新型运载火箭结构优化设计与试验验证

王金明[1],鲍国苗[2],刘　勇[1],顾铖璋[3],易　果[1],刘　博[1],吴春雷[3],亢　战[4]
(1.上海航天精密机械研究所,上海201600;2.上海航天技术研究院,上海201109;3.上海宇航系统工程研究所,上海201108;4.大连理工大学 运载工程与力学学部,辽宁 大连116024)

摘　要: 伴随着运载火箭大型化与重型化的趋势,结构优化技术在火箭轻量化设计中扮演着越来越重要的角色,同时更高精度的试验、测试以及更高置信度的分析评估需求也日益凸显。本文首先对运载火箭结构轻量化设计方法进行概述;然后针对几种典型密封类与非密封类结构优化案例及新型运载火箭结构中的不确定性优化方法进行了重点介绍,并对优化结果进行了试验验证;最后对亟待解决的技术问题与未来结构优化技术发展趋势进行了梳理与展望。

关键词: 运载火箭; 结构优化; 试验验证; 不确定性
中图分类号: TP 39　　**文献标志码:** A　　**DOI:** 10.19328/j.cnki.2096-8655.2021.03.015

Structure Optimization and Test Verification of New Launch Vehicles

WANG Jinming[1], BAO Guomiao[2], LIU Yong[1], GU Chengzhang[3], YI Guo[1], LIU Bo[1], WU Chunlei[3], KANG Zhan[4]
(1.Shanghai Aerospace Precision Machinery Institute, Shanghai 201600, China; 2.Shanghai Academy of Spaceflight Technology, Shanghai 201109, China; 3.Aerospace Systems Engineering Shanghai, Shanghai 201108, China; 4.Faculty of Vehicle Engineering and Mechanicals, Dalian University of Technology, Dalian 116024, Liaoning, China)

Abstract: Since launch vehicles tend to be large-scale and heavy, structure optimization technology plays a more and more important role in the lightweight design of launch vehicles. Meanwhile, the requirements of tests with higher precision and analysis and evaluation with higher reliability are also increasingly prominent. In this paper, firstly, the lightweight design methods of launch vehicles are summarized. Then, several typical sealed and non-sealed structure optimization cases and some uncertain optimization methods for new launch vehicle structure are emphatically introduced, and the optimization results are verified by tests. Finally, the technical problems to be solved and the development trend of structure optimization technology in the future are sorted out and prospected.

Key words: launch vehicle; structure optimization; experimental verification; uncertainty

0 引言

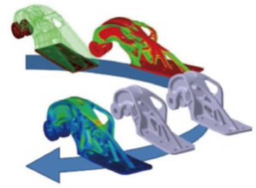
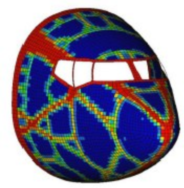
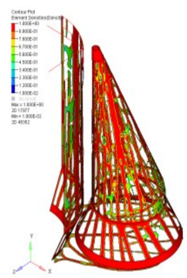
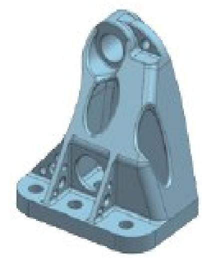
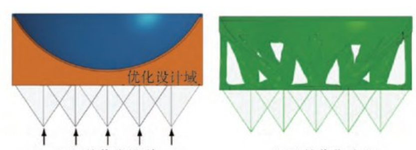
随着我国进入空间的需求不断增加,对运载火箭的运载能力和运载效率的要求也不断提高。其中,运载火箭的结构承载效率是制约运载效率提高的关键因素之一,而结构轻量化设计是提高结构承载效率的关键技术[1]。结构设计人员在基于高比强度、高比刚度结构材料方面做了很多研究工作,成功开发了如基于铝锂合金、复合材料的高性能运载火箭舱体结构。

近年来,随着结构优化理论和计算力学的不断发展,结构优化技术也逐步成为结构轻量化设计的主要手段,在航空航天领域得到了广泛的应用[2-5]。结构轻量化设计在航空航天结构设计中的应用案例见表1。由表可见,结构优化技术贯穿于航空航天结构概念设计、部件设计及具体零件设计等所有阶段。

收稿日期: 2021-03-15; **修回日期:** 2021-04-20
基金项目: 国家重点研发计划资助项目(2017YFB1102800)
作者简介: 王金明(1974—),男,本科,研究员,主要研究方向为强度环境试验、测试与仿真等。

表 1　结构优化技术在飞行器设计中的应用[1-5]

Tab.1　Applications of structure optimization technology in aircraft design[1-5]

飞行器	结构优化应用案例
 航空	 机舱铰链支架  A380前缘肋  机身头部设计  飞机外挂架设计
 航天	 头锥段优化  航天器支架设计  发动机传力结构设计  卫星天线支架  卫星支撑系统设计

根据设计变量的不同,结构优化可以分为拓扑优化、形状优化和尺寸优化[6]。其中,拓扑优化由于设计自由度最高,通常用于概念设计阶段,可以获得结构的传力拓扑特征。通过对传力拓扑包络的重构及详细传力拓扑特征的工程化表达,再利用形状与尺寸优化设计,可获得较优工程设计参数。

拓扑优化根据拓扑描述方式的不同,可以分为基于材料分布的方法与边界演化方法两类。基于材料分布的拓扑优化方法大多以单元密度作为设计变量,将连续体的材料分布问题转化为离散单元的删除与保留问题,主要包括均匀化法[7]、变密度法[8-11]和渐进结构优化法[12-14]等。基于边界演化的方法通过控制边界演化实现拓扑优化,主要包括水平集法[15-16]、相场法[17]等。

早期结构优化主要解决离散桁架的优化问题，连续体结构拓扑优化在CHENG等[18]以实心弹性板刚度最大化为目标对板厚度进行设计的工作得到快速发展。1988年，BENDSØE等[7]提出均匀化方法，即采用微观结构设计参数优化来表达宏观结构的拓扑变化。之后，以固体各向同性微结构材料惩罚模型法（Solid Isotropic Microstructure with Penalty，SIMP）为代表的变密度方法被提出并在工程中得到广泛的应用。在SIMP方法中，材料性质与单元密度设计变量之间的关系一般采用幂律[10]的形式给出。早期的SIMP方法虽然简单易行，但也存在着棋盘格效应、局部最优解等问题，许多学者对此提出了有效的解决方法[11,19-21]。目前，以SIMP为代表的变密度法已有许多公开的代码[22-23]，同时也被Optistruct等商业软件采用。大连理工大学具有完全自主知识产权的优化软件系统SiPESC.OPT集成了多种自主特色的结构优化算法，力图寻求打破国外对优化仿真软件的主导地位。

连续体拓扑优化还可采用特征驱动[24-29]或几何体组件[30-33]的描述模型，便于某些特殊问题中施加边界几何形状相关的约束条件。例如，张卫红等[26-27]采用隐式水平集函数描述结构工程特征，并将工程特征视为基本设计元素，获得了清晰的优化结果。亢战等[30-31]通过结合水平集模型与基于密度的拓扑优化方法实现了内嵌多组件与智能元件的结构设计。郭旭等[32]等基于水平集描述实体杆件，通过实体杆件的移动和变形来实现拓扑结构变化，并给出了显式的边界描述。CHEN等[34]和LUO等[35]在目标函数中引入二次泛函来实现水平集模型下的结构最小尺寸控制。

