



微裂纹的非线性超声检测研究进展

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摘要 非线性超声对微裂纹具有较高的检测灵敏度. 本文从理论模型、数值模拟和实验检测3个方面综述了非线性超声检测微裂纹的研究进展. 基于微裂纹面的“呼吸”效应和“滑移”机制, 介绍了非线性超声检测微裂纹的理论模型. 从微裂纹的非线性响应和几何参数对非线性超声的影响规律及微裂纹定位方面, 介绍了非线性超声检测微裂纹的数值模拟与实验研究进展. 最后, 对微裂纹的非线性超声检测方法进行了展望.

关键词 非线性超声, 微裂纹, 超声检测, 接触声非线性

为了努力实现碳排放减量, 现代工业设备正朝着高参数化、大型化和长寿命服役的趋势发展, 这将有效地提高能源的转化和利用效率^[1]. 在电力、核能、航空航天等重要工业领域, 均有大量核心部件在高温、高压、辐照等极端工况下长周期服役运行, 如超超临界电站机组的服役温度达600~650°C, 蒸汽压力达32~35 MPa, 设计寿命达30年. 虽然现代制造技术持续创新, 但诸多核心部件在制造过程中仍不可避免地存在微小缺陷. 在复杂交变载荷和波动热应力等持续作用下, 应力集中处的这些微小缺陷极易生成微裂纹. 研究发现, 疲劳微裂纹萌生和扩展阶段占据总疲劳寿命的70%~90%^[2], 且在扩展形成宏观裂纹前并无明显征兆, 极大增加了服役设备突发失效的风险并导致严重灾难性后果. 因此, 微裂纹的精确检出是现代工业设备安全运行的重要保障.

超声检测方法基于超声波与裂纹的复杂交互作用, 通过获取声速、衰减、倍频幅值等参量表征工程构件中的裂纹, 具有无损、快速、检测范围大等优点. 传统超声检测方法基于裂纹的衍射、反射和透射等原理,

可以有效检测的裂纹尺寸通常限制在半波长以上^[3], 仅能适用于宏观裂纹的检测. 对于微裂纹, 线性声学范畴内的传统超声响应一般比较微弱. 研究表明, 微裂纹与超声波相互作用会引起强烈的非线性响应, 产生高次谐波、次谐波、直流分量和混频信号等^[4,5]. 因此, 非线性超声检测方法可以有效克服线性超声对微裂纹不敏感的缺点, 有望应用于工程构件中微裂纹的有效检测. 本文从理论模型、数值模拟和实验检测3个方面综述非线性超声检测微裂纹的研究进展.

1 微裂纹非线性超声理论模型

为研究非线性超声与微裂纹相互作用的物理机制, 国内外学者从理论分析角度建立了多个非线性超声与微裂纹相互作用的模型, 主要有接触声非线性理论^[4]、双线性刚度模型^[6]、非线性弹簧模型^[7,8]、Hertz接触理论^[9]、粗糙接触面模型^[10,11]等.

当超声波作用在微裂纹的界面上时, 超声波的压缩部分使裂纹面闭合, 超声波正常通过; 拉伸部分使裂纹面张开, 传播的超声波是部分解耦的, 会发生波的反

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射和部分透射,这个过程是裂纹的“呼吸”效应^[12]. Solodov等人^[4]基于裂纹的“呼吸”效应对超声波的调制,提出了接触声非线性理论(contact acoustic nonlinearity, CAN).

裂纹张开和闭合的“拍击”行为会引起裂纹区域刚度的变化,而且裂纹张开的整体刚度比裂纹闭合时小. Ostrovsky^[6]基于上述原理将裂纹等效为两个刚性接触的光滑面,提出了双线性刚度模型,并引入波动方程分析高次谐波的生成. Solodov等人^[4]基于双线性刚度模型假设裂纹处刚度发生阶跃变化,发现当超声波的应变幅值大于裂纹面的初始应变时裂纹可以张开,验证了裂纹引起的高次谐波的产生,如图1所示. 另外,由于刚度的周期性变化,还会出现次谐波和零频分量.

双线性刚度模型的双刚度应力 σ -应变 ε 关系^[4]为

$$\sigma = C^{\text{II}}[1 - H(\varepsilon - \varepsilon_0)(\Delta C / C^{\text{II}})]\varepsilon, \quad (1)$$

$$\Delta C = [C^{\text{II}} - (d\sigma / d\varepsilon)_{\varepsilon > 0}],$$

式中, $H(\varepsilon)$ 是Heaviside单位阶跃函数; C^{II} 表示材料的二阶弹性常数; ε_0 为裂纹静态接触应变.

双线性刚度模型可以解释高次谐波的产生,但是存在一些局限性^[13]: (1) 裂纹仅有打开和闭合两种状态,在其过渡期间刚度突然变化; (2) 模型仅从宏观层面解释了裂纹面相对运动对超声波的非线性调制作用,但忽略了裂纹面的微观几何特征; (3) 无法解释当超声波应变幅值小于裂纹初始应变时产生的高次谐波现象.

考虑裂纹接触界面间隙宽度的变化, Richardson^[14]

分析了声波单侧激励后在两个半无限大介质接触界面中传播的非线性动力学问题,得到了方波和正弦波从单侧激发通过接触界面产生谐波的理论解. 单边接触理论^[14]是CAN问题经典的框架,但它没有考虑非线性界面刚度可能随接触条件不断变化的情况.

