

飞行器结构健康监测中压电-导波成像技术的发展与挑战



鲍峤¹, 邱雷^{2,*}, 袁慎芳²

1. 南京邮电大学, 江苏 南京 210046

2. 南京航空航天大学 机械结构力学及控制国家重点实验室, 江苏 南京 210016

摘要: 结构健康监测技术因其能够保障飞行器安全运行、指导结构设计、降低维护成本等, 得到了国内外广泛研究。基于导波的结构健康监测方法具有对小损伤敏感、可实现大面积区域监测, 以及既可主动损伤监测也可被动冲击监测等特点, 被认为是最有应用前景的方法之一。其中, 压电-导波成像技术能够直接对监测区域进行成像, 直观且抗干扰能力强, 已成为导波结构健康监测的一个重要方法。本文按照压电传感器布置方式的分类, 首先分别介绍了基于稀疏压电传感器阵列和密集压电传感器阵列的压电-导波成像方法的基本原理和国内外研究现状, 这两类方法在面向实际复杂航空结构的准确性监测方面取得了很好的研究进展。近年来, 时变服役环境对成像方法可靠性影响的问题逐渐得到重视, 针对该问题, 本文还介绍了现有时变环境条件下的压电-导波成像方法研究现状。最后, 对飞行器结构健康监测中的压电-导波成像技术进行了总结和展望。

关键词: 飞行器; 结构健康监测; 导波; 成像; 压电传感器

中图分类号: TH7

文献标识码: A

DOI: 10.19452/j.issn1007-5453.2020.03.002

结构健康监测 (Structural Health Monitoring, SHM) 技术采用智能材料结构的理念, 按照一定的网络将驱动元件和传感元件集成在结构中, 实时在线地采集传感器信号, 结合先进的信号处理算法, 提取相应的信号特征参数, 对结构状态进行评估甚至对结构损伤的位置和尺寸进行评估, 监测结构损伤的扩展趋势并预测损伤结构的使用寿命^[1-4]。该技术正在成为飞行器及时准确获取结构损伤状态及其演变规律的关键技术, 其发展将对飞行器的设计制造、维护管理及寿命挖掘等发挥重要影响。

结构健康监测技术对现代飞机结构设计思想能够产生重要影响^[5,6]。传统安全寿命设计为了保证安全, 选择的安全系数保守, 这意味着高可靠性的选材、大的疲劳裕度、精密的制造工艺及光洁的表面处理等要求, 而且无论结构是否产生损伤, 只要达到预计寿命都会退役, 带来很高的制造和使用成本。结构健康监测技术有潜力预计损伤可能出现的位置, 实

时监测和进行风险评估, 并及时采取措施缓解损伤的扩展。因此, 飞行器设计时可以适当降低安全寿命结构的安全因数、合理地减轻结构材料重量裕度、保障复合材料的应用, 而不会危及结构的完整性并降低制造和使用成本。

结构健康监测技术使得飞行器实施“视情维修”策略成为可能^[7,8]。传统的飞机维护通常采用无损检测技术定时地对飞行器结构状态进行检测, 并根据检测结果实施维修。这种检测是非连续的, 现场检测局限性较大, 无法检测隐藏部位的损伤, 费时且成本高。结构健康监测技术获取的结构状态、操作, 以及服役环境等信息, 可用于结构健康状况预判及辅助维修与维护决策。建立在结构实际健康状况与性能基础上的维护管理可大幅降低飞行器结构的维护成本、减少了结构无效拆装、避免了二次维护损伤、提高了飞行安全性。

结构健康监测技术有潜力发挥飞机延寿的重要作用, 推动群机粗放式管理向单机寿命监控实施精细化管理的发

收稿日期: 2019-11-08; 退修日期: 2019-12-12; 录用日期: 2019-12-30

基金项目: 国家自然科学基金(51921003, 51635008, 51575263); 江苏省重点研发计划(BE2018123); 江苏高校优势学科建设工程资助项目

*通信作者. Tel.: 025-84896637 E-mail: lei.qiu@nuaa.edu.cn

引用格式: Bao Qiao, Qiu Lei, Yuan Shenfang. Development and challenges of PZT-guided wave based imaging technique in aircraft structural health monitoring[J]. Aeronautical Science & Technology, 2020, 31(03): 15-33. 鲍峤, 邱雷, 袁慎芳. 飞行器结构健康监测中压电-导波成像技术的发展与挑战[J]. 航空科学技术, 2020, 31(03): 15-33.

展^[9-13]。在群机粗放式管理方法下,同一批飞机在达到预计寿命时无论其是否存在损伤都将退役。结构健康监测技术能够获取每架飞机的健康状态,预估其剩余寿命,从而可以充分挖掘单机的服役寿命。该技术的应用能够避免装备极大浪费,提高飞行器使用寿命。

飞行器结构健康监测系统一般由三部分组成,包括集

成在结构上的传感器网络、信号调理采集系统以及信号处理算法^[14,15]。一般常见的传感器包括压电片、光纤传感器、应变片等^[16-22],如图1所示。这些集成在飞行器结构上的传感器网络可对飞行器结构的损伤(包括分层与脱层、疲劳裂纹及腐蚀等)进行主动监测,也可同时对结构应变、气动压力以及外部冲击等进行被动监测。

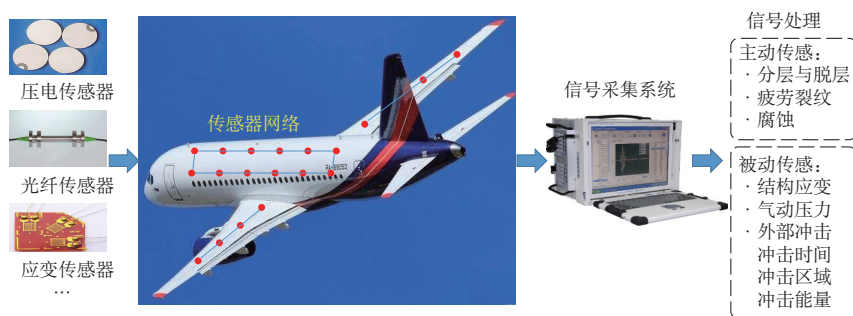


图1 结构健康监测系统的组成

Fig.1 Components of the structural health monitoring system

按照监测原理,结构健康监测技术主要分为被动监测及主动监测两大类,其中被动监测方法是基于结构应力应变分布变化、声发射现象等来进行的。这一类方法由传感器阵列进行监测,不需要额外增加驱动器。主动监测方法则需要在结构监测过程中依靠驱动器首先对结构施加特定激励,这类方法中包括基于主动导波激励的监测方法和基于结构机械阻抗变化的监测方法。基于结构振动的健康监测方法中,如振动是结构原有的状态,不需要外界激励,则此时属于被动监测方法,如有驱动器激励结构产生振动,则就属于主动监测。

上述方法中,基于导波的结构健康监测方法具有对小损伤敏感、可实现大面积区域监测、不依赖结构载荷、适用于金属和复合材料结构,以及既可主动损伤监测也可被动冲击监测等特点,因此被公认为最有工程应用前景的方法之一^[23-25]。导波是应力波的一种,是扰动或外力作用引起的应力和应变在弹性介质中传递的形式。基于导波的被动冲击监测原理如图2(a)所示,当结构受到冲击事件,引起结构中的导波的传播,通过传感器接受结构中传播的导波,再通过信号处理实现冲击位置及能量的评估。基于导波的主动损伤监测方法的基本原理为:采用驱动器向结构中激发出导波,结构中的损伤会造成导波传播特性发生变化,再通过信号处理方法可以获得与结构损伤相关的参数和图像,如图2(b)所示。

早期的弹性波SHM技术的原理性研究主要是通过分析弹性波受损伤作用后的信号时域、频域、时-频域特征或模式变换特征加以辨识,如信号飞行时间、幅值、能量、主要频率成分

及其幅值、时-频幅值、能量、奇异性特征等^[26-30]。这些研究大多将压电传感器网络中单个弹性波激励-传感通道独立处理或者仅考虑传感器布置的几何关系进行损伤定位,很少考虑整个网络多个弹性波激励-传感通道的综合信息,因此这些方法大多仅在简单平板结构上开展了研究和验证。近年来,在面向真实复杂航空结构的研究中,基于压电传感器阵列和弹性波的结构损伤波动成像方法逐步成为研究热点。该方法是利用压电传感器阵列中多个弹性波激励-传感通道的监测信息,通过控制阵列合成机制增强损伤影响。根据各成像方法采用的传感器布置方式,可将导波损伤成像方法分为两类:基于稀疏阵的导波损伤成像方法和基于密集阵的导波损伤成像方法。同时,时变环境下的损伤成像方法研究也得到了关注,以提高导波成像方法应用于服役条件下复杂结构时的诊断可靠性和准确性^[31,32]。

本文将围绕基于稀疏压电传感器阵列的导波损伤成像方法、基于密集压电传感器阵列的导波损伤成像方法以及时变环境下的导波损伤成像方法开展综述,分析、总结导波损伤成像方法的研究现状和发展趋势。

1 基于稀疏阵的导波成像方法

基于稀疏阵的导波成像方法主要有延时累加成像方法、路径成像方法、时间反转成像方法以及层析成像方法等。本节将分别介绍稀疏阵列成像方法的基本原理及其研究现状。

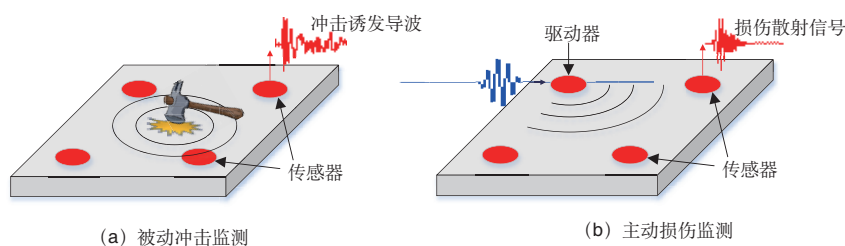


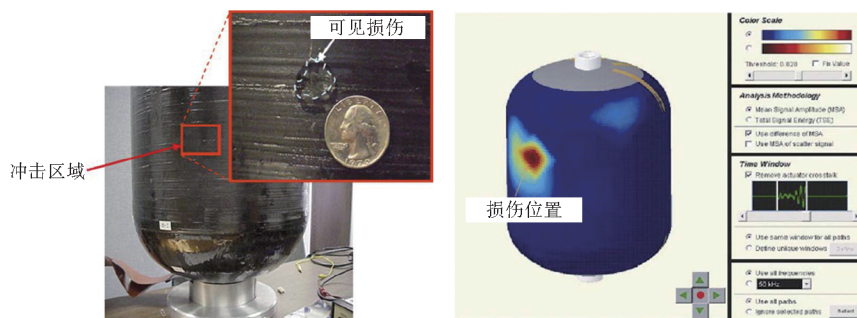
图2 基于导波方法的结构健康监测原理

Fig.2 Principle of the guided wave based structural health monitoring method

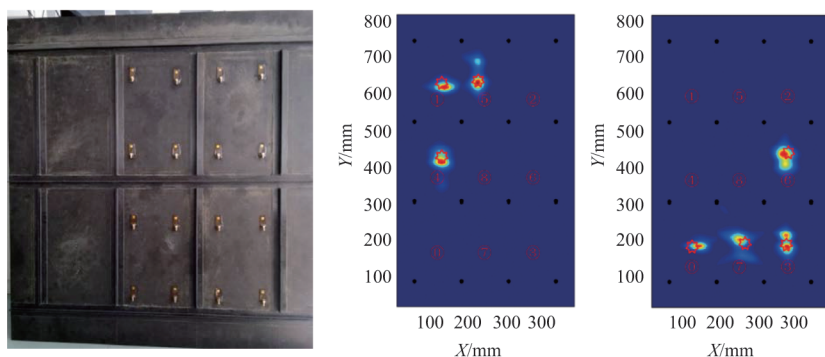
1.1 延时累加成像方法

延时累加成像方法是一种简单有效的损伤成像方法。在该方法中假设每一点均为潜在的损伤点,可以计算出阵列中每条压电片对相对于该点的损伤散射路径传播时间。把所有损伤散射信号在相应传播时间上的幅值进行相加得到该点的能量值。求出所有点的能量值并进行归一化可得到相应的成像结果,结果中能量较大的亮点对应为损伤散射点。该成像方法与椭圆定位法有些类似,但是在成像中无须提取损伤散射信号的飞行时间,而且适用于多损伤成像。