现有的拓扑优化方法不仅能够解决刚度优化问题，也被拓展到应力约束[36]、动力学优化[37-38]、温度场变化[39]等问题。随着3D打印技术的成熟，拓扑优化技术正朝着直接输出可3D打印优化结果的方向努力[40-41]，以便更好地服务于工程实际。同时，考虑材料、工艺偏差等不确定性因素的结构优化设计也得到越来越多研究者的关注[42-43]。

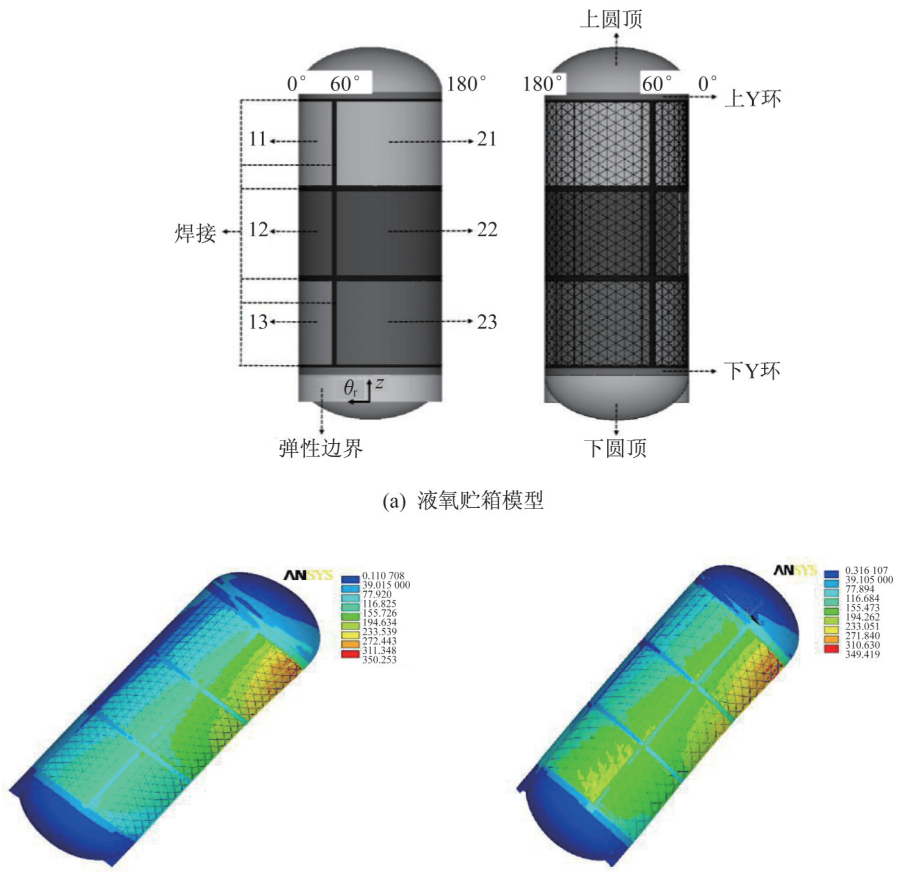
1 航天结构的确定性优化方法

1.1 优化技术在新型运载火箭密封类结构的应用

作为运载火箭密封类结构的典型代表，加筋薄壳结构具有较高的比强度与比刚度，广泛应用于运载火箭结构，包括大部分火箭型号的燃料贮箱、级间段等关键承力部件[44-46]。随着未来运载火箭的高承载需求，对加筋薄壳的结构性能提出了更加严格的要求。同时考虑结构减重与抗缺陷干扰，确定折减因子，对预示与提高薄壳结构承载力十分重要。

液氧贮箱在火箭发射过程中承受非均匀轴压载荷作用，如果仍按照传统的设计方法，设计效率低下，需要引入非均匀的设计理念。郝鹏等[45,47-49]针对受非均匀分布轴压载荷和内压载荷的液氧贮箱，提出了两步式代理模型优化方法。第1步优化，将原优化问题根据设计变量的属性进行分组，分解成若干子优化问题。第2步优化，将前一步优化结果叠加形成的组合设计作为初始设计，进行自适应抽样构建代理模型，根据代理模型对结构进行优化设计，得到最后的设计结果。如图1所示，通过非均匀加筋结构优化设计，最优设计结果相对于初始结构减重达到34%。并且通过优化前后的应力对比可以看出，优化后应力分布更加均匀，材料利用效率更高。

薄壁结构承载力的高精度预示对于大直径筒壳结构设计至关重要。通常，采用折减因子描述结构对初始缺陷的敏感程度。初始缺陷主要有几何缺陷[45]、边界缺陷[50-51]和刚度缺陷[52-53]。一般，确定折减因子的方法有实测缺陷法[54-55]、模态缺陷法[55-56]、单点扰动载荷法[53,57]和多点最不利扰动载荷法[58-60]。模态缺陷方法[56]基于特征值屈曲分析，将模态缺陷引入完美模型，得到相应结构承载力，不过这种方法容易造成较大的结构冗余。单点扰动载荷方法[57]通过在加筋薄壳中部施加径向扰动载荷，得到考虑几何大变形的位移场，之后将缺陷引入完美模型，进行后屈曲分析，通过不断改变扰动载荷的幅值，绘制缺陷敏感性曲线，如图2所示。缺陷敏感曲线的收敛值即为实际承载力。针对单点扰动载荷方法无法覆盖实际缺陷，王博等[58-60]提出多点最不利扰动载荷方法，并开展相关轴压试验对其准确性与可靠性进行了验证[55]。该方法通过将多个集中载荷引发的凹陷型缺陷作为基函数，寻找基函数的最不利组合作为预设缺陷，用以估计结构承载力。该方法预示的极限承载力一般低于随机缺陷结构承载力，有利于设计更可靠的薄壳结构。



(a) 液氧贮箱模型

(b) 优化前von Mises应力　　(c) 优化后von Mises应力

图 1　液氧贮箱模型示意图及优化前后 von Mises 应力对比[47]

Fig.1　Schematic diagram of fuel tank model and comparison of von Mises stress distribution before and after optimization[47]

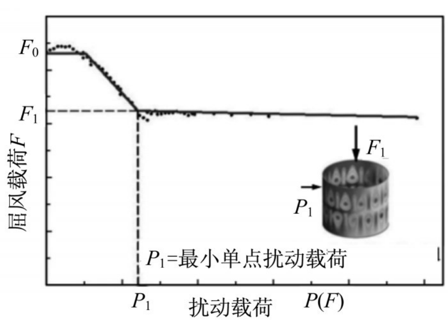


图 2　单点扰动载荷法的缺陷敏感性曲线[66]

Fig.2　Imperfection sensitivity curve of single perturbation load approach[66]