在单边接触理论的基础上, Biwa等人^[15,16]将接触界面建模为具有等效刚度特性的弹簧界面. 如图2所示, 接触压力 $p(h)$ 与界面间隙距离 $h(t)$ 的非线性关系^[8]为

$$p(h) = p_0 - K_1(h - h_0) + K_2(h - h_0)^2, \quad (2)$$

$$h(t) = h_0 + u(X_+, t) - u(X_-, t),$$

式中, $u(X_+, t)$ 和 $u(X_-, t)$ 为界面左右边界由超声波引起的位移, $h_0 = X_+ - X_-$ 为初始状态界面间隙距离, X_+ 和 X_- 为界面左右边界初始位置, K_1 为线性刚度系数, K_2 为二阶刚度, 静态压力 $p_0 = p(h_0)$. 将刚度系数与接触压力的幂次方关系引入弹簧界面模型来推导接触界面二次谐波的幅值, 构建了非线性弹簧界面模型^[7,8]. 接触界面刚度系数与接触压力的幂次方关系^[7]为

$$K_1 = Cp^m, \quad (3)$$

$$K_2 = \frac{1}{2}mC^2p^{2m-1}, \quad (4)$$

式中, K_1 为线性刚度系数, K_2 为二阶刚度, C 和 m 为常数, p 为接触压力. Biwa等人^[8]和Kim等人^[17]基于上述模型, 根据实测的压力-刚度关系得到了常数 C 和 m , 计算得到了非线性参量. 将该非线性参量与实验测量得到的不

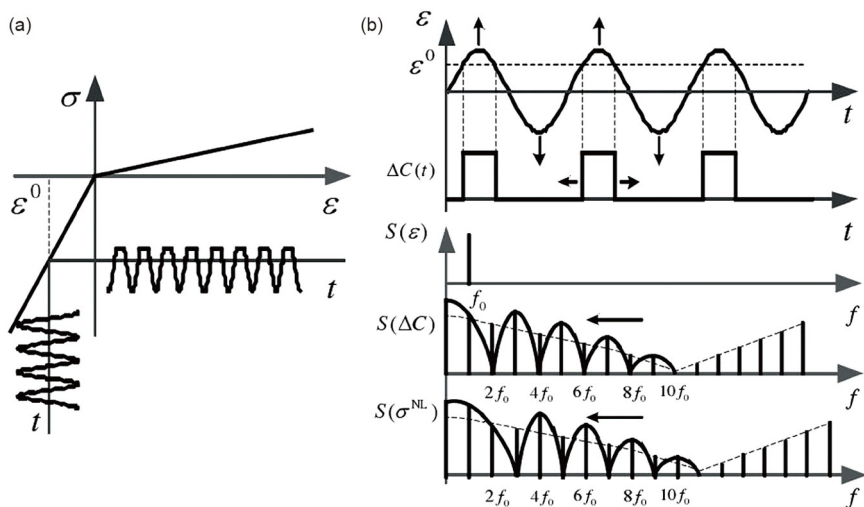


图1 双线性刚度模型^[4]. (a) 分段应力-应变关系; (b) 模型的时域和频域特性

Figure 1 Bilinear stiffness model^[4]. (a) Piecewise stress-strain relation; (b) time and frequency domain characteristics of the model

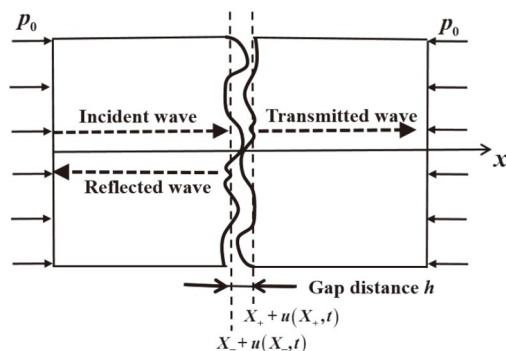


图2 弹簧界面模型^[8]
Figure 2 The spring interface model^[8]

同粗糙度铝块接触面的二次谐波进行比较,验证了该模型的有效性.郑慧峰等人^[18]采用非线性弹簧模型对振动声调制技术下微裂纹产生的非线性调制效应进行了解释.结果表明,微裂纹界面随低频声波呈周期性开合,使通过裂纹界面的高频声波与低频声波相互调制而产生非线性现象.该模型的缺点是刚度系数和接触压力的幂函数与接触界面表面状态之间的物理关系并不清楚.

为研究接触表面状态与接触外力之间的关系, Hertz接触理论假设两个球体弹性接触,得到接触面位移 h 与接触外力 F 的非线性关系^[9]: $h \propto F^{2/3}$. Belyaeva等人^[19]基于Hertz接触理论得到颗粒状材料接触面的非线性应力-应变关系.焦敬品等人^[20]基于Hertz接触理论建立了板中Lamb波二次谐波与微裂纹长度和宽度的模型. Solodov^[21]基于CAN理论和Hertz接触理论研究了单个接触面的变形,发现拍击接触声非线性强于Hertz接触声非线性,并通过研究不同粗糙度表面之间的接触,发现接触粗糙度是影响非线性的重要因素.

Hertz接触理论假定单个微凸体的接触条件并不能满足实际的裂纹接触,因为实际裂纹接触界面凹凸不平,非常复杂.为了解决这个问题,国内外研究者提出了许多裂纹粗糙面接触模型.最简单的模型是将粗糙表面等效为正弦曲线,更复杂的模型是基于统计学的方法表征裂纹面的高度和空间分布状态^[9].统计模型将随机过程和概率理论与Hertz理论结合用于表征接触表面的微凸体接触状态,是使用最为广泛的一类.最经典的统计接触模型为Greenwood和Williamson^[10]提出的光滑刚性平面与名义平坦粗糙表面的接触模型(GW模型).如图3所示,模型假设接触界面为数量一定的微凸体,微凸体的表面是具有相同曲率半径 R 的球形,高