J. E. Michaels^[33], F. K. Chang^[34]以及 Qing Xinlin^[35]等首先研究了该方法在导波结构健康监测中的应用以及实现的基本原理,其中 Qing Xinlin 等将方法应用至火箭复合材料燃料储箱的损伤成像中,如图 3(a)所示。Shan Shengbo^[36]、Cai Jian^[37,38]、J. S. Hall^[39]等分别提出了有效散射信号提取、线性频散信号构建和最小方差无失真响应算法,抑制了导波多模和频散效应对延时累加成像的影响,提高了延时累加成像方法的精度。其中,Shan Shengbo 等应用延时累加成像方法实现了碳纤维航空加筋壁板上的多损伤成像定位,如图 3(b)所示。刘梦龙^[40]、王莉^[41]等分别通过损伤数目



(a) 火箭复合材料燃料贮箱损伤成像



(b) 复合材料航空壁板损伤成像

图3 延时累加成像方法在飞行器结构上的应用

Fig.3 Applications of the delay and sum imaging method on aircraft structures

判定和基于概率模型的损伤尺寸分类、波速自适应选取等方法对延时累加成像方法进行了改进,实现了复合材料结构上的多损伤成像定位及损伤尺寸估计。M. Franklin^[42]、Wu Jianjun^[43]等采用非频散、不受流体载荷影响且可用于复合材料监测的SH0模式激励方法和三传感器稀疏阵列,结合延时累加成像方法在薄铝板上实现了多损伤成像,定位精度在5%之内。

1.2 路径成像方法

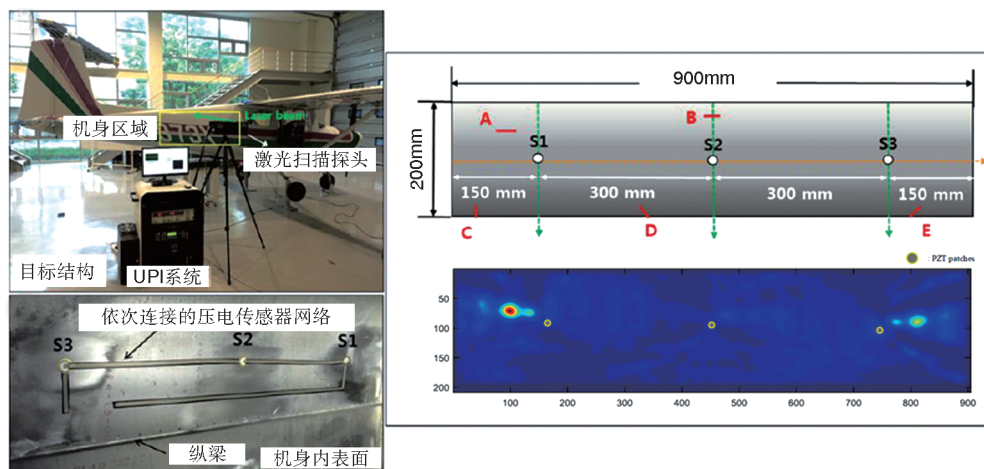
无须传播速度参数的路径成像方法也是一种常见的导波损伤成像方法。在路径成像方法中,计算每一条激励传感路径椭圆模式上的损伤特征因子,综合叠加所有路径上的损伤特征因子得到一个直观的定量图,反映了被监测结构中存在损伤的概率分布。

Yuan Fuguo^[44], P. D. Wilcox^[45], Wu Zhanjun^[46] 和 F. Yan^[47]等将路径成像方法引入基于导波的损伤监测中,并研

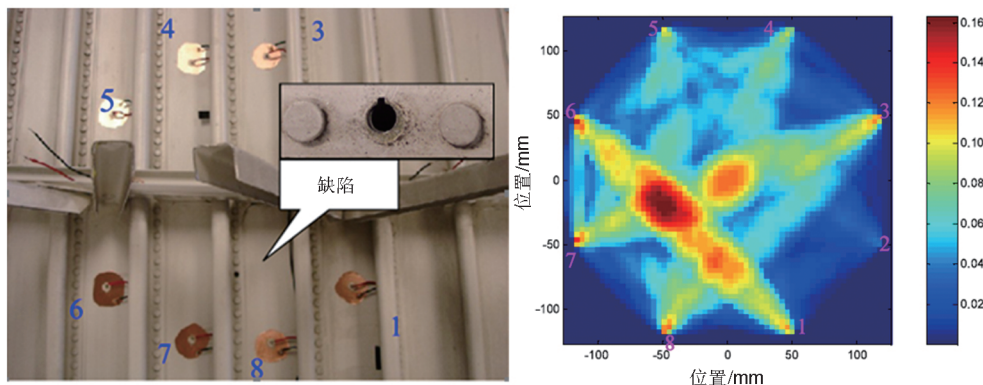
究了多种损伤因子。C. Yunshil^[48], Zhao Xiaoliang^[49], Wang Dong^[50]和 A. De Fenza^[51]等采用基于互相关损伤因子的路径成像方法,并分别结合虚拟传感路径概念和人工神经网络方法来提高路径成像的定位精度。其中 C. Yunshil 等将该方法应用至某无人机机翼结构的损伤成像定位,如图4(a)所示;Zhao Xiaoliang 等采用该方法在真实机翼壁板结构上进行了螺钉脱落监测的试验验证,如图4(b)所示。Wu Zhanjun^[52-54]和刘国强^[55]等通过单位权重分布函数优化了传感网络和控制影响区域的尺度参数。Yuan Fuguo^[56], M. Samir^[57]和 A. Muc^[58]等分别采用匹配追踪以及时间反转方法对每个波包进行分离并增强损伤散射信号,提高了路径成像方法的图像质量。

1.3 时间反转成像方法

时间反转方法可以抑制导波的频散效应,因而得到了许多研究者的关注。根据声波互易性原理,传感器和激励



(a) 无人机机翼结构损伤成像



(b) 全尺寸机翼壁板上的螺钉脱落成像

图4 路径成像方法的损伤监测试验验证

Fig.4 Experimental verification of path imaging based damage monitoring damage and impact method

器位置可以互易,且此时传递函数相同。因此将时间反转后的信号在对应的传感器上加载,激励源处的接收信号的幅值会增强且与激励信号波形一致,同时有效抑制了导波频散效应对损伤监测的影响。将损伤散射信号时间反转并在各自对应的传感器上加载,则各信号将在损伤处发生聚焦,损伤处的信号能量为最大。以信号能量为参数将结构各点信号幅值映射为图像矩阵中各像素点的像素值,则信号传播的波动图可以用图像的方法显示出来,且图像最亮处显示的是信号聚焦处,即损伤位置。

F. K. Chang^[59]、H. W. Park^[60]和袁慎芳^[61]等研究了该方法在结构健康监测中的应用以及实现的基本原理。N. Mori^[62]和D. K. Kim^[63]等采用双面传感器激励单模式方法、全向SH波磁致伸缩贴片换能器等方法对导波信号的模式进行了优化选取,抑制了导波信号的混叠,并应用时间反转成像方法实现了损伤定位,提高了导波成像精度。A. Migot^[64]和Wang Qiang^[65]等研究了不同方向裂纹作用下的导波散射波信号以及时间反转成像谱峰与驱动器的方位角之间的规律,采用时间反转成像方法实现了金属结构上裂纹方向和尺寸的估计,如图5(a)所示。V. Giurgiutiu^[66]、Yuan Fuguo^[67]、邱雷^[68]和石立华^[69]等就将时间反转成像方

法应用于复合材料的损伤监测中,并进一步验证了时间反转成像方法监测多损伤的有效性。邱雷^[70]和F. Ciampa^[71]等还对冲击引起的导波信号进行处理并提取频谱和窄带信号,采用时间反转成像方法实现了复合材料结构上的冲击成像定位,如图5(b)所示。

1.4 层析成像方法

导波层析成像方法从医学X射线成像中的计算机断层扫描(Computed Tomography, CT)技术发展而来。该方法中,传感器布置于被测区域周围并工作于pitch-catch模式,利用与损伤相关的波速、能量衰减和模式变换等特征参数进行图像构建。导波层析成像可采用标准平行投影、扇形波束投影或十字交叉投影方式。

L. J. Breon^[72]、K. R. Leonard^[73]和S. M. Prasad^[74]等将层析成像技术从医学领域引入至结构健康监测中,并实现了损伤成像。M. K. Hinders^[75]和K. Balasubramaniam^[76]等应用十字交叉投影方式和迭代重构算法,分别采用 A_0 、 S_0 和 A_1 这三个模式信号的波达时间进行层析成像以识别铝板中的不同损伤。Zhang Weifang^[77,78]等采用导波层析成像方法对腐蚀损伤进行成像定位并对腐蚀程度进行了定量化估计。