针对加筋薄壳的缺陷敏感性问题,王博等[61-64]提出了多级加筋构型优化设计方案。该方法为了提高薄壳结构抵抗局部缺陷的能力,优化了加筋筒壳环向与轴向刚度周期性分布,显著提高了薄壳结构抵抗初始缺陷的能力,且不会增加总体质量,并通过单点凹陷缺陷敏感性曲线验证了设计结果的可靠性。为了降低优化求解困难,郝鹏等[62-63]发展了基于名义承载力指标的鲁棒性优化设计方法,避免了一般鲁棒性优化双层嵌套问题(如图 3 所示)。郝鹏等[65-66]还进行了考虑材料、几何不确定性与缺陷敏感性的基于可靠度的优化设计。

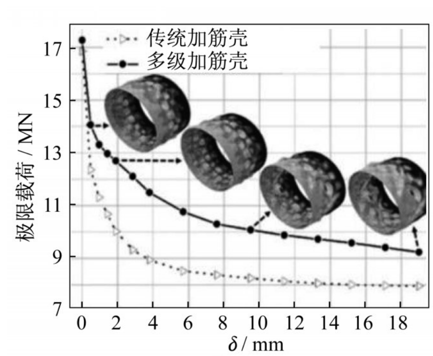


图 3　传统加筋与多层级加筋缺陷敏感性曲线[63]

Fig.3　Imperfection sensitivity curves of hierarchical stiffened shells and traditional stiffened shells[63]

采用上述优化设计方案，能够提升贮箱结构应力分布均匀性，从而提高材料使用率。为了验证该新型优化加筋结构设计和工艺制造的有效性，需要开展试验并测量加载过程中结构全场位移、应力分布。试验中采用电阻应变计、位移计、全场光学及声发射等综合测量方法。试验加载采用四点式1 000 t加载梁，试件通过800 mm高度的钢框固定于试验平台，试件上端通过钢框与加力帽进行转接。4个油压作动筒同时收缩，实现轴向载荷的施加。试件最终在623 t发生失稳破坏，符合贮箱结构承载设计要求（如图4所示）。

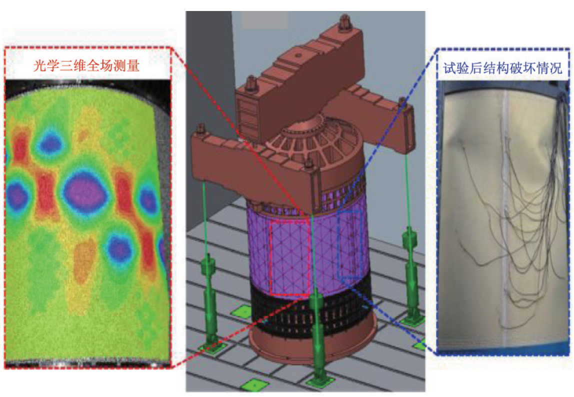


图4　贮箱结构试验测量技术方案

Fig.4　Technical plan for tank structure test and measurement

1.2　优化技术在新型运载火箭非封闭类结构的应用

运载火箭非密封类结构包括箱间段、级间段、尾段、头锥等。本文以新一代捆绑火箭前主传力助推器头锥为例，介绍非密封类结构拓扑优化设计方法。

助推器前主传力头锥前端无其他结构约束，载荷大且偏置集中，不同于常规运载火箭载荷分布均匀、结构刚度均匀分布的特点。如果对于偏置集中载荷作用下的头锥结构设计不够优化、强度分析不够精确，容易出现局部承载能力不足导致结构提前破坏，或结构质量较重影响运载火箭承载能力等问题[67-70]。

助推器头锥结构优化设计技术流程如图5所示。首先需要根据载荷工况、结构空间包络及限制等进行结构整体拓扑优化及传力路径分析；根据拓扑优化结果、最优传力路径以及制作工艺等，进行结构具体参数优化设计，确定结构方案；然后对结构进行仿真分析，直到结构满足优化指标及强度、刚度等设计要求；最后对结构进行试验验证，验证结构设计、工艺以及仿真的合理性及可靠性。根据以上设计流程，助推器头锥的具体优化过程如图6所示。

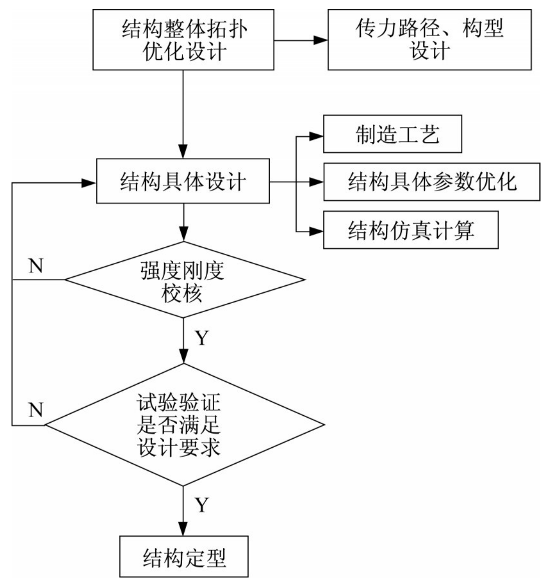


图5　助推器头锥优化设计技术流程

Fig.5　Flow chart of optimum design for booster nose cone

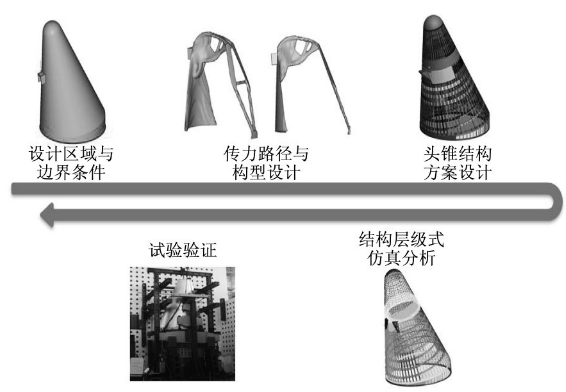
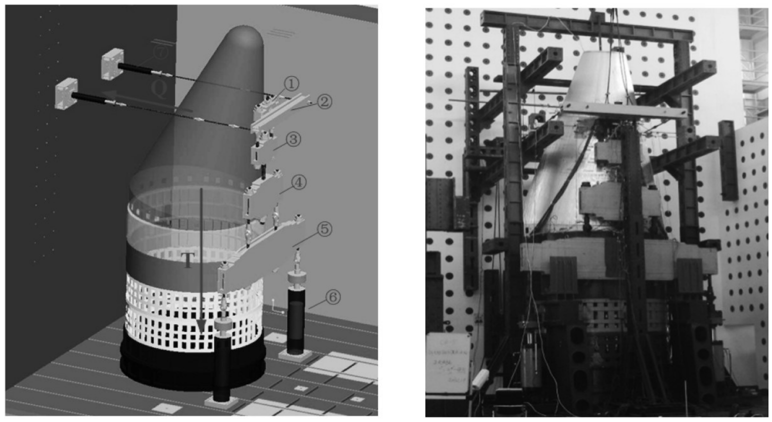


