很难考虑内流的影响, 因此无法准确预测管道流固耦合振动响应.

(2) 对于轴向外流作用下管道非线性动力学问题的研究, 现有报道大多只考虑了与内流方向相反且有直接联系的外部流体, 并局限于具有钝形自由端的管道结构. 而对于与内流方向同向且无直接联系的轴向外流作用下输流直管的相关研究, 目前也仅限于线性动力学分析, 由于很难建立非线性动

力学理论模型,因此无法预测管道的非线性动力学响应。

(3) 对于外流作用下管束流固耦合动力学问题的研究,目前国内外报道十分少见,尤其是轴向外流下管束非线性动力学行为的研究。现有研究也大多基于计算流体动力学方法或实验研究方法,在理论建模研究上存在明显的不足。这也是因为很难描述管束流体力,无法建立管束流固耦合振动理论模型,给管束非线性动力学机理研究带来了巨大挑战。

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