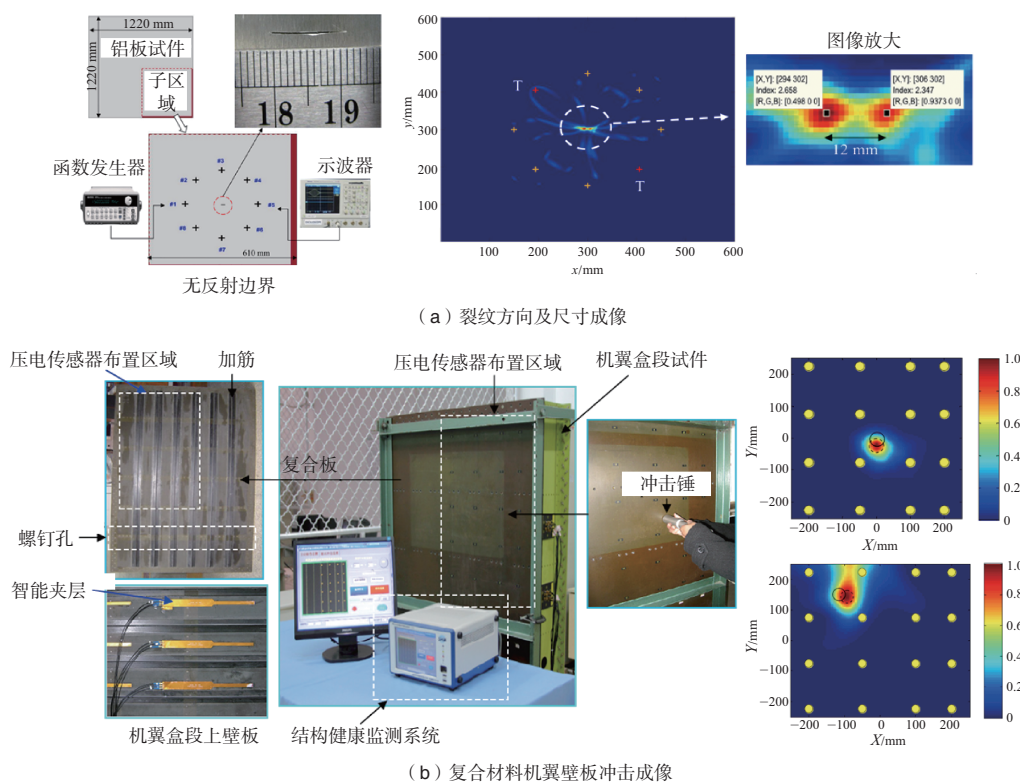


图5 基于时间反转成像的损伤和冲击成像验证

Fig.5 Experimental verification of time reversal based imaging method

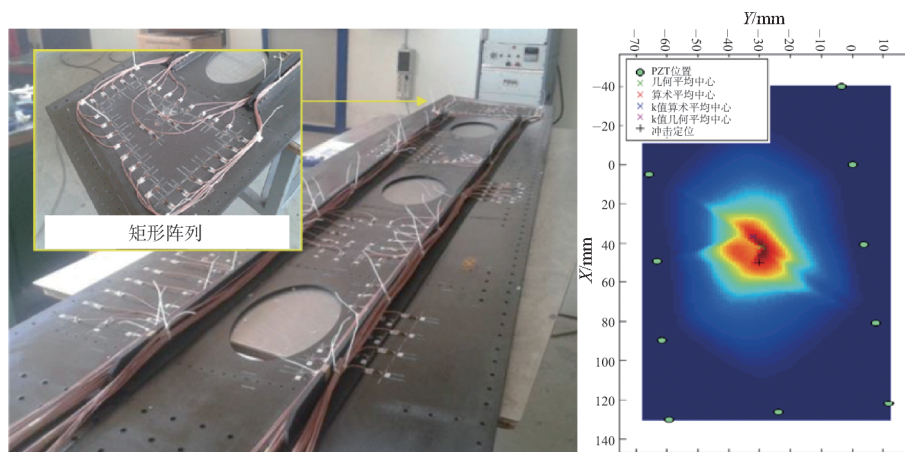
T. R. Hay^[79], J. Lee^[80], E. Monaco^[81]和 Zhao Xiang^[82]等采用基于盖然损伤分布(RAPID)的构建算法,以损伤前后导波传感信号的相关性作为特征量作为图像重建的输入,计算激励-传感路径椭圆分布上的损伤概率。其中, E. Monaco 等采用矩形阵列实现了全尺寸复合材料机翼壁板的损伤成像,如图 6(a)所示。Zhao Xiang 等在结构上布置环形阵列,采用该方法实现了飞机机翼上的冰块定位,如图 6(b)所示。Liu Menglong^[83]和 H. Sohn^[84]等通过提取非线性损伤特征参数,采用 RAPID 成像方法实现了铝板上微缺陷的监测以及复合材料结构冲击损伤的监测。

综上所述,稀疏阵方法相对简单易行,能够监测多损伤,且适合大面积区域监测,在飞行器结构健康监测领域中得到了大量的研究。延时累加成像方法和路径成像方法在真实航空结构上进行了初步应用,可消除频散效应的时间反转方法不仅应用于损伤监测,还被用于被动冲击监测,以及层析成像方法被用于损伤位置、程度乃至形状的估计。在工程应用中,许多学者围绕这些成像方法也进行了改进

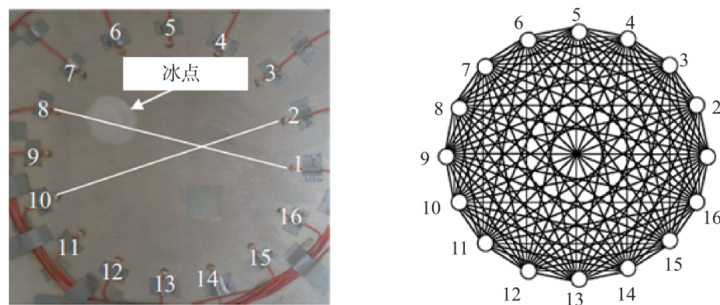
研究。例如,一些学者分别提出频散补偿、单模式激励和损伤散射波包提取方法来抑制工程应用中导波传播的波包混叠,以提高成像方法的精度^[37,62]。也有一些学者通过事先测量复合材料结构各方向上的导波速度,并在成像过程中自适应选取相应方向上的速度来抑制各向异性对成像精度的影响^[41]。总体来说,围绕稀疏阵导波成像方法的主要问题,大量学者进行了深入的研究和改进,并且一些研究已在真实航空结构上进行了初步应用。

2 基于密集阵的导波成像方法

相比于稀疏阵方法,密集阵列成像方法主要具有以下优势:(1)密集阵更容易布置在结构紧凑、空间狭小的航空结构上,且导线可集中引出;(2)密集阵方法可以聚焦增强损伤散射信号而抑制其他干扰信号,可实现定向扫描且定位精度高。近年来,基于密集阵的导波成像方法逐渐被引入结构健康监测领域,主要包括相控阵方法、空间滤波器和多重信号分类。本节将分别介绍密集阵列导波成像方法的基本原理和研究现状。



(a) 复合材料机翼壁板损伤成像结果



(b) 机翼表面冰块成像结果

图6 层析成像方法在飞行器结构上的应用

Fig.6 Applications of the tomography methods on aircraft structures

2.1 相控阵方法

基于相控阵的导波成像方法中一般选用压电元件组成密集阵,轮流驱动阵列中的每个压电元件向结构中激发导波,阵列中其余所有压电元件作为传感器接受响应信号。对于某扫描的角度,按照该扫描角度计算阵列各阵元相对于参考阵元的延时,根据此延时对每组传感信号前移或后移并叠加为一个波束合成信号。对监测区域的所有方向进行扫描,把每个角度的聚焦信号的能量作为像素值对监测区域绘成图像。相控阵方法的原理如图7所示,由于相控阵方法涉及激励、传感两个聚焦过程,因此相控阵方法只能实现损伤成像,而不能用于瞬时的冲击成像。

V. Giurgiutiu^[85,86], P. Malinowski^[87], T. Stepinski^[88] 和 Wang Zhiling^[89]等通过对传感器阵列进行优化,提出了二维阵列的相控阵方法,抑制了相控阵方法的角度盲区和近场盲区问题。例如,Wang Zhiling应用基于十字阵的相控阵方法实现了航空复合材料油箱结构上的损伤定位,如图8(a)所示。Tian Zhenhua^[90,91], Wang Zhiling 等分别采用波数域补偿与线性映射方法对导波信号进行了频散补偿,Huan Qiang^[92]则采用全向SH波压电换能器激发非频散的SH波,

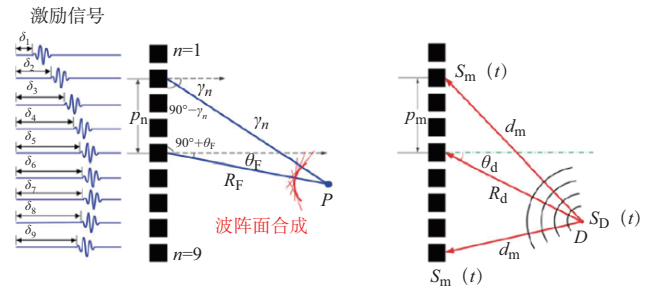


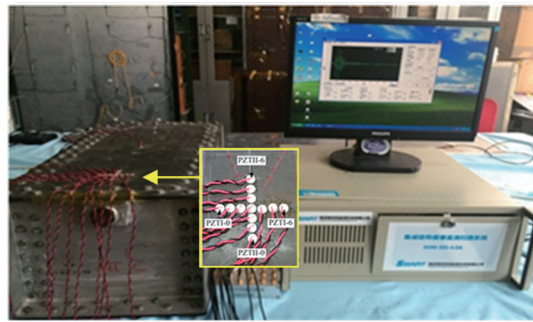
图7 相控阵方法的基本原理

Fig.7 Principle of phased array based imaging method

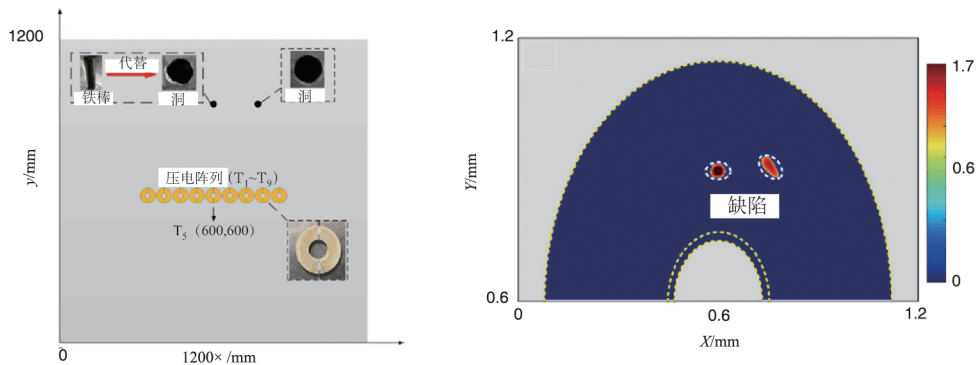
他们将消除频散效应的导波信号应用至相控阵方法中,提高了成像精度且实现了多损伤定位,如图8(b)所示。V. Y. Senyurek^[93], Su Yajie^[94]等通过紧凑型传感器阵列与压缩感知方法,减少了相控阵传感器数量和计算量,提高了成像效率。Yu Lingyu^[95]等在波束形成公式上考虑了方向相关的导波特性和能量偏移效应,减少了各向异性对相控阵方法波束形成的影响。

2.2 空间滤波器方法

空间滤波器方法同样采用密集阵传感器布置,作用于信号的波数这一表征信号频率、传播速度以及传播方向三



(a) 复合材料油箱的损伤成像



(b) 多损伤相控阵成像结果

图8 相控阵损伤成像方法的试验验证

Fig.8 Experimental verification of phased array based damage imaging method

者之间关系的周期性空间物理量。该方法通过设置滤波权值,形成特定波数带宽的空间滤波器,对结构进行全方位扫描。当扫描到与声源相对于传感器阵列的角度相同且响应信号的波数属于滤波器带宽范围时,信号可以通过该滤波器,合成响应的幅度较大;在扫描其他角度时,由于声源不在该方位上,所以信号无法通过滤波器而合成响应幅度较弱。最后,基于空间滤波器的监测方法将各个方位滤波后得到的响应信号强度进行图像表征后实现对损伤的成像和定位。