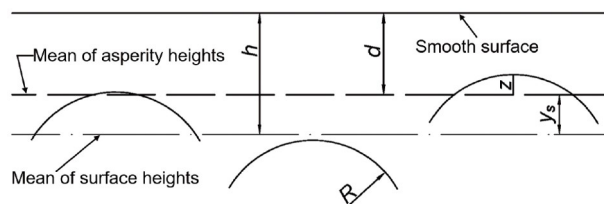


图3 光滑平面与粗糙表面的接触模型
Figure 3 The model of the rough surface in contact with the smooth surface

度 z 服从高斯分布, d 为两接触面间的平均距离, h 为粗糙表面平均高度与刚性平面之间的距离, y_s 为微凸体平均高度与粗糙表面平均高度的距离.在这种假设下,单个微凸体的接触可以直接应用Hertz接触理论进行分析,从而得到粗糙界面的接触面积 A 和接触应力 P 的关系^[10]:

$$A = \pi N R \int_d^{\infty} (z - d) \phi(z) dz, \quad (5)$$

$$P = \frac{4}{3} N E' R^{1/2} \int_d^{\infty} (z - d)^{3/2} \phi(z) dz, \quad (6)$$

式中, N 为微凸体的数量; $\phi(z)$ 为微凸体高度的概率函数; E' 为平面应变模量,当两个接触面材料相同时, $E' = E / 2(1 - \nu^2)$, ν 为泊松比.

在GW模型的基础上, Nazarov和Sutin^[11]将裂纹表示为两个弹性接触的粗糙表面,非线性来源于裂纹面接触的非线性应力-应变关系,他们推导了具有均匀分布、方向和形状随机裂纹的非线性参量.模型考虑了3种裂纹面形状:半径为 a 的球体、顶角为 2ψ 的圆锥体和半径为 b 的圆柱体.在GW模型的基础上, Baltazar^[22]通过Brown和Scholz^[23]提出的粗糙界面静态模型将粗糙界面宏观弹性响应与界面微观形貌联系起来,提出了一组界面刚度系数 K_N 和 K_T ,分别表示法向刚度和切向刚度,表征两粗糙接触面之间的宏观弹性响应. Pecorari^[24]将 K_N 和 K_T 进行泰勒级数展开,通过边界条件求解得到了粗糙裂纹面高度服从 χ^2 分布的接触界面与纵波相互作用的二次谐波幅值.肖齐等人^[25]通过简化的Brown-Scholz模型^[23]研究了线性模型、指数模型和高斯模型3种分布弹性接触界面的超声相互作用,并通过仿真和实验进行了验证.结果表明,高斯模型更适合描述固体接触界面.在GW模型框架下仅考虑微凸体的弹性接触, Kim等人^[26,27]进一步考虑裂纹面的弹塑性变形,应用弹塑性微观力学分析来描述两种固体之间粗糙界面接触的超声波相互作用,并通过实验验证了该

模型对于解释声波在加载-卸载过程滞后现象的有效性。

虽然上述研究已经考虑了裂纹接触界面的粗糙度,但是GW模型的统计参数——界面粗糙峰的高度分布、峰顶的密度和峰顶曲率半径并没有从实际接触界面中得到。Jin等人^[28]使用GW模型框架,直接从真实疲劳裂纹的高分辨率扫描电子显微镜(scanning electron microscope, SEM)图像中提取接触界面的微观几何特征,利用疲劳裂纹真实粗糙界面的微观特征验证了该模型。

通过上述分析可以看出,裂纹与超声波的非线性相互作用有两方面:一是宏观层面上超声波与裂纹面开合的非线性作用,二是微观层面上相互接触的粗糙界面与超声波的非线性作用。接触面模型研究了在微观层面上解释粗糙界面与超声波的非线性作用,但是没有考虑超声波与宏观开合的粗糙界面的非线性相互作用。为完整描述宏观、微观层面上超声波与微裂纹之间的非线性相互作用,杨斌等人^[29]提出了基于等效弹性模量的微裂纹-超声波非线性作用多阶段模型。该模型将微观层面微裂纹粗糙界面和宏观层面裂纹面的相对运动统一为介观弹性模量的变化,然后利用分段函数描述了一个谐波周期内超声波经过微裂纹损伤区域时波形会发生畸变。Hoffmann等人^[30]将双线性刚度模型与粗糙表面接触模型相结合,建立了微裂纹声非线性产生的微观力学模型,描述了分布微裂纹的激振非线性行为。李海洋等人^[31]根据界面粗糙峰的几何分布特征,采用分段概率函数描述粗糙接触界面劲度系数的变化,从而得到界面粗糙度和界面相对运动对声波的非线性调制作用。

上述模型主要是建立在一维纵波条件下,而当裂纹与Lamb波相互作用时,超声波与裂纹的相互作用是二维的。Wang等人^[12]结合模态分解方法和变分原理算法建立了二维“呼吸”裂纹的解析模型,并基于波在三维波导中的传播理论将模型扩展到三维^[32]。通过该模型,可以定量地研究裂纹长度等关键参数与接触声非线性产生的关系。Xu等人^[33,34]提出了一种基于弹性动力学互易定理的理论模型,得到了疲劳裂纹对Lamb波传播过程调制的封闭解。该模型将呼吸裂纹假设为一个附加的波源,该波源在裂纹表面施加的附加力相当于应力张量的积分,并干扰激发信号的波场。

除裂纹“呼吸”效应外,近年来裂纹“滑移”产生的非线性效应也得到了研究者的关注^[35-37]。为了研究微裂

纹“滑移”摩擦引起的非线性,O'Neill等人^[35]在单边接触理论的基础上,利用静摩擦系数和动摩擦系数来计算随时间变化的边界条件,从而推导出横波在粗糙界面上的调制情况,并以此计算入射横波的波形畸变。Aleshin等人^[36]考虑粗糙界面摩擦对超声波的调制,基于库仑摩擦定律建立了弹性波在粗糙裂纹面传播的二维模型。在此基础上,他们还将法向和切向本构模型引入有限元方法中,同时考虑了裂纹的“拍击”和“滑移”行为^[37]。