图6　助推器头锥优化设计

Fig.6　Optimization design for booster nose cone

为模拟真实的受力情况，通过虚拟试验仿真预示方法，模拟头锥在试验中的倾斜变化趋势，设计了自适应活动关节装置的加载系统。试验中，头锥下端框与试验刚框固定连接，前捆绑支座处施加轴向力和剪切力，载荷通过加载工装传递至承力墙或地面抗拔点处。试验加载原理及试验安装如图7所示。

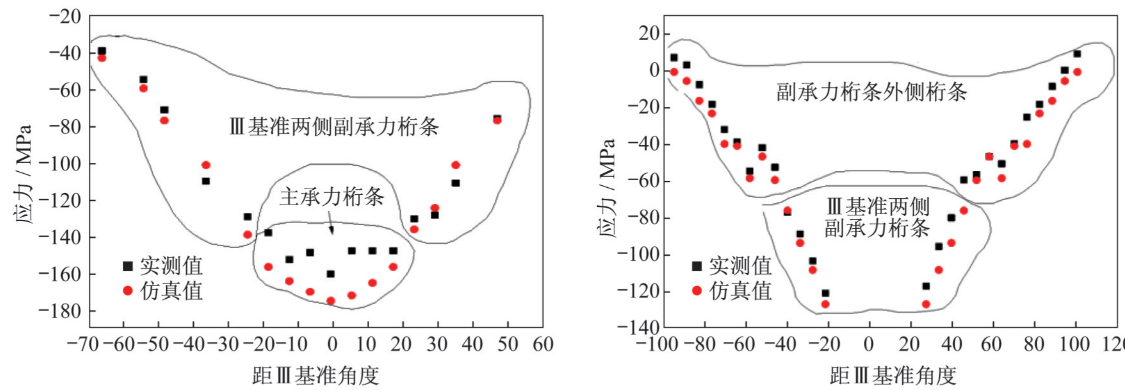


(a) 试验加载示意图　　(b) 试验加载实景图

图 7　试验加载原理及安装

Fig.7　Loading method and installment of tests

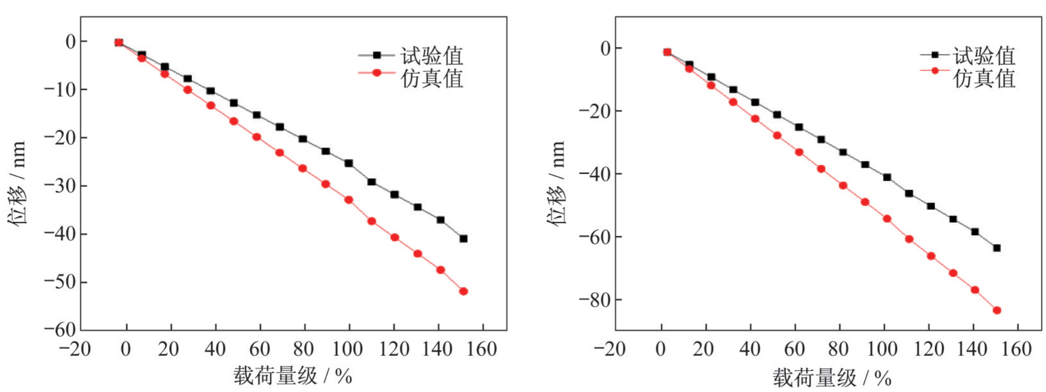
通过头锥静力试验对典型位置的应力和位移进行实测，头锥典型承力结构中，主副承力桁条上测点的应力仿真计算值与试验实测值对比如图 8 所示，前捆绑支座处轴向和径向位移试验实测与仿真计算值对比如图 9 所示。试验结果表明，仿真计算结果与试验结果吻合较好，结构传力、承载和变形符合预期。



(a) 两侧副承力桁条与主承力桁条应力对比　　(b) 副承力桁条外侧桁条与两侧副承力桁条应力对比

图 8　主副承力桁条试验实测与仿真应力值对比图

Fig.8　Stress comparison of the main and secondary stringers obtained by tests and simulation



(a) 前捆绑支座处轴向试验值与仿真值对比　　(b) 前捆绑支座处径向试验值与仿真值对比

图 9　前捆绑支座处轴向和径向位移试验实测与数值仿真值对比图

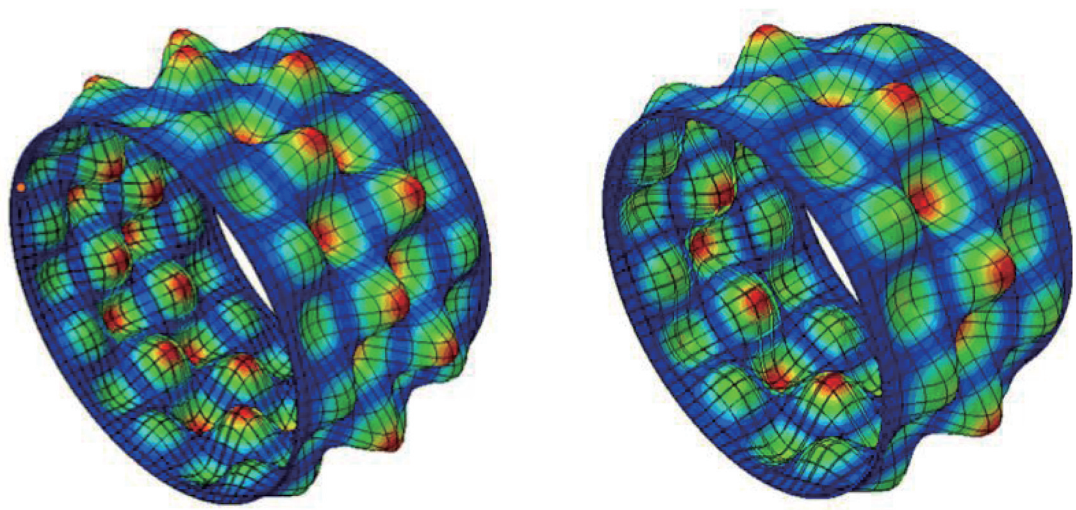
Fig.9　Results of axial and radial displacement obtained by tests and simulation on the front binding support

2 航天结构的不确定性优化方法

2.1 考虑不确定性的结构优化

结构优化技术大部分应用都是基于确定性的假设，而在实际生产中，载荷、制造误差等不确定因素将会导致结构参数出现偏差，从而影响结构的性能。这时传统的结构设计方法具有较大的局限性，如何建立合理的不确定性优化模型，降低结构功能对不确定性参数的敏感性（鲁棒性的设计优化[71-72]，Robust Design Optimization，RDO）、保障结构可靠性（可靠度优化[73-74]，Reliability-Based Design Optimization，RBDO），成为受到日益关注的研究方向。

运载火箭结构中的不确定性主要来源于载荷、材料以及几何制造误差。载荷不确定性在运载火箭结构中非常常见，比如气动载荷、发射场的风载荷等；材料不确定主要表现在弹性模量空间分布不确定性与材料局部缺陷，如焊接气泡影响结构强度等；贮箱薄壁的几何缺陷、加工误差等都是典型的火箭结构几何制造误差不确定性。目前，考虑不确定性的结构优化在火箭结构设计中的应用还处于初步应用阶段，如图10所示。