P. F. Pai^[96], Tian Zhenhua^[97]和 O. Mesnil^[98]等采用扫描激光测振仪(Scanning Laser Doppler Vibrometer, SLDV)作为空间采样设备,结合信号的空间-波数分析以及时-频域分析,对复合材料结构中冲击损伤的位置和损伤进行了评估研究。但这些研究均通过采用SLDV测量结构的波场从而获得波数分布并在此基础上进一步评估损伤位置,耗时较长,并不适用于结构的在线健康监测。A. S. Purekar^[99]、王瑜^[100]等采用线型压电传感器阵列代替SLDV作为空间采样设备,并在此基础上分别开展了单个损伤的在线成像方法研究,但均需要提前获得准确的波数曲线以实施空间-波数滤波。Liu Bin^[101], Qiu Lei^[102,103]等提出了基于二维传感器阵列的空间滤波器方法,开展了不依赖波速的冲击成像定位方法研究,实现了远场情况下单源冲击的无角度盲区

定位。Ren Yuanqiang^[104,105]等采用十字阵的空间滤波器方法,实现了碳纤维复合材料平板结构上的多冲击和多损伤成像定位,如图9所示。

2.3 多重信号分类方法

多重信号分类(MUSIC)方法是近年来新引入导波结构健康监测的一种阵列信号处理方法。MUSIC方法通过将任意阵列输出数据的协方差矩阵进行特征值分解,从而得到与信号分量相对应的信号子空间和与信号分量相正交的噪声子空间,然后利用这两个子空间的正交性来估计信号源的方向。正是由于MUSIC方法在特定条件下具有很高的分辨力、估计精度及稳定性,从而吸引了大量的学者对其进行深入的研究和分析。

M. Engholm^[106], H. J. Yang^[107], He Jiaze^[108]采用均匀圆阵和线型阵等一维阵列,应用基于远场信号模型的MUSIC方法,实现了金属结构上的损伤定位。但远场MUSIC方法只能估计损伤角度,欲实现损伤距离估计还需要结合几何方法。Yuan Shenfang^[109,110], Zuo Hao^[111]等提出了一种近场2D-MUSIC方法,该方法通过建立近场信号模型,解决了一维线阵的近场盲区问题,实现了损伤角度和距离的同时定位,并在复合材料结构中进行了试验验证。其中Yuan Shenfang还将空间平滑与近场MUSIC方法相结合,实现了多损伤成像定位。Bao Qiao^[112,113]等采用双传感器阵列布

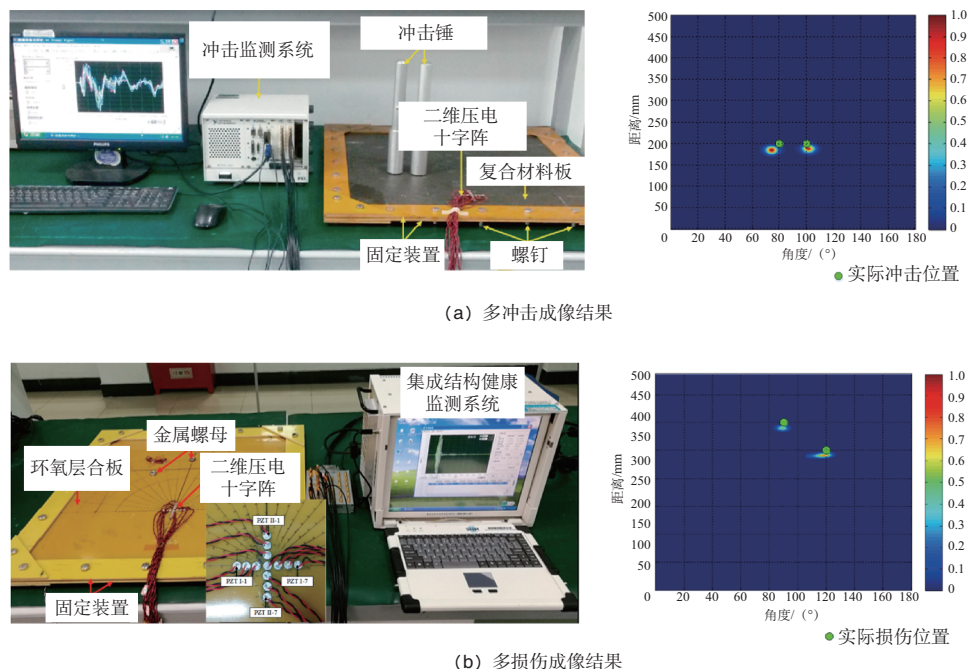


图9 空间滤波器成像的试验验证

Fig.9 Experimental verification of spatial filter based imaging method

置,提出了激励波束成形和全方位误差校正方法,增强复合材料结构上的导波散射信号和补偿各向异性,提高了MUSIC成像方法在复合材料结构上的精度和可靠性,如图10(a)所示。Yuan Shenfang^[114],Zhong Yongteng^[115]等还采用

近场2D-MUSIC对冲击引起的导波阵列信号进行处理,实现了多冲击成像定位,并对冲击能量等级进行了估计,该研究在某无人机复合材料机翼盒段及航空油箱结构上进行了试验验证,如图10(b)所示。

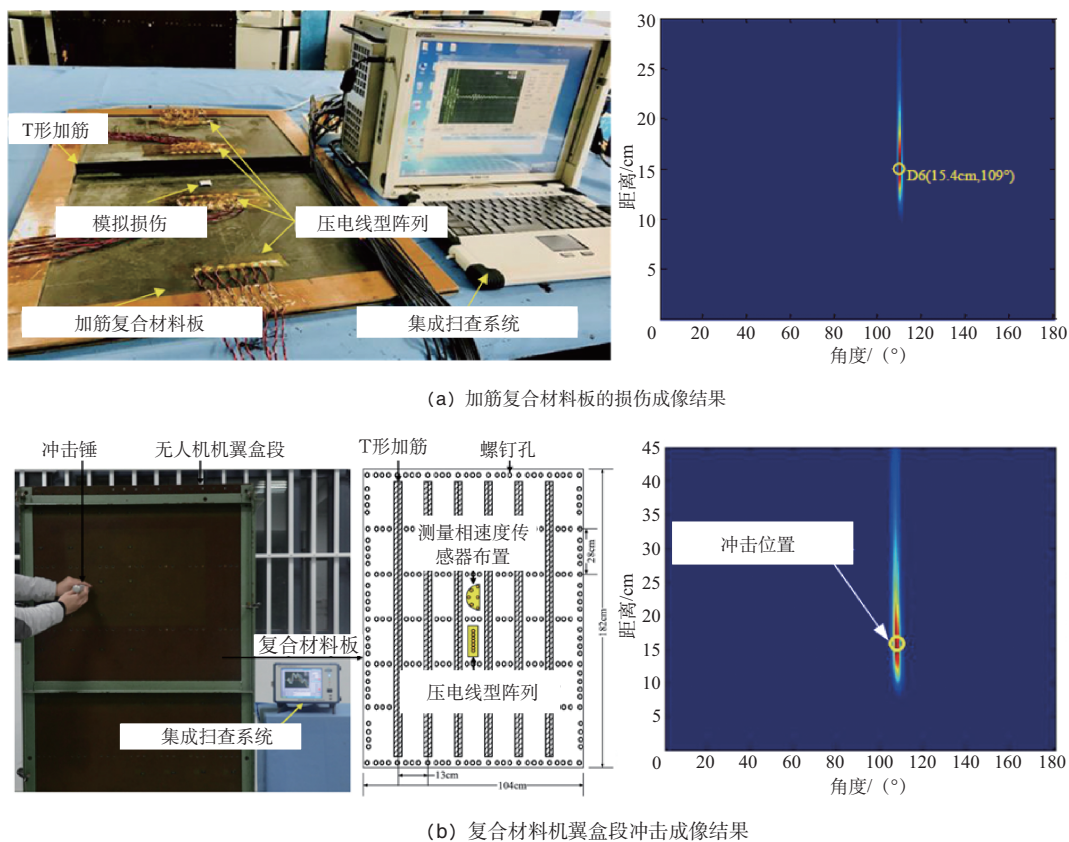


图10 MUSIC损伤和冲击成像的试验验证

Fig.10 Experimental verification of MUSIC based damage and impact imaging

密集阵列方法由于其适合狭小空间监测且能够定向扫描而被引入至飞行器结构健康监测中并得到了大量研究。相控阵、空间滤波器和多重信号分类方法均实现了多损伤成像定位,后两种方法还实现了多冲击成像。这些方法分别在复合材料机翼盒段、航空油箱等结构上进行了试验验证。但将密集阵方法应用于实际工程依然存在问题。首先,密集阵方法中均需要导波的速度参数,因而其精度受到复合材料各向异性的影响。针对该问题,一些学者采取了与改进稀疏阵类似的方法,即事先测量结构上各方向的导波速度,并在方向扫描时选取对应的速度^[89,114]。其次,密集阵方法具有角度盲区和近场盲区问题。针对角度盲区问题,许多研究提出了二维阵列,如十字阵和矩形阵^[85,86,101-105],一些学者建立了近场阵列信号模型以改进远场信号模型在近场范围内的监测盲区问题^[109]。此外,在监

测多损伤时,损伤散射信号之间存在相干性,导致一些密集阵方法失效,如多重信号分类方法。因此,一些学者研究了改进的多重信号分类方法,采用空间平滑对相干信号源解耦从而实现多损伤的成像定位^[110]。总的来说,基于密集阵的导波成像方法取得了一定的研究进展,但面向实际航空结构亟待进一步深入。

3 时变导波损伤成像方法

基于稀疏阵和密集阵的导波成像方法已经在实验室条件下进行了大量飞行器结构的试验验证,实现了冲击和损伤的准确成像。然而不同于实验室所进行的简单研究,航空工程应用时,结构健康监测方法必须面临复杂而苛刻的航空服役条件。服役环境中存在温湿度等环境参数影响、结构的气动载荷作用、不同飞行任务下结构边界条件变化

等多种时变因素,而且这些时变因素相互交织耦合,严重影响结构损伤诊断方法的可靠性。很多在实验室或地面有效的算法在实际服役条件下往往出现误判甚至失效。目前,时变环境影响下的导波成像研究主要包括三大类:环境参数补偿方法、无基准方法和概率统计方法。

3.1 环境参数补偿方法

环境参数补偿方法首先获取某个环境参数下,如不同温度下,传感器信号及损伤特征的基准或建立其物理模型,结合实测环境参数进行补偿。J. E. Michaels^[116], M. S. Salmanpour^[117]和 P. Ostiguy^[118]等研究了温度这一重要环境参数对传感信号的影响情况,并根据实时温度自适应选取最优基准信号或对基准信号进行校正补偿,提高了延时累加成像结果的准确性。基于温度补偿的延时累加成像方法原理如图 11 所示。