2 微裂纹非线性超声数值模拟分析

近年来,随着数值模拟技术的发展,研究者采用了许多数值方法对微裂纹与超声波的非线性相互作用进行模拟,主要包括有限元法(finite element method, FEM)^[38]、谱有限元法(spectral finite element, SFE)^[39]、有限差分法(finite difference, FD)^[40,41]、边界元法(boundary element method, BEM)^[42,43]和局部相互作用模拟法(local interaction simulation approach, LISA)^[44,45]等。Shen和Giurgiutiu^[38]基于单元生死法与接触分析的非线性有限元方法、He和Ng^[39]采用时域谱有限元方法分析了“呼吸”裂纹与非线性Lamb波的相互作用关系。时域SFE方法与FEM方法都有较高的灵活性和计算精度,但SFE方法需要的计算单元较少,计算效率比较高。Yamanaka等人^[40,41]通过时域有限差分法(finite difference time domain, FDTD)分析了闭合裂纹中次谐波的产生。Hirose等人^[42,43]用边界元法求解了裂纹接触表面在无摩擦和无形变边界条件下高次谐波的产生。Shen和Cesnik^[44,45]基于局部相互作用模拟方法和罚函数法提出了一种模拟非线性超声Lamb波与疲劳裂纹相互作用过程中“接触-拍击”行为的并行算法。研究发现,Lamb波与疲劳裂纹的非线性相互作用会产生高次谐波和直流分量。

除了研究多种算法对模拟裂纹非线性行为的适用性,利用数值模拟的方法研究裂纹与超声波非线性相互作用的规律同样受到了研究者的关注。在微裂纹与超声波相互作用的发生和传播效应方面,Wang等人^[46]研究了含局部塑性变形区“呼吸”裂纹的非线性效应,结果表明,信号激发频率的选择不需要遵循材料非线性中相速度匹配和非零能量流的条件。Ye等人^[47]以非线性弹簧模型为基础,研究了Lamb波在板平行闭合裂纹处二次谐波的产生,建立了两个激发频率选择规则,同时解释了二次谐波的增强产生效果。在对称性方面,

Xie等人^[48]研究了裂纹的对称性对骨材料二次谐波响应的影响,结果表明,基频S0模式和A0模式与对称裂纹相互作用后产生S0模式的二次谐波分量。

在非线性发生效率方面, He和Ng^[39]研究了不同模式入射波的发生效率,结果表明, S0模式的入射波比A0模式产生的二次谐波相对幅度更大。Yang等人^[49,50]比较了脱黏和裂纹两种接触缺陷产生的二次谐波,结果表明, S0模式对疲劳裂纹更敏感, A0模式对脱黏更敏感。这个结果说明, 与切向摩擦接触相比, 法向拍击接触是产生二次谐波的主要非线性源。研究者通过对不同入射波方式和不同裂纹角度进行模拟, 研究了切向接触和法向接触对裂纹非线性的影响。Blanloeuil等人^[51~55]研究发现, 在横波垂直入射的情况下, 仅有裂纹的切向“滑移”影响裂纹非线性, 而且仅生成奇次谐波; 当声波斜入射时, 裂纹的法向“拍击”和切向“滑移”行为同时影响裂纹非线性, 且会同时生成二次谐波和三次谐波; 当两束横波斜入射时会发生非线性响应, 产生纵波混频。不同于入射波角度对非线性效应的影响, Gao等人^[56]研究了水平和倾斜裂纹角度引起的非线性

响应。结果表明, 对于水平裂纹模型, 非线性响应主要由法向接触产生, 且沿裂纹界面均匀分布; 对于倾斜裂纹模型, 法向接触和切向接触均产生非线性响应。

在裂纹几何参数对裂纹与超声相互作用非线性响应的效果方面, 研究者主要从微裂纹的长度、宽度、深度、密度和方向等方面进行研究。

2.1 长度和宽度

在微裂纹长度和宽度的非线性超声表征方面, 基于体波高次谐波、Lamb波二次谐波和Lamb波混频的数值模拟均表明, 非线性参量随微裂纹长度单调增加, 随微裂纹宽度单调减小^[48,57~61], 如图4(a), (b)所示。Hirata和Sugiura^[57]及Okada等人^[58]分别采用有限元模型和奇异单元模型模拟微裂纹与体波的非线性相互作用, 结果表明, 裂纹越长、裂纹宽度越小, 高次谐波幅值越大。Wan等人^[59]和Xie等人^[48]针对金属材料及骨材料中的微裂纹开展了Lamb波二次谐波的数值模拟研究。Jiao等人^[60]和Aslam等人^[61]分别采用Lamb波同向及对向混频信号表征了不同长度与宽度的微裂纹。Lamb波