(a) 确定性优化设计　　(b) 可靠度优化设计

图10 考虑材料与几何不确定性的线性屈曲优化[66]

Fig.10 Linear bucking optimization of stiffened shells with material and geometric uncertainties[66]

根据不确定性的来源及数据特征，可以分为概率模型与非概率模型两种建模方式[42-43]。非概率模型一般采用椭球模型[75-76]或区间模型[77]。椭球模型一般采用超椭球包络已知数据，寻找最佳的包络面[76]，区间模型则采用超盒包络所有不确定量[77]。一些工作中也采用两种模型的混合进行不确定性描述[78-79]。通常，区间模型相对椭球模型较为保守。概率模型根据已知信息建立具有某种概率密度分布的随机变量或随机场，然后求解相应的统计特征，比如均值、方差等。分析方法主要包括摄动法[80]、多项式混沌展开（Polynomial Chaos Expansion，PCE）[81-82]和 Monte Carlo 法[83]等。不确定性对结构最优设计点的影响如图11所示。

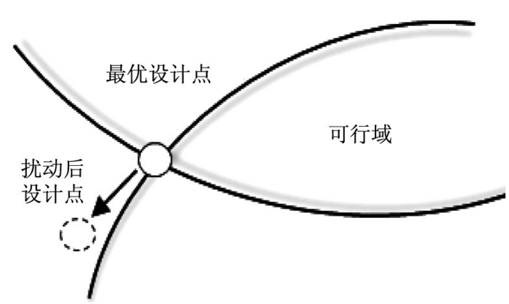


图11 不确定性影响最优设计点

Fig.11 Effect of uncertainty on the optimal design point

目前，基于随机场模型描述结构不确定性得到了极大的关注。CHEN等[72,84]用随机场描述材料与几何不确定性，求解了基于水平集方法的鲁棒性拓扑优化问题；SCHEVENEL等[85]基于密度法给出了

随机场描述载荷、材料与几何不确定性的鲁棒性优化框架;张文博等[86]基于几何随机场不确定性发展了一种随机水平集方法。另外,文献[87-90]中基于PCE的不确定性拓扑优化也得到了极大的发展。如图12给出了随机场模型描述球形贮箱厚度不确定性示意图。

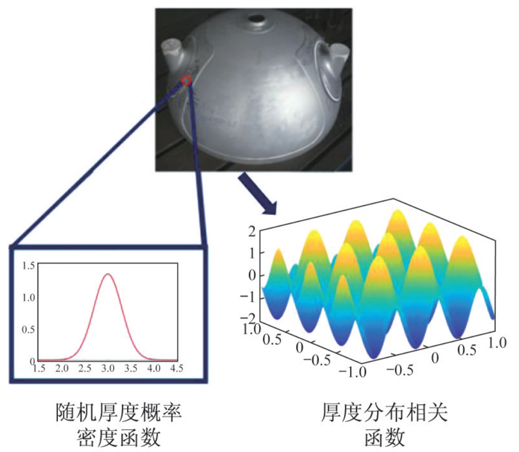


图 12　球形贮箱厚度随机场描述

Fig.12　Thickness random field of spherical tank

2.2　示例:球形贮箱不确定性优化设计

薄壳球形贮箱在制造过程中,由于贮箱半球体拉深成型工艺、化铣工艺及球体与承力支座搅拌摩擦焊接工艺等将引入球体结构关键位置的厚度不确定性,对结构承载的安全性产生影响。为了同时考虑大集中载荷在薄壳球形贮箱局部的扩散问题及球体结构关键位置的厚度不确定性,降低结构对不确定性的敏感程度,需要进行结构鲁棒性设计。其鲁棒性优化设计流程如图13所示。

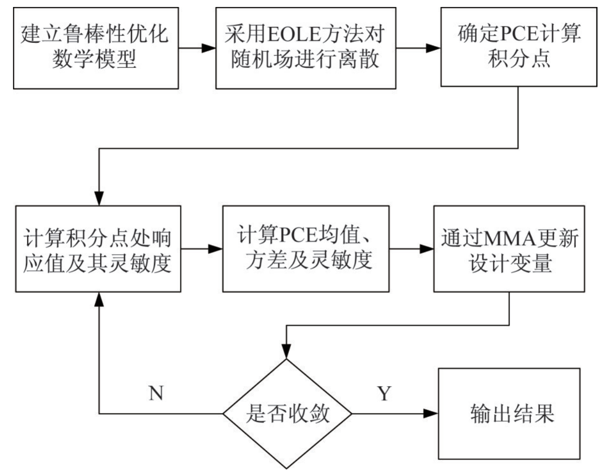


图 13　球形贮箱优化技术实现流程

Fig.13　Flow chart of the optimal design for spherical tank

基于以上鲁棒性拓扑优化方法得到的某飞行器推进器球形承力贮箱构型如图14(a)所示,通过优化结果指导设计得到的实际结构如图14(b)所示。优化结果中的加厚区域主要分布在集中受力位置,材料利用效率更高。同时,通过鲁棒性优化降低了结构对厚度加工制造误差的敏感性。