Qing Xinlin^[119], Li Dan^[120], C. Fendzi^[121]等利用神经网络算法研究导波信号幅值、相位及飞行时间与温度之

间的关系,建立了重构基准信号的数据驱动模型,并应用层析成像方法进行了试验验证。

3.2 无基准方法

常规损伤成像方法往往依赖结构健康状态时的基准信号,通过提取差信号获取损伤散射信号。但真实服役条件下的多种时变参数往往造成基准信号的明显变化,常常完全淹没了损伤所产生的微弱信号变化。因此有学者考虑采用不依赖基准的损伤成像方法。Wang Qiang^[122], S. J. Lee^[123]和 Huan Qiang^[124]等结合一定的传感器布置,采用时域窗函数、频散校正和自适应源去除算法在不使用任何基准信号的情况下提取损伤散射信号,以避免其受到环境和操作变化的影响,并将该方法用于散射源成像。J. Hettler^[125]等提出了一种无须基准信号的非线性损伤特征,并将其应用于 RAPID 算法中,通过冲击损伤成像进行了验证。Qing Xinlin^[126]等利用层析成像中相似激励-传感路径较多的特点,按照方向和距离将传感路径划分为若干组,并利用同组内路径上的信号计算损伤因子,最后通过 RAPID 成像方法对损伤位置进行了估计。该研究在碳纤维复合材料板结构上进行了试验验证,如图 12 所示。

3.3 概率统计方法

从上述研究分析可知,环境参数补偿成像方法需要测量当前的环境参数,而实际工程应用中大多数时变服役环境参数往往都无法准确测量,因而也难以实现补偿后的损伤成像,并且方法也只能补偿单一时变环境参数。而无基准成像方法基本没有考虑多种时变环境参数耦合作用的复杂影响情况,并且大多只是结合稀疏阵列并在简单结构上进行了验证,忽略了复杂复合材料结构的各向异性、信号边界反射等问题,目前的研究进展还难以应用于实际航空结构。

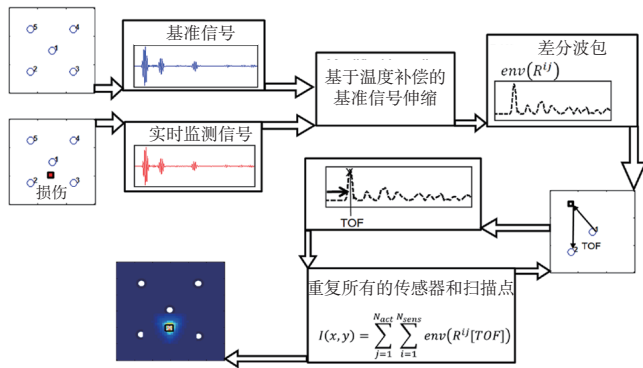


图 11 基于温度补偿的延时累加成像方法

Fig.11 Temperature compensation based delay and sum imaging method

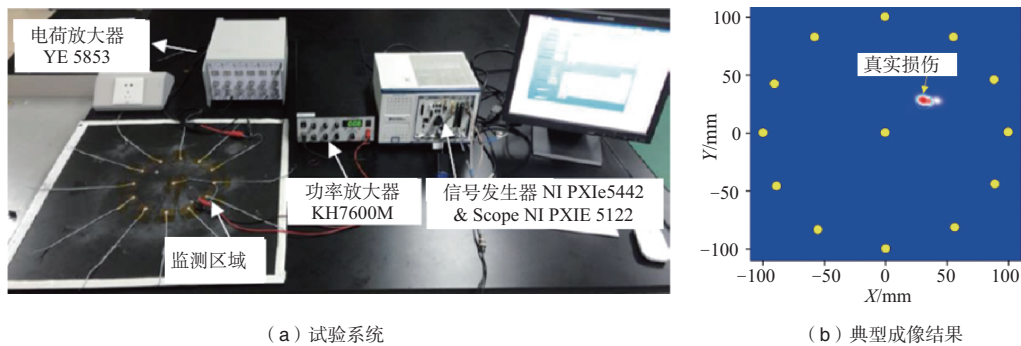


图 12 无基准层析成像的试验验证

Fig.12 Experimental verification of baseline-free tomography method

近年来,有学者逐渐开始将动态概率建模方法作为一种有效处理时变不确定性问题的方法和导波阵列成像方法相结合,开展服役环境影响下的可靠损伤诊断研究^[127,128]。动态概率建模方法能够采用不同分布和不同数目的概率分量组合更好地逼近描述复杂时变不确定因素的影响,同时通过动态概率建模来有效表征时变条件下结构状态及其迁移趋势。因此,可以通过动态概率建模描述并抑制时变环境因素对阵列导波信号的不确定性影响,提取仅对损伤敏感的阵列信号特征;在此基础上优化导波阵列成像方法并

通过成像进一步增强损伤影响,从而最终实现结构损伤的可靠成像定位。

Qiu Lei, Yuan Shenfang 等学者^[129,130]提出了一种基于高斯混合模型和延迟累加算法的4D成像方法,用于复杂飞机复合结构在温度时变影响下的可靠损伤监测,其原理如图13所示。该方法采用高斯混合模型抑制时变因素的不确定性影响,并为压电传感器网络中每个激励传感通道构造仅受损伤影响的时不变特征信号。通过在监测过程中不断更新高斯混合模型以及构建时不变特征信号,并开展基于延

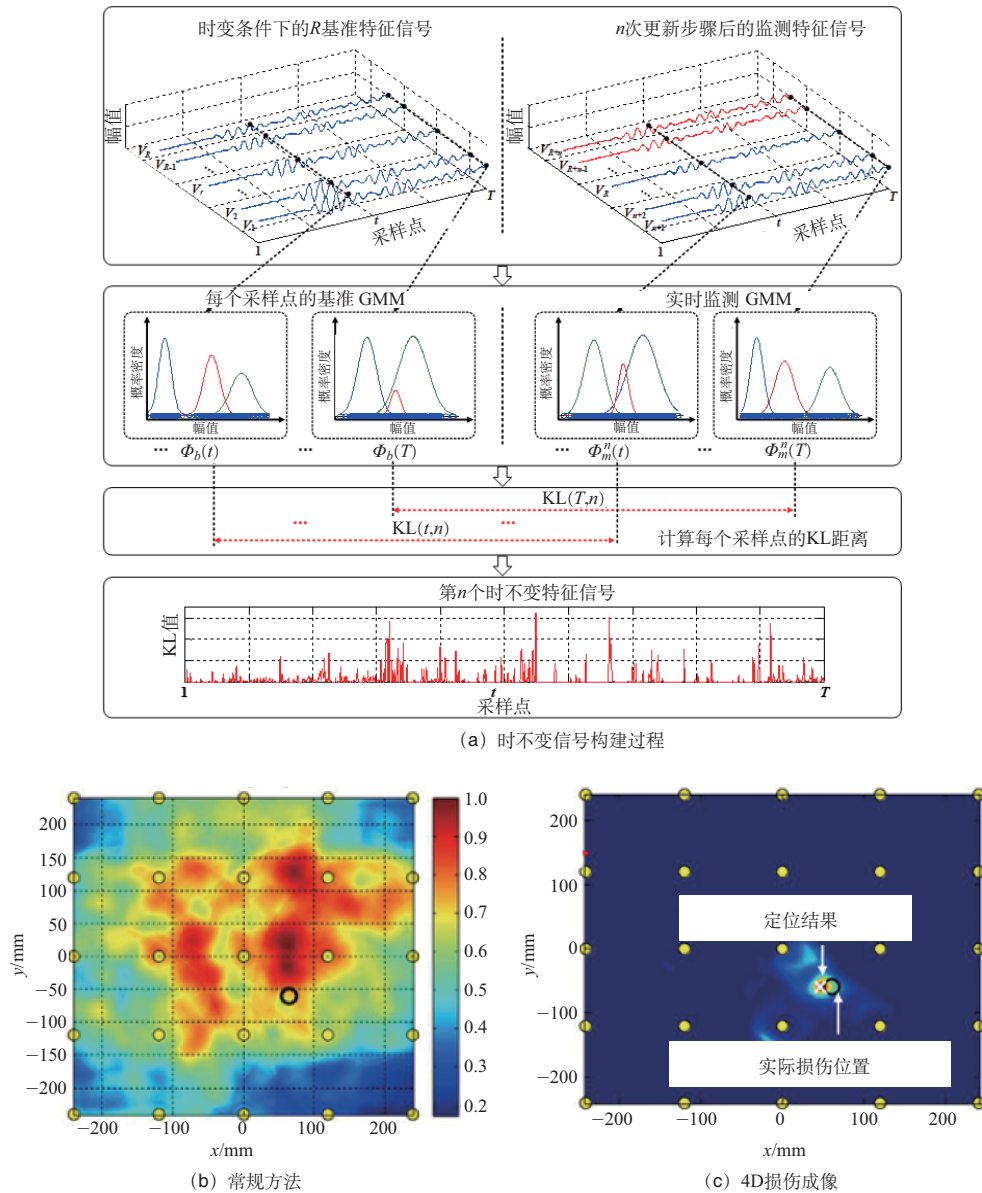


图13 基于高斯混合模型和延迟累加的4D成像

Fig.13 4D imaging method based on Gaussian mixture model and delay and sum algorithm

迟累加算法的4D成像,生成一系列损伤逐渐凸显的图像,从而最终实现损伤的准确定位。

相对于环境参数补偿和无基准方法,基于概率统计的时变损伤监测方法更具有工程适用性。采用概率建模方法和损伤成像方法相结合,可以通过不同分布和不同数目的概率分量混合有效考虑结构状态在多种时变因素耦合作用下的非线性、多模态不确定性影响,同时通过动态概率建模可以有效表征具有动态变化特征的时变条件下结构状态的迁移趋势,有助于提高损伤成像的可靠性和鲁棒性。

4 结论

压电-导波成像方法能够直接对监测区域进行成像,直观且精度高,已成为飞行器结构健康监测的一个重要方法,得到了大量研究。其中,稀疏阵列成像方法已在真实航空结构上进行了应用,并在研究中结合频散补偿、单模式激励等方法提高了其成像精度;密集阵列成像方法在实验室条件下得到了大量试验验证并初步应用于真实航空结构,二维阵列、近场模型等方法的引入也逐步提高了其监测范围。此外,压电-导波成像方法与环境参数补偿、无基准方法和概率统计方法相结合,提高了成像方法在复杂服役条件下的可靠性和鲁棒性。

目前压电-导波成像方法的应用案例表明了该方法在飞行器结构健康监测技术中具有广阔的应用前景,但面向实际工程化应用依然存在挑战,压电-导波成像方法未来的发展趋势总结如下:

(1)压电-导波成像方法大多只能实现对损伤位置的估计,能够实现高精度、高分辨率损伤定位,损伤程度以及形状量化估计的压电-导波成像方法有待进一步研究。

(2)大部分压电-导波成像方法采用线性导波特征参数,因而对结构的早期微小损伤不敏感。基于非线性导波特征参数的微小损伤成像方法研究也是未来的发展方向。

(3)飞行器服役环境严重影响了压电-导波成像方法的可靠性,虽然通过环境参数补偿、无基准和概率统计等方法有所改善,但这些研究刚刚起步,亟待系统性地开展时变环境下的导波损伤成像机制研究。