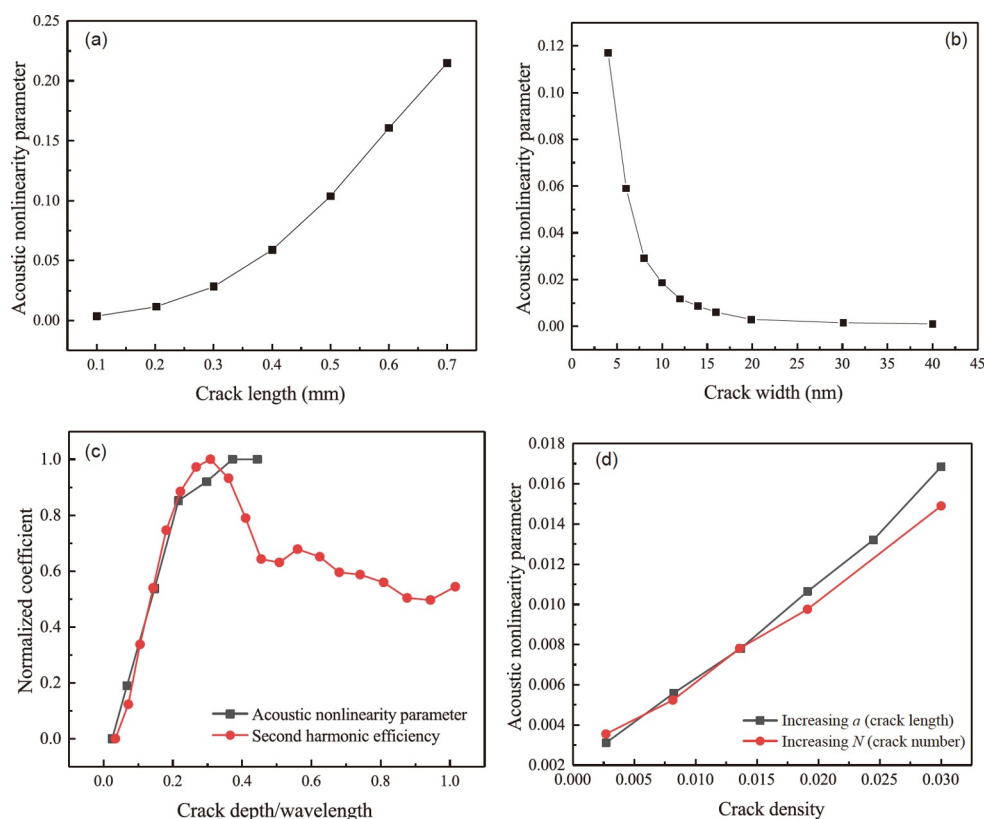


图4 (网络版彩色) 裂纹几何参数对声非线性响应的影响。(a) 裂纹长度^[59]; (b) 裂纹宽度^[59]; (c) 裂纹深度^[63,64]; (d) 裂纹密度^[65]
Figure 4 (Color online) The influence of geometric parameters of the crack on the acoustic nonlinearity effect. (a) Crack length^[59]; (b) crack width^[59]; (c) crack depth^[63,64]; (d) crack density^[65]

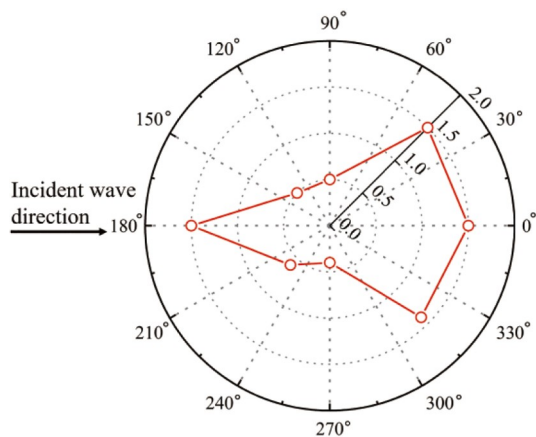


图5 (网络版彩色)疲劳裂纹归一化非线性参数的方向性
Figure 5 (Color online) Directivity pattern of normalized nonlinear parameters for fatigue cracks

二次谐波及混频信号幅值随微裂纹长度和宽度的变化趋势与体波高次谐波一致。Wang等人^[46]进一步的研究表明, Lamb波传播方向与裂纹的夹角和激励信号周期数可以有效影响非线性参量随裂纹长度的增加速率。此外, 针对微裂纹引起的非线性信号弱、易被背景噪声掩盖等问题, Liu等人^[62]采用Duffing-Holmes系统信号增强技术, 模拟微裂纹与非线性Lamb波的相互作用关系, 结果表明, Lyapunov指数与裂纹长度具有良好的线性增长关系。

2.2 深度

Kawashima等人^[63]和Yuan等人^[64]分别采用裂纹非线性本构模型及库仑摩擦硬接触模型数值分析了Rayleigh波与不同深度表面微裂纹相互作用产生的二次谐波。结果表明, 当裂纹深度小于波长的1/4左右时, 非线性参量随裂纹深度增加而增加。如图4(c)所示, 随着裂纹深度的进一步增加, Kawashima等人^[63]发现非线性参量趋于饱和, 而Yuan等人^[64]发现非线性参量略有下降后趋于饱和。Xie等人^[48]研究了骨科材料中水平裂纹的深度对Lamb波二次谐波响应的影响。结果表明, 水平裂纹在厚度方向的位置不影响S0模式Lamb波二次谐波的检测灵敏度。

2.3 密度

Zhao等人^[65]数值模拟了非线性Lamb波在含随机微裂纹薄板中的传播特性。结果表明, 非线性参量随微裂纹密度和微裂纹区域大小线性增加, 如图4(d)所示, 且与微裂纹表面摩擦系数相关性不大。类似地, Li等

人^[66]研究了3层胶黏结构中黏接层随机分布微裂纹对非线性Lamb波传播的影响, 黏接层微裂纹会生成Lamb波二次谐波, 且非线性参量随微裂纹区域大小和微裂纹密度的增加而增加。对于非线性Lamb波混频响应, Yin等人^[67]研究发现, 板中随机分布微裂纹可以生成Lamb波和频与差频信号。非线性参量对微裂纹密度有很强的依赖性, 当密度不变时, 非线性参量随微裂纹区域的增大呈线性增加。