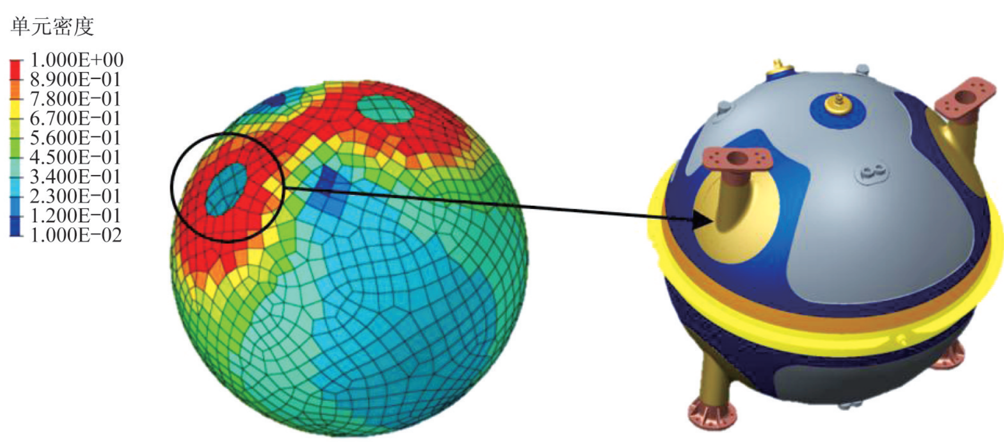


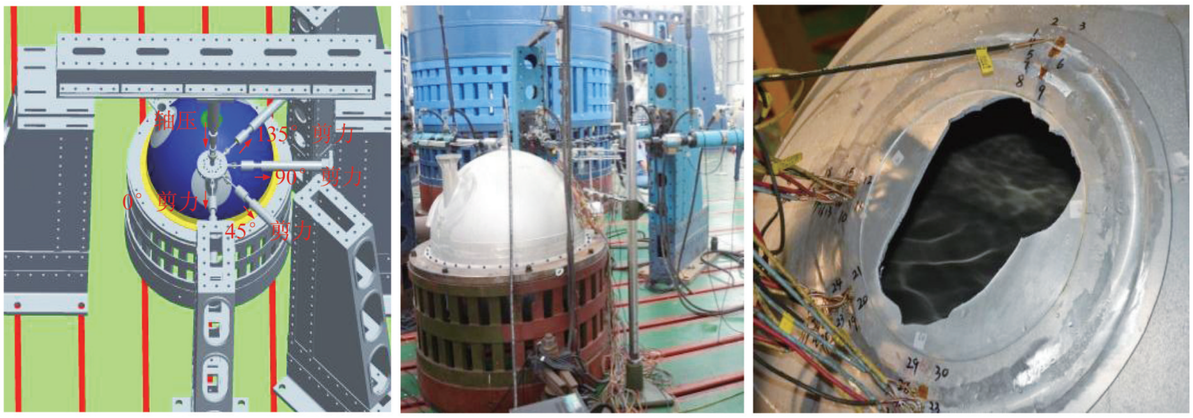
图 14　鲁棒性拓扑优化设计结果与设计方案对比

Fig.14　Results obtained by the robust topology optimization design and the final design scheme

基于级数最优线性估值法[91]的薄壳类结构厚度不确定性鲁棒性拓扑优化方法可应用于因板材原材料、加工制造等方面的原因造成的厚度不确定性。本案例建立了设计与工艺之间的量化关系,并进行了设计与工艺耦合设计,获得性能稳定的实际薄壳结构产品方案,可降低实际产品的报废率,提

高型号研制水平和整体效益。

为了验证结构设计的可行性与合理性,需要开展球形贮箱强度试验,如图 15 所示。从球形贮箱试验中获得了结构的极限承载载荷,及其所能承担的任务极限,可为后续型号应用奠定基础。



(a) 试验加载原理图　(b) 试验系统安装　(c) 试验件破坏形式

图 15　球形贮箱试验设计及现场

Fig.15　Test design and implementation of spherical tank

3　结束语

结构优化在航天领域得到了大量应用,从贮箱、级间段到发动机支架、卫星支架等都展示出了其在航天结构设计中的巨大价值。目前,航天领域中的结构优化主要考虑刚度、强度、稳定性以及固有频率等结构性能,动载荷、高温热扩散和极端载荷等条件下的优化案例很有限。同时,考虑载荷、几何等不确定性的结构优化技术应用也非常少见。其一,在于航天结构设计中载荷、几何等不确定性参数的数据缺乏,无法进行精确的不确定性建模;其二,现有的不确定性拓扑优化方法需要进行大规模的有限元计算,使得其在航天结构设计中的使用受到限制;另外,现有的拓扑优化方法在特征提取方面大多凭借设计人员的手动操作,优化结果的工艺性欠考虑。虽然现在也有一些基于特征的拓扑优化方法,但实现过程较为复杂。

作为创新设计手段,结构优化技术在航天结构设计中还具有更加广泛的应用前景。为了满足未来航天结构设计的需求,以下技术方向亟待突破:1) 建立并完善动载荷、高温热扩散以及极端载荷条件下的结构优化设计方法,拓宽结构优化技术在航天结构设计中的应用范围;2) 建立针对航天结构设计的高精度不确定性建模方法,进一步完善现有的不确定性优化方法;3) 建立超大规模的高性能计算平台,实现大部件的精细化概念设计与不确定性优化设计的高效率计算;4) 发展全新的基于特征驱动的拓扑优化方法取代人工进行特征提取,避免特征提取过程中的精度损失。

参考文献

[1] ZHU J H, ZHANG W H, XIA L. Topology optimization in aircraft and aerospace structures design [J]. Archives of Computational Methods in Engineering, 2016, 23(4): 595-622.

[2] 全栋梁,时光辉,关成启,等.结构优化技术在高速飞行器上的应用与面临的挑战[J].力学与实践, 2019, 41(4): 373-381.

[3] 陈献平,鄢东洋,姚瑞娟,等.轻质箭体结构优化设计[J].导弹与航天运载技术,2019, 367(2): 17-21.

[4] ZHU J H, GU X J, ZHANG W H, et al. Structural design of aircraft skin stretch-forming die using topology optimization [J]. Journal of Computational and Applied Mathematics, 2013, 246: 278-288.

[5] 范瑞祥,姚瑞娟,朱振涛,等.一种新型7台火箭发动机并联推力传递结构方案[J].载人航天,2020,26(5): 97-101.

[6] BENDSØE M P, SIGMUND O. Topology optimization: theory, methods, and applications [M].

Berlin: Springer Science and Business Media, 2013: 1-68.

[7] BENDSØE M P, KIKUCHI N. Generating optimal topologies in structural design using a homogenization method [J]. Computer Methods in Applied Mechanics and Engineering, 1988, 71: 197-224.

[8] BENDSØE M P. Optimal shape design as a material distribution problem [J]. Structural Optimization, 1989, 1: 193-202.

[9] ZHOU M, ROZVANY G I N. The COC algorithm, Part II: topological, geometrical and generalized shape optimization [J]. Computer Methods in Applied Mechanics and Engineering, 1991, 89: 309-336.

[10] BENDSØE M P, SIGMUND O. Material interpolation schemes in topology optimization [J]. Archive of Applied Mechanics, 1999, 69 (9/10) : 635-654.

[11] SIGMUND O, PETERSSON J. Numerical instabilities in topology optimization: a survey on procedures dealing with checkerboards, mesh-dependencies and local minima [J]. Structural Optimization, 1998, 16(1): 68-75.

[12] XIE Y M, STEVEN G P. A simple evolutionary procedure for structural optimization [J]. Computers and Structures, 1993, 49(5): 885-896.

[13] QUERIN O M, STEVEN G P, XIE Y M. Evolutionary structural optimization (ESO) using a bidirectional algorithm [J]. Eng Comput Engineering Computations, 1998, 15: 1031-1048.

[14] QUERIN O M, YOUNG V, STEVEN G P, et al. Computational efficiency and validation of bi-directional evolutionary structural optimization [J]. Computer Methods in Applied Mechanics and Engineering, 2000, 189(2): 559-573.

[15] WANG M Y, WANG X, GUO D. A level set method for structural topology optimization [J]. Computer Methods in Applied Mechanics and Engineering, 2003, 192: 227-246.

[16] ALLAIRE G, JOUVE F, TOADER A M. Structural optimization using sensitivity analysis and a level-set method [J]. Journal of Computational Physics, 2004, 194: 363-393.

[17] TAKEZAWA A, NISHIWAKI S, KITAMURA M. Shape and topology optimization based on the phase field method and sensitivity analysis [J]. Journal of Computational Physics, 2010, 229(7): 2697-2718.

[18] CHENG K T, OLHOFF N. An investigation concerning optimal design of solid elastic plates [J]. International Journal of Solid and Structures, 1981, 17: 305-323.

[19] SIGMUND O. On the design of compliant mechanisms using topology optimization [J]. Mechanics of Structures and Machines, 1997, 25:493-524.