AST

参考文献

- [1] Qing Xinling, Li Wenzhou, Wang Yishou, et al. Piezoelectric transducer-based structural health monitoring for aircraft applications [J]. *Sensors*, 2019, 19(3): 545.
- [2] Diamanti K, Soutis C. Structural health monitoring techniques for aircraft composite structures [J]. *Progress in Aerospace Sciences*, 2010, 46(8): 342-352.
- [3] 武湛君, 渠晓溪, 高东岳, 等. 航空航天复合材料结构健康监测技术研究进展[J]. *航空制造技术*, 2016, 510(15):92-102.
Wu Zhanjun, Qu Xiaoxi, Gao Dongyue, et al. Research progress on structural health monitoring technology for aerospace composite structures[J]. *Aeronautical Manufacturing Technology*, 2016, 510(15): 92-102. (in Chinese)
- [4] 袁慎芳, 邱雷, 吴键, 等. 大型飞机的发展对结构健康监测的需求与挑战[J]. *航空制造技术*, 2009(22):62-67.
Yuan Shenfang, Qiu Lei, Wu Jian, et al. Challenge in structural health monitoring of large aircraft development [J]. *Aeronautical Manufacturing Technology*, 2009(22): 62-67. (in Chinese)
- [5] 张卫方, 何晶靖, 阳劲松, 等. 面向飞行器结构的健康监控技术研究现状[J]. *航空制造技术*, 2017, 60(19):38-47.
Zhang Weifang, He Jingjing, Yang Jinsong, et al. Research status on structural health monitoring technology for aircraft structures[J]. *Aeronautical Manufacturing Technology*, 2017, 60(19): 38-47. (in Chinese)
- [6] García I, Zubia J, Durana G, et al. Optical fiber sensors for aircraft structural health monitoring[J]. *Sensors*, 2015, 15(7): 15494-15519.
- [7] 孙侠生, 肖迎春. 飞机结构健康监测技术的机遇与挑战[J]. *航空学报*, 2014, 35(12): 3199-3212.
Sun Xiasheng, Xiao Yingchun. Opportunities and challenges of aircraft structural health monitoring [J]. *Acta Aeronautica et Astronautica Sinica*, 2014, 35(12): 3199-3212. (in Chinese)
- [8] Katunin A, Dragan K, Dziendzikowski M. Damage identification in aircraft composite structures: a case study using various non-destructive testing techniques[J]. *Composite Structures*, 2015, 127:1-9.
- [9] Frangopol D M, Soliman M. Life-cycle of structural systems: recent achievements and future directions[J]. *Structure and Infrastructure Engineering*, 2016, 12(1): 1-20.
- [10] Neerukatti R K, Liu K C, Kovvali N, et al. Fatigue life prediction using hybrid prognosis for structural health monitoring[J]. *Journal of Aerospace Information Systems*, 2014, 11(4): 211-232.
- [11] Li Gang, Yuan F G. Gradient enhanced damage sizing for

- structural health management[J]. *Smart Materials and Structures*, 2015, 24(2): 025036.
- [12] 王利恒. 复合材料飞机结构健康监测系统的若干问题探讨[J]. *航空科学技术*, 2011(5):63-66.
Wang Liheng. Discussion on composite structural health monitoring system[J]. *Aeronautical Science & Technology*, 2011(5):63-66. (in Chinese)
- [13] 曲帆, 邢晨光, 郭鑫. 国外老龄化飞机结构健康监测方法[J]. *航空科学技术*, 2014, 25(9):1-5.
Qu Fan, Xing Chenguang, Guo Xin. Study on foreign aging airframes structural condition monitoring[J]. *Aeronautical Science & Technology*, 2014, 25(9):1-5. (in Chinese)
- [14] Song Gangbing, Li Weijie, Wang Bo, et al. A review of rock bolt monitoring using smart sensors[J]. *Sensors*, 2017, 17(4): 776.
- [15] Farrar C R, Worden K. An introduction to structural health monitoring[J]. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 2006, 365(1851): 303-315.
- [16] 王奕首, 卿新林. 复合材料连接结构健康监测技术研究进展[J]. *复合材料学报*, 2016, 33(1):1-16.
Wang Yishou, Qing Xinlin. Progress on study of structural health monitoring technology for composite joints [J]. *Acta Materize Compositae Sinica*, 2016, 33(1):1-16. (in Chinese)
- [17] Di Sante R. Fibre optic sensors for structural health monitoring of aircraft composite structures: Recent advances and applications[J]. *Sensors*, 2015, 15(8): 18666-18713.
- [18] Zhou Pengyu, Liao Yaozhong, Li Yehai, et al. An inkjet-printed, flexible, ultra-broadband nanocomposite film sensor for in-situ acquisition of high-frequency dynamic strains[J]. *Composites Part A: Applied Science and Manufacturing*, 2019, 125: 105554.
- [19] Holford K M, Eaton M J, Hensman J J, et al. A new methodology for automating acoustic emission detection of metallic fatigue fractures in highly demanding aerospace environments: an overview[J]. *Progress in Aerospace Sciences*, 2017, 90: 1-11.
- [20] Guo Y, Schütz S, Vaghi A, et al. Stand-alone stretchable absolute pressure sensing system for industrial applications[J]. *IEEE Transactions on Industrial Electronics*, 2017, 64(11): 8739-8746.
- [21] 刘晓明, 王国才, 熊峻江. 飞机结构健康监测中的信息获取技术[J]. *航空科学技术*, 2012(3):56-60.
Liu Xiaoming, Wang Guocai, Xiong Junjiang. Information processing technology of aircraft structure health monitoring [J]. *Aeronautical Science & Technology*, 2012(3): 56-60. (in Chinese)
- [22] 陈伟, 罗华. 多传感器信息融合技术与无人机 PHM 系统[J]. *航空科学技术*, 2009(6):6-7.
Chen Wei, Luo Hua. The multisensory data fusion technology and the UAV PHM system[J]. *Aeronautical Science & Technology*, 2009(6):6-7. (in Chinese)
- [23] Abbas M, Shafiee M. Structural Health Monitoring (SHM) and determination of surface defects in large metallic structures using ultrasonic guided waves[J]. *Sensors*, 2018, 18(11): 3958.
- [24] Chan H, Masserey B, Fromme P. High frequency guided ultrasonic waves for hidden fatigue crack growth monitoring in multi-layer model aerospace structures[J]. *Smart Material Structures*, 2015, 24(2):025037.
- [25] Qiu Lei, Yuan Shenfang, Bao Qiao, et al. Crack propagation monitoring in a full-scale aircraft fatigue test based on guided wave-Gaussian mixture model [J]. *Smart Materials & Structures*, 2016, 25(5):055048.
- [26] Ihn J B, Chang F K. Pitch-catch active sensing methods in structural health monitoring for aircraft structures[J]. *Structural Health Monitoring*, 2008, 7(1): 5-19.
- [27] Guan Ruiqi, Lu Ye, Wang Kai, et al. Fatigue crack detection in pipes with multiple mode nonlinear guided waves[J]. *Structural Health Monitoring*, 2019, 18(1): 180-192.
- [28] Yan F, Royer Jr R L, Rose J L. Ultrasonic guided wave imaging techniques in structural health monitoring[J]. *Journal of intelligent material Systems and Structures*, 2010, 21(3): 377-384.
- [29] Ostiguy P C, Le Duff A, Quaegebeur N, et al. In situ characterization technique to increase robustness of imaging approaches in structural health monitoring using guided waves [J]. *Structural Health Monitoring*, 2014, 13(5): 525-536.
- [30] Mitra M, Gopalakrishnan S. Guided wave based structural health monitoring: a review[J]. *Smart Materials & Structures*, 2016, 25(5):053001.

- [31] Mei Hanfei, Yuan Shenfang, Qiu Lei, et al. Damage evaluation by a guided wave-hidden Markov model based method[J]. Smart Materials and Structures, 2016, 25(2): 025021.
- [32] Qiu Lei, Fang Fang, Yuan Shenfang. Improved density peak clustering-based adaptive Gaussian mixture model for damage monitoring in aircraft structures under time-varying conditions [J]. Mechanical Systems and Signal Processing, 2019, 126: 281-304.
- [33] Michaels J E. Detection, localization and characterization of damage in plates with an in situ array of spatially distributed ultrasonic sensors [J]. Smart Materials and Structures, 2008, 17 (3): 035035.
- [34] Ihn J B, Chang F K. Pitch-catch active sensing methods in structural health monitoring for aircraft structures [J]. Structural Health Monitoring, 2008, 7(1): 5-19.
- [35] Qing Xinlin, Beard S J, Kumar A, et al. Advances in the development of built-in diagnostic system for filament wound composite structures[J]. Composites Science and Technology, 2006, 66(11-12): 1694-1702.
- [36] Shan Shengbo, Qiu Jinhao, Zhang Chao, et al. Multi-damage localization on large complex structures through an extended delay-and-sum based method[J]. Structural Health Monitoring, 2016, 15(1): 50-64.
- [37] Cai Jian, Yuan Shenfang, Qing X P, et al. Linearly dispersive signal construction of Lamb waves with measured relative wavenumber curves[J]. Sensors and Actuators A: Physical, 2015, 221: 41-52.
- [38] Cai Jian, Yuan Shenfang, Wang Tongguang. Signal construction-based dispersion compensation of lamb waves considering signal waveform and amplitude spectrum preservation [J]. Materials, 2017, 10(1): 4.
- [39] Hall J S, Michaels J E. Multipath ultrasonic guided wave imaging in complex structures[J]. Structural Health Monitoring, 2015, 14(4): 345-358.
- [40] 刘梦龙, 袁慎芳, 卿新林, 等. 采用Lamb波对复合材料板结构进行多损伤检测[C]// 航空试验测试技术学术交流会, 2012.
- Liu Menglong, Yuan Shenfang, Qing Xinlin, et al. Lamb wave based multi-damage detection for composite structures [C]// Aviation Test Technology Academic Exchange Meeting, 2012.
- (in Chinese)
- [41] 王莉, 肖迎春, 刘国强. 复合材料层合板损伤的延迟累加成像算法[J]. 科学技术与工程, 2019, 19 (14): 365-370.
- Wang Li, Xiao Yingchun, Liu Guoqiang. Delay and sum damage imaging algorithm of laminates composite panel [J]. Science Technology and Engineering, 2019, 19(14): 365-370. (in Chinese)
- [42] Franklin Mansur Rodrigues Filho J, Tremblay N, Soares da Fonseca G, et al. The feasibility of structural health monitoring using the fundamental shear horizontal guided wave in a thin aluminum plate[J]. Materials, 2017, 10(5): 551.
- [43] Wu Jianjun, Tang Zhifeng, Yang Keji, et al. Ultrasonic guided wave-based circumferential scanning of plates using a synthetic aperture focusing technique[J]. Applied Sciences-Basel, 2018, 8(8): 1315.
- [44] Wang Lei, Yuan F G. Damage identification in a composite plate using prestack reverse-time migration technique [J]. Structural Health Monitoring, 2005, 4(3): 195-211.
- [45] Wilcox P D. Omni-directional guided wave transducer arrays for the rapid inspection of large areas of plate structures [J]. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2003, 50(6): 699-709.
- [46] Wu Zhanjun, Qing X P, Chang F K. Damage detection for composite laminate plates with a distributed hybrid PZT/FBG sensor network [J]. Journal of Intelligent Material Systems and Structures, 2009, 20(9): 1069-1077.
- [47] Yan F, Royer Jr R L, Rose J L. Ultrasonic guided wave imaging techniques in structural health monitoring [J]. Journal of Intelligent Material Systems and Structures, 2010, 21(3): 377-384.
- [48] Choi Y, Abbas S H, Lee J R. Aircraft integrated structural health monitoring using lasers, piezoelectricity, and fiber optics [J]. Measurement, 2018, 125: 294-302.
- [49] Zhao Xiaoliang, Gao Huidong, Zhang Guangfan, et al. Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: defect detection, localization and growth monitoring[J]. Smart Materials and Structures, 2007, 16(4): 1208.
- [50] Wang Dong, Ye Lin, Su Zhongqing, et al. Probabilistic damage identification based on correlation analysis using guided wave signals in aluminum plates[J]. Structural Health Monitoring,