2.4 方向

在二次谐波方面, Yang等人^[50]对不同裂纹长度的疲劳裂纹产生Lamb波二次谐波的方向性开展了仿真研究, 如图5所示。研究发现, 疲劳裂纹产生的二次谐波主要分布在裂纹前向和后向的散射方向, 且仅前向散射方向的二次谐波幅值随裂纹长度的增大而单调增大。Wang等人^[68]研究了横波与微裂纹相互作用生成二次谐波的方向性, 结果表明, 二次谐波的方向性随微裂纹取向角的变化而变化。在非线性混频方面, Lü等人^[69]数值分析了两列横波和裂纹之间的非共线混频作用, 结果表明, 生成最大混频纵波幅值对应的两列横波相互作用角与裂纹的方向相关。Lü等人^[70]分析了两列A0模式Lamb波与微裂纹的非线性混频作用, 结果表明, 两列A0模式Lamb波与微裂纹相互作用产生了透射及反射和频S0模式Lamb波, 两种和频S0模式Lamb波的传播方向随微裂纹方向的变化呈现不同的趋势: 透射和频的传播方向角与微裂纹的取向基本一致, 而反射和频的传播方向角则随微裂纹的取向线性增加。

此外, 关于接触压力对裂纹非线性的影响也有报道^[71~73]。Yang等人^[71]研究了拉伸载荷作用下裂纹面张开对不同长度疲劳裂纹非线性响应的影响, 结果表明, 施加在板上的载荷能明显改变裂纹的非线性响应。Saidoun等人^[72,73]分析了纵波与单向接触界面的相互作用, 建立了界面接触压力与生成二次谐波的对应关系, 结果表明, 随着界面接触压力的增加, 二次谐波先增加后减小。

3 非线性超声检测评价微裂纹的实验研究

近年来, 国内外学者对裂纹与超声波的非线性作用开展了大量检测实验研究。目前, 非线性超声检测方法主要包括: 高次谐波检测方法、混频检测方法、次谐波检测方法、直流分量检测方法、振动调制检测方法、共振频率偏移检测方法等^[74~76]。高次谐波、次谐

波和直流分量检测方法都是通过提取新产生的谐波或直流分量来表征微裂纹。其一般过程为：一系列频率为 f 的超声信号在材料或结构中传播，信号在传播过程中与损伤进行非线性相互作用，产生频率为 $nf(n=2,3,4\cdots)$ 的高次谐波、频率为 $f/n(n=2,3,4\cdots)$ 的次谐波以及频率为0的直流分量。混频检测方法是激发两列频率为 f_1 和 f_2 的超声波信号，两列波在传播过程中经过微裂纹区域时会发生相互作用，产生频率为 $f_1 \pm f_2$ 的和频与差频信号用于微裂纹的检测。另外，混频检测方法根据两列入射超声波的传播方向可分为共线混频和非共线混频^[77]。

在微裂纹非线性效应的实验测量方面，Buck等人^[78]在实验中观察到Al2024疲劳试样表面裂纹产生的纵波二次谐波信号。Morris等人^[79]开展了非线性Rayleigh波检测铝合金疲劳试样实验，发现高次谐波生成主要源于表面闭合裂纹。Thumma和Besheers^[80]研究了碳纤维复合材料(carbon fibre reinforced plastics, CFRP)悬臂梁试样层间裂纹的非线性响应，在高激励振幅的情况下生成高次谐波。除了高次谐波的生成，Yamanaka等人^[81,82]提出了闭合裂纹的“低通滤波效应”，实验测量到铝块疲劳裂纹试样中的次谐波和直流分量。Jeong和Barnard^[83]通过对CT(compact tension)试样进行体波非线性实验，发现超声波与闭合裂纹相互作用能够产生次谐波和二次谐波。Korshak和Korshak^[84]采用Rayleigh波对LiNbO₃晶体表面裂纹进行实验测量，发现裂纹反射波场中包含高次谐波和次谐波成分。Gao等人^[5]利用压电传感器激励两个不同频率的低频Lamb波信号，结合时间反转技术对2024铝合金板中疲劳裂纹进行混频检测，检测信号时频域中出现了明显的和频与差频分量。

在疲劳裂纹扩展的非线性超声高次谐波检测方面，Lunev等人^[85]开展了A516-70钢三点弯疲劳试样的非线性体波测量。结果表明，非线性参量随疲劳加载呈先增加后减小的趋势，非线性参量最大值对应闭合裂纹扩展形成宏观裂纹的临界点。Zhu等人^[86]分别采用S0-s0相速度近似匹配模式和S1-s2相速度匹配模式对7075铝板疲劳试样进行非线性Lamb测量。如图6所示，非线性参量同样呈现先增加后减小的趋势，疲劳后期微裂纹宽度增大是导致非线性参量减小的主要原因。Lyu等人^[87]采用体波对铝合金疲劳试样进行非线性超声测量，发现高次谐波幅值先上升后下降，他们将下降阶段归因于裂

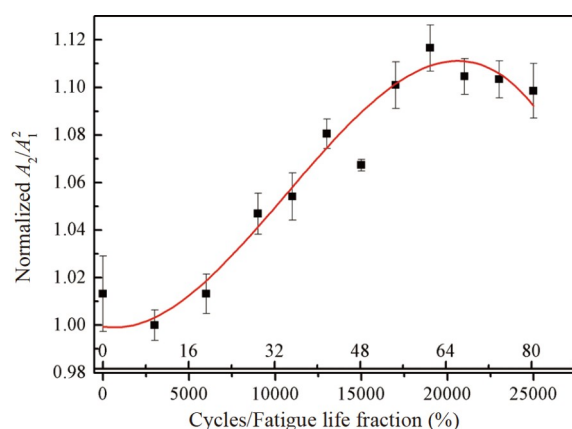


图6 (网络版彩色)归一化的相对非线性参量随疲劳周期的变化^[86]

Figure 6 (Color online) Normalized relative nonlinearity parameter with respect to the fatigue cycles^[86]