[20] SIGMUND O, MAUTE K. Sensitivity filtering from a continuum mechanics perspective [J]. Structural and Multidisciplinary Optimization, 2012, 46:471-475.

[21] SIGMUND O. Manufacturing tolerant topology optimization [J]. Acta Mechanica Sinica, 2009, 25: 227-239.

[22] ANDREASSEN E, CLAUSEN A, SCHEVENELS M, et al. Efficient topology optimization in Matlab using 88 lines of code [J]. Structural and Multidisciplinary Optimization, 2010, 43:1-16.

[23] SIGMUND O. A 99 line topology optimization code written in Matlab [J]. Structural and Multidisciplinary Optimization, 2014, 21:120-127.

[24] ZHU J, ZHANG W, BECKERS P. Integrated layout design of multi-component system [J]. International Journal for Numerical Methods in Engineering, 2009, 78(6):631-651.

[25] ZHANG J, ZHANG W H, ZHU J H, et al. Integrated layout design of multi-component systems using XFEM and analytical sensitivity analysis [J]. Computer Methods in Applied Mechanics and Engineering, 2012, 245:75-89.

[26] ZHOU Y, ZHANG W, ZHU J, et al. Feature-driven topology optimization method with signed distance function [J]. Computer Methods in Applied Mechanics and Engineering, 2016, 310: 1-32.

[27] ZHANG W, ZHOU Y, ZHU J. A comprehensive study of feature definitions with solids and voids for topology optimization [J]. Computer Methods in Applied Mechanics and Engineering, 2017, 325: 289-313.

[28] ZHANG W, ZHAO L, GAO T, et al. Topology optimization with closed B-splines and Boolean operations [J]. Computer Methods in Applied Mechanics and Engineering, 2017, 315: 652-670.

[29] CHEN J, SHAPIRO V, SURESH K, et al. Shape optimization with topological changes and parametric control [J]. International Journal for Numerical Methods in Engineering, 2007, 71: 313-348.

[30] KANG Z, WANG Y. Integrated topology optimization with embedded movable holes based on combined description by material density and level sets [J]. Computer Methods in Applied Mechanics and Engineering, 2013, 255:1-13.

[31] WANG Y, LUO Z, ZHANG X, et al. Topological design of compliant smart structures with embedded movable actuators [J]. Smart Materials and Structures, 2014, 23(4):045024.

[32] GUO X, ZHANG W, ZHONG W. Doing topology optimization explicitly and geometrically: a new moving morphable components based framework [J]. Journal of Applied Mechanics, 2014, 81(8):081009.

[33] NORATO J A, BELL B K, TORTORELLI D A. A geometry projection method for continuum-based topology optimization with discrete element [J]. Computer Methods in Applied Mechanics and Engineering, 2015, 293:306-327.

[34] CHEN S, WANG M Y, LIU A Q. Shape feature control in structural topology optimization [J]. Computer-Aided Design, 2008, 40(9):951-962.

[35] LUO J, LUO Z, CHEN S, et al. A new level set method for systematic design of hinge-free compliant mechanisms [J]. Computer Methods in Applied Mechanics and Engineering, 2008, 198(2):318-331.

[36] DUYSINX P, BENDSØE M P. Topology optimization of continuum structures with local stress constraints [J]. International Journal for Numerical Methods in Engineering, 1998, 43(8):1453-1478.

[37] LIU H, ZHANG W, GAO T. A comparative study of dynamic analysis methods for structural topology optimization under harmonic force excitations [J]. Structural and Multidisciplinary Optimization, 2015, 51(6):1321-1333.

[38] KANG Z, HE J, SHI L, et al. A method using successive iteration of analysis and design for large-scale topology optimization considering eigenfrequencies [J]. Computer Methods in Applied Mechanics and Engineering, 2020, 362:112847.

[39] DBOUK T. A review about the engineering design of optimal heat transfer systems using topology optimization [J]. Applied Thermal Engineering, 2017, 112:841-854.

[40] SEABRA M, AZEVEDO J, ARAÚJO A, et al. Selective laser melting (SLM) and topology optimization for lighter aerospace components [J]. Procedia Structural Integrity, 2016, 1:289-296.

[41] TOMLIN M, MEYER J. Topology optimization of an additive layer manufactured (ALM) aerospace part [C]// Proceeding of the 7th Altair CAE Technology Conference. 2011:1-9.

[42] 罗阳军, 亢战. 连续体结构非概率可靠性拓扑优化[J]. 力学学报, 2007, 39(1): 125-131.

[43] 姜潮, 郑静, 韩旭, 等. 一种考虑相关性的概率-区间混合不确定模型及结构可靠性分析[J]. 力学学报, 2014, 46(4):591-600.

[44] HILBURGER M W, NEMETH M P, STARNES J H, Jr. Shell buckling design criteria based on manufacturing imperfection signatures [J]. AIAA Journal, 2006, 44(3):654-663.

[45] 郝鹏. 面向新一代运载火箭的网格加筋柱壳结构优化研究[D]. 大连: 大连理工大学, 2013.

[46] 王博, 郝鹏, 田阔. 加筋薄壳结构分析与优化设计研究进展[J]. 计算力学学报, 2019, 36(1):1-12.

[47] HAO P, WANG B, LI G. Surrogate-based optimum design for stiffened shells with adaptive sampling [J]. AIAA Journal, 2012, 50(11):2389-2407.

[48] HAO P, WANG B, TIAN K, et al. Efficient optimization of cylindrical stiffened shells with reinforced cutouts by curvilinear stiffeners [J]. AIAA Journal, 2016, 54(4):1350-1363.

[49] HAO P, WANG B, LI G, et al. Hybrid framework for reliability-based design optimization of imperfect stiffened shells [J]. AIAA Journal, 2015, 53(10): 2878-2889.

[50] KRIEGESMANN B, JANSEN E L, ROLFES R. Design of cylindrical shells using the single perturbation load approach potentials and application limits [J]. Thin-Walled Structures, 2016, 108:369-380.

[51] ARBELO M A, DEGENHARDT R, CASTRO S G P, et al. Numerical characterization of imperfection sensitive composite structures [J]. Composite Structures, 2014, 108:295-303.

[52] DEGENHARDT R, CASTRO S G P, ARBELO M A, et al. Future structural stability design for composite space and airframe structures [J]. Thin-Walled Structures, 2014, 81:29-38.

[53] WAGNER H N R, HÜHNE C, ROHWER K, et al. Stimulating the realistic worst case buckling scenario of axially compressed unstiffened cylindrical composite shells [J]. Composite Structures, 2017, 160: 1095-1104.