- 2010, 9(2): 133-144.
- [51] De Fenza A, Petrone G, Pecora R, et al. Post-impact damage detection on a winglet structure realized in composite material [J]. *Composite Structures*, 2017, 169: 129-137.
- [52] Wu Zhanjun, Liu Kehai, Wang Yishou, et al. Validation and evaluation of damage identification using probability-based diagnostic imaging on a stiffened composite panel[J]. *Journal of Intelligent Material Systems and Structures*, 2015, 26(16): 2181-2195.
- [53] Wu Zhan, Gao Dongyue, Wang Yishou, et al. In-service structural health monitoring of a full-scale composite horizontal tail[J]. *Journal of Wuhan University of Technology-Materials: Science Edition*, 2015, 30(6):1215-1224.
- [54] Liu Kehai, Ma Shuyi, Wu Zhanjun, et al. A novel probability-based diagnostic imaging with weight compensation for damage localization using guided waves[J]. *Structural Health Monitoring: An International Journal*, 2016, 15(2): 162-173.
- [55] 刘国强, 肖迎春, 张华, 等. 复合材料加筋壁板损伤识别的概率成像方法[J]. *复合材料学报*, 2018, 35(2): 311-319.
Liu Guoqiang, Xiao Yingchun, Zhang Hua, et al. Probability-based diagnostic imaging for damage identification of stiffened composite panel [J]. *Acta Materize Compositae Sinica*, 2018, 35(2): 311-319. (in Chinese)
- [56] Kim H W, Yuan F G. Enhanced damage imaging of a metallic plate using matching pursuit algorithm with multiple wavepaths [J]. *Ultrasonics*, 2018, 89: 84-101.
- [57] Mustapha S, Ye L. Propagation behaviour of guided waves in tapered sandwich structures and debonding identification using time reversal[J]. *Wave Motion*, 2015, 57: 154-170.
- [58] Muc A, Stawiarski A. Location of delaminations in curved laminated panels[J]. *Composite Structures*, 2015, 133: 652-658.
- [59] Wang C H, Rose J T, Chang F K. A synthetic time-reversal imaging method for structural health monitoring [J]. *Smart Materials and Structures*, 2004, 13(2): 415.
- [60] Park H W, Kim S B, Sohn H. Understanding a time reversal process in Lamb wave propagation [J]. *Wave Motion*, 2009, 46(7): 451-467.
- [61] 王强, 袁慎芳. 主动 Lamb 波结构健康监测中信号增强与损伤成像方法 [J]. *航空学报*, 2008, 29(4): 1061-1067.
Wang Qiang, Yuan Shenfang. Amplifying signal and imaging damage method for active Lamb wave structure health monitoring [J]. *Acta Aeronautica et Astronautica Sinica*, 2008, 29(4): 1061-1067. (in Chinese)
- [62] Mori N, Biwa S, Kusaka T. Damage localization method for plates based on the time reversal of the mode-converted Lamb waves[J]. *Ultrasonics*, 2019, 91: 19-29.
- [63] Kim D K, Lee J K, Seung H M, et al. Omnidirectional shear horizontal wave based tomography for damage detection in a metallic plate with the compensation for the transfer functions of transducer[J]. *Ultrasonics*, 2018, 88: 72-83.
- [64] Migot A, Bhuiyan Y, Giurgiutiu V. Numerical and experimental investigation of damage severity estimation using Lamb wave based imaging methods[J]. *Journal of Intelligent Material Systems and Structures*, 2019, 30(4): 618-635.
- [65] Wang Qiang, Xu Yanfeng, Su Zhongqing, et al. An enhanced time-reversal imaging algorithm-driven sparse linear array for progressive and quantitative monitoring of cracks[J]. *IEEE Transactions on Instrumentation and Measurement*, 2019, 68(10): 3433-3445.
- [66] Mei Hanfei, Haider M F, Joseph R, et al. Recent advances in piezoelectric wafer active sensors for structural health monitoring applications[J]. *Sensors*, 2019, 19(2): 383.
- [67] Xiang Dan, Yuan F G, He J. Damage detection in composite structures using time-reversal migration technique [C]// 2018 Prognostics and System Health Management Conference, 2018.
- [68] 邱雷, 袁慎芳, 张道越, 等. 基于 Shannon 复数小波的复合材料结构时间反转聚焦多损伤成像方法[J]. *复合材料学报*, 2010, 27(2): 101-107.
Qiu Lei, Yuan Shenfang, Zhang Xiaoyue, et al. Shannon complex wavelet and time reversal focusing based multi-damage imaging method on composite structures [J]. *Acta Materize Compositae Sinica*, 2010, 27(2): 101-107. (in Chinese)
- [69] 蔡建, 石立华, 袁慎芳. 基于虚拟时间反转的高分辨率复合材料板结构损伤成像[J]. *复合材料学报*, 2012, 29(1):183-189.
Cai Jian, Shi Lihua, Yuan Shenfang. High-resolution damage imaging for composite plate structures based on virtual time reversal [J]. *Acta Materize Compositae Sinica*, 2012, 29(1): 183-189. (in Chinese)
- [70] 邱雷, 袁慎芳, 苏永振, 等. 基于 Shannon 复数小波和时间反

- 转聚焦的复合材料结构多源冲击成像定位方法[J]. 航空学报, 2010, 31(12):2417-2424.
- Qiu Lei, Yuan Shenfang, Su Yongzhen, et al. Multiple impact source imaging and localization on composite structure based on Shannon complex wavelet and time reversal focusing [J]. Acta Aeronautica et Astronautica Sinica, 2010, 31(12): 2417-2424. (in Chinese)
- [71] Ciampa F, Meo M. Impact detection in anisotropic materials using a time reversal approach[J]. Structural Health Monitoring: An International Journal, 2011, 11(1): 43-49.
- [72] Breon L J, Van Velsor J K, Rose J L. Guided wave damage detection tomography for structural health monitoring in critical zones of pipelines [J]. Materials Evaluation, 2007, 65 (12): 1215-1219.
- [73] Leonard K R, Malyarenko E V, Hinders M K. Ultrasonic Lamb wave tomography [J]. Inverse Problems, 2002, 18(6): 1795-1808.
- [74] Prasad S M, Balasubramaniam K, Krishnamurthy C V. Structural health monitoring of composite structures using Lamb wave tomography [J]. Smart Materials and Structures, 2004, 13(5): N73-N79.
- [75] Hou J, Leonard K R, Hinders M K. Automatic multi-mode Lamb wave arrival time extraction for improved tomographic reconstruction[J]. Inverse Problems, 2004, 20(6): 1873-1888.
- [76] Sekhar B V S, Balasubramaniam K, Krishnamurthy C V. Structural health monitoring of fiber-reinforced composite plates for low-velocity impact damage using ultrasonic Lamb wave tomography[J]. Structural Health Monitoring, 2006, 5(3): 243-253.
- [77] Wang Dengjiang, Zhang Weifang, Wang Xiangyu, et al. Lamb-wave-based tomographic imaging techniques for hole-edge corrosion monitoring in plate structures[J]. Materials, 2016, 9 (11): 916.
- [78] Dai Wei, Wang Xiangyu, Zhang Meng, et al. Corrosion monitoring method of porous aluminum alloy plate hole edges based on piezoelectric sensors[J]. Sensors, 2019, 19(5): 1106.
- [79] Hay T R, Royer R L, Gao H, et al. A comparison of embedded sensor Lamb wave ultrasonic tomography approaches for material loss detection[J]. Smart Materials and Structures, 2006, 15(4): 946-951.
- [80] Lee J, Sheen B, Cho Y. Multi-defect tomographic imaging with a variable shape factor for the RAPID algorithm[J]. Journal of Visualization, 2015, 19(3): 393-402.
- [81] Monaco E, Boffa N D, Memmolo V, et al. Detecting delaminations and disbondings on full-scale wing composite panel by guided waves based SHM system[C]//Health Monitoring of Structural and Biological Systems 2016. International Society for Optics and Photonics, 2016.
- [82] Zhao Xiang, Rose J L. Ultrasonic guided wave tomography for ice detection[J]. Ultrasonics, 2016, 67: 212-219.
- [83] Liu Menglong, Wang Kai, Lissenden C, et al. Characterizing hypervelocity impact (HVI) -induced pitting damage using active guided ultrasonic waves: From linear to nonlinear[J]. Materials, 2017, 10(5): 547.
- [84] Hwang S, An Y, Kim J, et al. Monitoring and instantaneous evaluation of fatigue crack using integrated passive and active laser thermography [J]. Optics and Lasers in Engineering, 2019, 119: 9-17.
- [85] Giurgiutiu V. Structural health monitoring with piezoelectric wafer active sensors [M]. Columbia: Academic Press, 2007.
- [86] Giurgiutiu V, Yu L, Kendall J R, et al. In-situ imaging of crack growth with piezoelectric-wafer active sensors[J]. AIAA Journal, 2007, 45(11): 2758-2769.
- [87] Malinowski P, Wandowski T, Trendafilova I, et al. A phased array-based method for damage detection and localization in thin plates[J]. Structural Health Monitoring, 2009, 8(1): 5-15.
- [88] Ambroziński Ł, Stepinski T, Uhl T. Efficient tool for designing 2D phased arrays in lamb waves imaging of isotropic structures [J]. Journal of Intelligent Material Systems and Structures, 2014, 26(17): 2283-2294.
- [89] Wang Zhiling, Xiao Zhenwei, Li Yonglin, et al. An omnidirectional near-field comprehensive damage detection method for composite structures[J]. Applied Sciences, 2019, 9 (3): 567.
- [90] Tian Zhenhua, Howden S, Ma Zhaoyun, et al. Pulsed laser-scanning laser Doppler vibrometer (PL-SLDV) phased arrays for damage detection in aluminum plates[J]. Mechanical Systems and Signal Processing, 2019, 121: 158-170.
- [91] Tian Zhenyua, Yu Lingyu, Sun Xiaoyi, et al. Damage localization with fiber Bragg grating Lamb wave sensing