纹快速扩展促使裂纹面弹簧刚度下降。Lissenden等人^[88]采用SH0波对2024-T3铝板疲劳试样进行了非线性超声测量实验。结果表明，三次谐波非线性参量可以在宏观裂纹形成前有效表征材料疲劳损伤，且随疲劳损伤程度和裂纹长度的增加而增加。上述研究表明，非线性超声能够有效地表征疲劳过程中微裂纹的扩展。

针对裂纹的长度、深度、取向和数量等参数对非线性超声的影响规律方面，Wang等人^[46]采用非线性Lamb波测量不同长度的疲劳裂纹。结果表明，非线性参量随裂纹长度增加而增加，且激发周期和频率会影响其增加速率。Jiao等人^[60]对钢板试样疲劳裂纹进行了共线Lamb波混频测量实验，发现和频非线性参量对板内微裂纹较为敏感，且随裂纹长度的增加而增加。Lu等人^[69]提出了一种非线性超声检测疲劳裂纹长度的混频方法。研究表明，与线性全聚焦成像相比，非共线横波混频方法可以有效检测疲劳裂纹尖端闭合区，且疲劳裂纹长度测量精度更高。在裂纹深度方面，Chen等人^[89]对含不同深度的裂纹试样进行了非线性超声Lamb波测量实验。结果表明，裂纹的加深会增加试件的超声非线性响应，但当裂纹深度达到一定程度时非线性响应不再增加。Yelve等人^[90]采用非线性Lamb波测量了铝板中不同深度裂纹的非线性响应，提出用于表示高次谐波的谱损伤指标随裂纹深度的增加呈增加趋势。在裂纹取向方面，Wang等人^[91]将疲劳裂纹作为非线性散射体，研究Lamb波与疲劳裂纹相互作用产生的接触声非线性，不同的裂纹取向呈现出不同的非线性散射特性。Lu等人^[92]对0°和90°的疲劳裂纹进行非共线横波

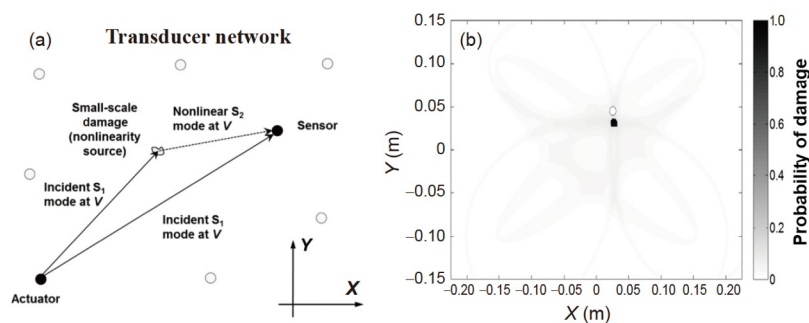


图7 基于飞行时间的概率成像算法^[97]. (a) 成像算法的原理; (b) 诊断成像结果

Figure 7 Time of flight based probabilistic imaging algorithm^[97]. (a) The principle of the imaging algorithm; (b) the diagnostic images

混频测量实验, 结果表明, 产生最大和频纵波幅值的两列横波相互作用角与裂纹的方向相关. 在裂纹数量方面, Wang等人^[93]使用非线性超声对3点弯曲试验中碳纤维增强塑料基体裂纹数量进行检测, 结果表明, 非线性参量随基体裂纹数量的增加而增加. 由上述分析可见, 裂纹的非线性响应同时受裂纹的几何参数、位置等多种因素的影响. 因此, 对实验检测中裂纹超声非线性响应还有待进一步探讨.

基于微裂纹与超声波相互作用的非线性响应可以实现微裂纹的定位和成像. 目前的定位成像方法主要有3种: (1) 超声混频定位方法; (2) 换能器阵列定位成像; (3) 非线性超声相控阵成像. 超声混频方法主要是基于超声波与裂纹相互作用后非线性响应增强原理, 根据不同位置非线性参量的大小对裂纹进行定位. 非线性混频检测利用时间延迟方法控制两列基波的混频位置, 对试样进行扫查实现微裂纹定位^[61,94].

超声混频定位方法主要是微裂纹一维方向的定位. 为实现微裂纹二维的定位, 研究者对损伤试样进行传感器布阵, 结合定位算法对微裂纹进行定位. Zhou等人^[95]和Li等人^[96]基于概率损伤重构算法对铝板稀疏传感阵列和平行传感阵列内的疲劳裂纹进行定位成像. Hong等人^[97]基于飞行时间的概率诊断成像算法对铝板方形传感阵列内铆接孔附近的疲劳微裂纹实现定位成像, 成像原理和成像结果如图7所示. Zhou等人^[98]通过分解时间反转算子提取谐波信号, 基于全聚焦方法对铝板平行阵列中两个疲劳微裂纹实现准确定位.

研究者将微裂纹的非线性响应与相控阵技术相结合, 提出了非线性超声相控阵技术实现微裂纹的定位成像. Ohara等人^[99~105]基于次谐波效应提出了一种非线性超声相控阵检测方法, 能够实现疲劳裂纹和应力腐蚀裂纹闭合部分的检测, 并分别利用外载荷、热应

力以及基波幅度差法等方法进一步提高了检测性能. 通过与超声相控阵多阵元灵活控制特性的结合, 基波幅度差法在非线性超声相控阵中显示出了更高的工作效率: 基于奇数阵元、偶数阵元和全阵元差分方法的非线性超声相控阵成像检测法, 实现了更高的裂纹检测特异性和图像对比度^[106]; 基于不同相控聚焦模式的非线性超声相控阵成像检测法, 实现了疲劳微裂纹的定位成像, 并有望通过对疲劳微裂纹扩展的监测来量化疲劳寿命^[107~109].