[54] HILBURGER M W, STARNES J H, Jr. Effects of imperfections of the buckling response of composite shells [J]. Thin-Walled Structures, 2004, 42(3): 369-397.
[55] WANG B, ZHU S, HAO P, et al. Buckling of quasi-perfect cylindrical shell under axial compression: a combined experimental and numerical investigation [J]. International Journal of Solids and Structures, 2018, 130:232-247.
[56] SONG C Y, TENG J G, ROTTER J M. Imperfection sensitivity of thin elastic cylindrical shells subject to partial axial compression [J]. International Journal of Solids and Structures, 2004, 41(24/25):7155-7180.
[57] HÜHNE C, ROLFES R, BREITBACH E, et al. Robust design of composite cylindrical shells under axial compression-simulation and validation [J]. Thin-Walled Structures, 2008, 46(7/8/9):947-962.
[58] WANG B, HAO P, LI G, et al. Determination of realistic worst imperfection for cylindrical shells using surrogate model [J]. Structural and Multidisciplinary Optimization, 2013, 48(4):777-794.
[59] HAO P, WANG B, LI G, et al. Worst multiple perturbation load approach of stiffened shells with and without cutouts for improved knockdown factors [J]. Thin-Walled Structures, 2014, 82:321-330.
[60] WANG B, DU K, HAO P, et al. Numerically and experimentally predicted knockdown factors for stiffened shells under axial compression [J]. Thin-Walled Structures, 2016, 109:13-24.
[61] 王博,田阔,郝鹏,等.多级加筋板结构承载性能与缺陷敏感度研究[J].固体火箭技术,2014,37(3):408-412.
[62] HAO P, WANG B, LI G, et al. Hybrid optimization of hierarchical stiffened shells based on smeared stiffener method and finite element method [J]. Thin-Walled Structures, 2014, 82:46-54.
[63] WANG B, HAO P, LI G, et al. Optimum design of hierarchical stiffened shells for low imperfection sensitivity [J]. Acta Mechanica Sinica, 2014, 30(3): 391-402.
[64] WANG B, TIAN K, ZHOU C, et al. Grid-pattern optimization framework of novel hierarchical stiffened shells allowing for imperfection sensitivity [J]. Aerospace Science and Technology, 2017, 62: 114-121.
[65] HAO P, WANG B, LI G, et al. Hybrid framework for reliability-based design optimization of imperfect stiffened shells [J]. AIAA Journal, 2015, 53(10): 2878-2889.
[66] MENG Z, HAO P, LI G, et al. Non-probabilistic reliability-based design optimization of stiffened shells under buckling constraint [J]. Thin-Walled Structures, 2015, 94:325-333.
[67] 梅勇,冯韶伟.大推力捆绑运载火箭传力路径优化设计[J].导弹与航天运载技术,2017(4):6-9.
[68] 冯韶伟,刘竹生,栾宇,等.运载火箭捆绑装置力学特性研究[J].弹与航天运载技术,2014(1):11-16.
[69] 梅勇,雷勇军,冯韶伟,等.超静定捆绑火箭传力路径的组合优化策略[J].南京航空航天大学学报,2016,48(6):909-916.
[70] 王志祥,顾名坤,雷勇军,等.大型运载火箭助推器超静定捆绑方案研究[J].振动与冲击,2020,39(4): 129-135.
[71] DOLTSINIS I, KANG Z. Robust design of structures using optimization methods [J]. Computer Methods in Applied Mechanics and Engineering, 2004, 193(23/24/25/26):2221-2237.
[72] CHEN S, CHEN W, LEE S. Level set based robust shape and topology optimization under random field uncertainties [J]. Structural and Multidisciplinary Optimization, 2010, 41(4):507-524.
[73] JUNG H S, CHO S. Reliability-based topology optimization of geometrically nonlinear structures with loading and material uncertainties [J]. Finite Elements in Analysis and Design, 2004, 41(3):311-331.
[74] ALLEN M, MAUTE K. Reliability-based shape optimization of structures undergoing fluid-structure interaction phenomena [J]. Computer Methods in Applied Mechanics and Engineering, 2005, 194(30/31/32/33):3472-3495.
[75] JIANG C, HAN X, LIU G R. Optimization of structures with uncertain constraints based on convex model and satisfaction degree of interval [J]. Computer Methods in Applied Mechanics and Engineering, 2007, 196(49/50/51/52):4791-4800.
[76] LUO Y, KANG Z, LUO Z, et al. Continuum topology optimization with non-probabilistic reliability constraints based on multi-ellipsoid convex model [J]. Structural and Multidisciplinary Optimization, 2009, 39(3):297-310.
[77] QIU Z, ELISHAKOFF I. Antioptimization of structures with large uncertain-but-non-random parameters via interval analysis [J]. Computer Methods

in Applied Mechanics and Engineering, 1998, 152(3/4):361-372.

[78] LUO Y, KANG Z, LI A. Structural reliability assessment based on probability and convex set mixed model [J]. Computers and Structures, 2009, 87(21/22):1408-1415.

[79] KANG Z, LUO Y. Non-probabilistic reliability-based topology optimization of geometrically nonlinear structures using convex models [J]. Computer Methods in Applied Mechanics and Engineering, 2009, 198(41/42/43/44):3228-3238.

[80] LIU W K, BELYTSCHKO T, MANI A. Random field finite elements [J]. International Journal for Numerical Methods in Engineering, 1986, 23(10): 1831-1845.

[81] GHANEM R G, SPANOS P D. Stochastic finite elements: a spectral approach [M]. Chicago: Courier Corporation, 2003:63-92.

[82] XIU D, KARNIADAKIS G E. The Wiener-Askey polynomial chaos for stochastic differential equations [J]. SIAM Journal on Scientific Computing, 2002, 24(2): 619-644.

[83] MELCHERS R E, BECK A T. Structural reliability analysis and prediction [M]. New York: John Wiley and Sons, 2018:65-73.

[84] CHEN S, CHEN W. A new level-set based approach to shape and topology optimization under geometric uncertainty [J]. Structural and Multidisciplinary Optimization, 2011, 44(1):1-18.

[85] SCHEVENELS M, LAZAROV B S, SIGMUND O. Robust topology optimization accounting for spatially varying manufacturing errors [J]. Computer Methods in Applied Mechanics and Engineering, 2011, 200(49/50/51/52):3613-3627.

[86] ZHANG W, KANG Z. Robust shape and topology optimization considering geometric uncertainties with stochastic level set perturbation [J]. International Journal for Numerical Methods in Engineering, 2017, 110(1):31-56.

[87] KESHAVARZZADEH V, FERNANDEZ F, TORTORELLI D A. Topology optimization under uncertainty via non-intrusive polynomial chaos expansion [J]. Computer Methods in Applied Mechanics and Engineering, 2017, 318:120-147.

[88] ZHANG X, HE J, TAKEZAWA A, et al. Robust topology optimization of phononic crystals with random field uncertainty [J]. International Journal for Numerical Methods in Engineering, 2018, 115(9): 1154-1173.

[89] TORII A J, LOPEZ R H, MIGUEL L F F. A gradient-based polynomial chaos approach for risk and reliability-based design optimization [J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2017, 39(7):2905-2915.

[90] KESHAVARZZADEH V, MEIDANI H, TORTORELLI D A. Gradient based design optimization under uncertainty via stochastic expansion methods [J]. Computer Methods in Applied Mechanics and Engineering, 2016, 306:47-76.

[91] LI C C, KIUREGHIAN ADER. Optimal discretization of random fields [J]. Journal of Engineering Mechanics, 1993, 119(6):1136-1154.