- through adaptive phased array imaging[J]. *Structural Health Monitoring*, 2019, 18(1): 334-344.
- [92] Huan Qiang, Chen Mingtong, Su Zhongqing, et al. A high-resolution structural health monitoring system based on SH wave piezoelectric transducers phased array[J]. *Ultrasonics*, 2019, 97: 29-37.
- [93] Senyurek V Y, Baghalian A, Tashakori S, et al. Localization of multiple defects using the Compact Phased Array (CPA) method[J]. *Journal of Sound and Vibration*, 2018, 413: 383-394.
- [94] Sun Yajie, Gu Feihong, Ji Sai, et al. Composite plate phased array structural health monitoring signal reconstruction based on orthogonal matching pursuit algorithm[J]. *Journal of Sensors*, 2017: 3157329.
- [95] Yu Lingyu, Tian Zhenhua. Guided wave phased array beamforming and imaging in composite plates[J]. *Ultrasonics*, 2016, 68: 43-53.
- [96] Pai P F, Sundaresan M J. Space-wavenumber and time-frequency analysis for damage inspection of thin-walled structures[J]. *Structural Health Monitoring*, 2012, 11(4): 452-471.
- [97] Tian Zhenhua, Yu Lingyu, Leckey C, et al. Guided wave imaging for detection and evaluation of impact-induced delamination in composites[J]. *Smart Materials and Structures*, 2015, 24(10): 105019.
- [98] Mesnil O, Yan H, Ruzzene M, et al. Fast wavenumber measurement for accurate and automatic location and quantification of defect in composite[J]. *Structural Health Monitoring*, 2016, 15(2): 223-234.
- [99] Purekar A S, Pines D J. Damage detection in thin composite laminates using piezoelectric phased sensor arrays and guided Lamb wave interrogation[J]. *Journal of Intelligent Material Systems and Structures*, 2010, 21(10): 995-1010.
- [100] 王瑜, 袁慎芳, 邱雷. 基于改进空间滤波器的复合材料结构损伤成像方法[J]. *复合材料学报*, 2011, 28(1): 186-193.
Wang Yu, Yuan Shenfang, Qiu Lei. Improved spatial filter based damage imaging method on composite structures [J]. *Acta Materize Compositae Sinica*, 2011, 28 (1): 186-193. (in Chinese)
- [101] 刘彬, 邱雷, 袁慎芳, 等. 基于多维阵列和空间滤波器的损伤无波速成像定位方法[J]. *复合材料学报*, 2014, 31(3): 835-844.
- Liu Bin, Qiu Lei, Yuan Shenfang, et al. Damage imaging and localization method based on multi-dimension arrays and spatial filter without wave velocity [J]. *Acta Materize Compositae Sinica*, 2014, 31(3): 835-844. (in Chinese)
- [102] Qiu Lei, Liu Bin, Yuan Shenfang, et al. Impact imaging of aircraft composite structure based on a model-independent spatial-wavenumber filter [J]. *Ultrasonics*, 2016, 64: 10-24.
- [103] Qiu Lei, Liu Bin, Yuan Shenfang, et al. A scanning spatial-wavenumber filter and PZT 2-D cruciform array based on-line damage imaging method of composite structure[J]. *Sensors and Actuators A: Physical*, 2016, 248: 62-72.
- [104] Ren Yuanqiang, Qiu Lei, Yuan Shenfang, et al. A diagnostic imaging approach for online characterization of multi-impact in aircraft composite structures based on a scanning spatial-wavenumber filter of guided wave[J]. *Mechanical Systems and Signal Processing*, 2017, 90: 44-63.
- [105] Ren Yuanqiang, Yuan Shenfang, Qiu Lei, et al. On-line multi-damage scanning spatial -wavenumber filter based imaging method for aircraft composite structure [J]. *Materials*, 2017, 10 (5): 519.
- [106] Engholm M, Stepinski T. Direction of arrival estimation of Lamb waves using circular arrays [J]. *Structural Health Monitoring*, 2011, 10(5): 467-480.
- [107] Yang H, Lee Y J, Lee S K. Impact source localization in plate utilizing multiple signal classification[J]. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2013, 227(4): 703-713.
- [108] He Jiase, Yuan F G. Lamb wave-based subwavelength damage imaging using the DORT-MUSIC technique in metallic plates [J]. *Structural Health Monitoring*, 2016, 15(1): 65-80.
- [109] Yuan Shenfang, Zhong Yongteng, Qiu Lei, et al. Two-dimensional near-field multiple signal classification algorithm-based impact localization[J]. *Journal of Intelligent Material Systems & Structures*, 2015, 26(4): 703-704.
- [110] Zhong Yongteng, Yuan Shenfang, Qiu Lei, et al. Multiple damage detection on aircraft composite structures using near-field MUSIC algorithm[J]. *Sensors and Actuators A: Physical*, 2014, 214: 234-244.
- [111] Zuo Hao, Yang Zhibo, Xu Caibin, et al. Damage identification

- for plate-like structures using ultrasonic guided wave based on improved MUSIC method[J]. *Composite Structures*, 2018, 203: 164-171.
- [112] Bao Qiao, Yuan Shenfeng, Guo Fangyu, et al. Transmitter beamforming and weighted image fusion based multiple signal classification algorithm for corrosion monitoring[J]. *Structural Health Monitoring*, 2019, 18(2): 621-634.
- [113] Bao Qiao, Yuan Shenfeng, Wang Yanwen, et al. Anisotropy compensated MUSIC algorithm based composite structure damage imaging method[J]. *Composite Structures*, 2019, 214: 293-303.
- [114] Yuan Shenfeng, Bao Qiao, Qiu Lei, et al. A single frequency component-based re-estimated MUSIC algorithm for impact localization on complex composite structures[J]. *Smart Materials & Structures*, 2015, 24(10): 105021.
- [115] Zhong Yongteng, Xiang Jiawei. A two-dimensional plum-blossom sensor array-based multiple signal classification method for impact localization in composite structures[J]. *Computer-Aided Civil and Infrastructure Engineering*, 2016, 31(8): 633-643.
- [116] Hall J, Michaels J E. Minimum variance ultrasonic imaging applied to an in situ sparse guided wave array[J]. *IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control*, 2010, 57(10): 2311-2319.
- [117] Salmanpour M S, Sharif Khodaei Z, Aliabadi M H. Guided wave temperature correction methods in structural health monitoring[J]. *Journal of Intelligent Material Systems and Structures*, 2016, 28(5): 604-618.
- [118] Ostiguy P, Le Duff A, Quaegebeur N, et al. In situ characterization technique to increase robustness of imaging approaches in structural health monitoring using guided waves[J]. *Structural Health Monitoring: An International Journal*, 2014, 13(5): 525-536.
- [119] Sun Hu, Yi Junyan, Xu Yu, et al. Identification and compensation technique of non-uniform temperature field for Lamb wave-and multiple sensors-based damage detection[J]. *Sensors*, 2019, 19(13): 2930.
- [120] Li Dan, Shi Ming, Xu Feng, et al. A new approach to guided wave ray tomography for temperature-robust damage detection using piezoelectric sensors[J]. *Sensors*, 2018, 18(10): 3518.
- [121] Fendzi C, Rébillat M, Mechbal N, et al. A data-driven temperature compensation approach for structural health monitoring using Lamb waves[J]. *Structural Health Monitoring: An International Journal*, 2016, 15(5): 525-540.
- [122] Wang Qiang, Yuan Shenfeng. Baseline-free imaging method based on new PZT sensor arrangements[J]. *Journal of Intelligent Material Systems and Structures*, 2009, 20(14): 1663-1673.
- [123] Lee S J, Gandhi N, Hall J S, et al. Baseline-free guided wave imaging via adaptive source removal[J]. *Structural Health Monitoring*, 2012, 11(4): 472-481.
- [124] Huan Qiang, Li Faxin. A baseline-free SH wave sparse array system for structural health monitoring[J]. *Smart Materials and Structures*, 2019, 28(10): 105010.
- [125] Hettler J, Tabatabaeipour M, Delrue S, et al. Linear and non-linear guided wave imaging of impact damage in CFRP using a probabilistic approach[J]. *Materials*, 2016, 9(11): 901.
- [126] Sun Hu, Zhang Aijia, Wang Yishou, et al. Baseline-free damage imaging for metal and composite plate-type structures based on similar paths[J]. *International Journal of Distributed Sensor Networks*, 2019, 15(4): 1550147719843054.
- [127] Qiu Lei, Yuan Shenfeng, Chang F K, et al. On-line updating Gaussian mixture model for aircraft wing spar damage evaluation under time-varying boundary condition[J]. *Smart Materials and Structures*, 2014, 23(12): 125001.
- [128] Yuan Shenfeng, Zhang Jinjin, Chen Jian, et al. A uniform initialization Gaussian mixture model based guided wave hidden Markov model with stable damage evaluation performance[J]. *Structural Health Monitoring*, 2019, 18(3): 853-868.
- [129] Ren Yuanqiang, Qiu Lei, Yuan Shenfeng, et al. Gaussian mixture model based path-synthesis accumulation imaging of guided wave for damage monitoring of aircraft composite structures under temperature variation[J]. *Structural Health Monitoring*, 2019, 18(1): 284-302.
- [130] Ren Yuanqiang, Qiu Lei, Yuan Shenfeng, et al. Gaussian mixture model and delay-and-sum based 4D imaging of damage in aircraft composite structures under time-varying conditions[J]. *Mechanical Systems and Signal Processing*, 2020, 135: 106390.

(责任编辑 王为)

作者简介

鲍娇(1990—)男,博士,讲师。主要研究方向:导波损伤成像。

Tel: 025-85866526

E-mail: baoqiao@njupt.edu.cn

邱雷(1983-)男,博士,教授,博士生导师。主要研究方向:
飞行器结构健康监测与智能蒙皮。

Tel: 025-84896637

E-mail: lei.qiu@nuaa.edu.cn

袁慎芳(1968-)女,博士,教授,博士生导师。主要研究方
向:飞行器智能结构与健康监测。

Tel: 025-84893460

E-mail: ysf@nuaa.edu.cn

Development and Challenges of PZT-Guided Wave Based Imaging Technique in Aircraft Structural Health Monitoring

Bao Qiao¹, Qiu Lei^{2,*}, Yuan Shenfeng²

1. *Nanjing University of Posts and Telecommunications, Nanjing 210046, China*

2. *The State Key Lab of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

Abstract: Structural Health Monitoring (SHM) technique plays an important role in ensuring the aircraft safety, guiding structural design, reducing maintenance costs and extending life, which has been widely studied and applied at home and abroad. Since it is sensitive to small damage and able to realize large area monitoring, as well as both active damage monitoring and passive impact monitoring, the PZT-guided wave based SHM method is considered to be one of the most promising methods. Especially, PZT-guided wave based imaging technology can directly image the monitoring area with high precision, which features intuition and strong anti-interference capability, and has become an important method in guided wave based SHM. According to the sensor layout, the basal principles and research situation of sparse array and compact array based PZT-guided wave imaging methods are introduced in this paper respectively. These two kinds of methods have made a good progress in the accurate monitoring of real complex aircraft structures. In recent years, the influence of time-varying service environment on the reliability of imaging methods has been paid attention to gradually. On this issue, the research situation of PZT-guided wave based imaging methods under time-varying conditions is reviewed in this paper. At last, the PZT-guided wave based imaging methods in aircraft SHM are summarized and prospected.

Key Words: aircraft; SHM; guided wave; imaging; piezoelectric sensor

Received: 2019-11-08; **Revised:** 2019-12-12; **Accepted:** 2019-12-30

Foundation item: National Natural Science Foundation of China (51921003, 51635008, 51575263); Jiangsu Provincial Key Research and Development Program of China (BE2018123); The Priority Academic Program Development of Jiangsu Higher Education Institutions of China

*Corresponding author. Tel. : 025-84896637 E-mail: lei.qiu@nuaa.edu.cn