4 总结与展望

本文主要从理论模型、数值模拟和实验检测3个方面介绍了非线性超声表征微裂纹的研究进展. 在理论模型方面, 概述了不同的微裂纹模型: 接触声非线性理论、双线性刚度模型、非线性弹簧模型、Hertz接触理论、粗糙接触面模型等. 在数值模拟方面, 分析了多种数值模拟算法对微裂纹非线性行为的适用性以及微裂纹与非线性超声相互作用的规律. 在实验检测方面, 研究了微裂纹的非线性效应、微裂纹参数对非线性超声的影响规律和微裂纹定位等.

根据目前的研究进展, 非线性超声表征微裂纹的工作还需要从以下几个方面开展研究.

(1) 在理论模型方面, 微裂纹的“拍击”和“滑移”机制同时影响非线性超声的生成. 同时, 微裂纹的微观形貌也会对微裂纹的非线性行为产生影响. 在后续研究中, 可以对裂纹的宏观行为与微观形貌结合进行研究. 在宏观行为上, 研究不同物理机制对微裂纹非线性行为的综合作用效果; 在微观形貌上, 研究实际裂纹的几何特征如尺寸、倾斜角和粗糙度等对微裂纹非线性行为的影响, 建立微裂纹非线性效应宏观-微观结合的综合模型.

(2) 在实验检测方面, 实验测得的超声非线性不仅

来源于微裂纹,还可能来源于传感器与被测材料的耦合以及检测设备的系统非线性。同时,检测信号还受到环境(温度、压力等)变化、噪声水平和操作条件等外部因素影响,如何提高非线性超声检测的抗干扰能力,提高检测精度是实验测量的一项难题。后续研究可以通过设计超材料和超结构等声学器件,实现激发端系统非线性的滤波以及接收端微弱非线性信号的放大和提取,从而提高非线性超声测量的稳定性和精度。

(3) 在实际应用方面,目前大部分研究还停留在对

微裂纹扩展或微裂纹参数的定性研究,缺乏微裂纹扩展和寿命预测的定量评价方法,这限制了非线性超声在检测微裂纹方面的应用。对于微裂纹的非线性超声定量评价,研究者可以从两方面考虑:一方面,通过数据驱动的方法解耦微裂纹与非线性超声的关系,建立非线性超声定量评价微裂纹的数据模型;另一方面,将裂纹扩展模型与微裂纹的非线性超声理论模型相结合,建立微裂纹定量评价的理论模型,实现非线性超声对微裂纹的评价以及寿命预测。

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Summary for “微裂纹的非线性超声检测研究进展”

Advances in nonlinear ultrasonic detection of microcracks

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A large number of key components are widely operated under extreme conditions of high temperature and high pressure in power, nuclear energy, aerospace and other important industrial fields. Microdefects are inevitably generated in these key components during the process of manufacturing. Due to the periodic loading and thermal stress, microcracks are generally initiated from these microdefects at the location with stress concentration. It has been found that the initiation and propagation of fatigue microcracks usually occur prior to 70%–90% of fatigue life. It is difficult to observe the evidence before the formation of macrocracks, which may result in catastrophic accidents. Thus, the risk of sudden failure of key components increases greatly. Therefore, the accurate detection of microcracks is crucial for guaranteeing the safe operation of key components. Based on the diffraction, reflection and transmission, traditional ultrasonic testing method is merely validated to effectively detect macroscopic defects within half a wavelength. The nonlinear ultrasonic testing method is found to be sensitive to microcracks, as high order harmonics, sub-harmonics, DC components and frequency mixing waves can be generated due to the strong nonlinear interaction microcracks and ultrasonic waves. With the outstanding effectiveness to detect microcracks, the nonlinear ultrasonic testing method has attracted much attention in recent years. In this work, the research on detection of microcracks using nonlinear ultrasonic testing method is systematically reviewed in terms of theoretical models, numerical simulations and experimental measurements. Firstly, according to the breathing effect and sliding mechanism of microcrack surfaces, we present several theoretical models of nonlinear interaction between ultrasonic waves and microcracks, namely contact acoustic nonlinearity (CAN), bi-linear stiffness model, nonlinear spring model, Hertz contact theory, and rough contact surface model. The advantages and disadvantages of these theoretical models are discussed comparatively. Two mechanisms are mainly considered for the nonlinear interaction of microcracks and ultrasonic waves, namely the macroscopic opening and closing of crack surfaces and the microscopic contact of rough microcracks surfaces. Secondly, we introduce numerical simulation studies on the nonlinear ultrasonic generation induced by microcracks. The applicability is analyzed for several simulation methods, such as finite element method, spectral finite element method, finite difference method, boundary element method and local interaction simulation approach, and the generation and propagation of nonlinear ultrasonic waves are analyzed as well. The effect of microcrack geometries on the nonlinear ultrasonic waves is then summarized. The microcrack geometries are considered mainly clouding the microcrack length, width, depth, density and direction. Furthermore, we present the experimental measurements on the generation of nonlinear ultrasonic waves induced by microcracks and on the localization and imaging of microcracks based on the nonlinear ultrasonic waves. The generation of high order harmonics, sub-harmonics, DC components and frequency mixing waves was observed in the specimens with microcracks. The nonlinear ultrasonic detection is presented to evaluate fatigue microcracks with various microcrack length, width, depth, density and direction. Based on this phenomenon, nonlinear ultrasonic mixing method, transducer array imaging method and nonlinear ultrasonic phased array method are introduced to localize the microcracks. Finally, further studies on evaluation of microcracks using nonlinear ultrasonic waves are proposed, including the comprehensive physical model for actual microcracks in engineering components, robust detection method, and quantitative evaluation of microcracks and service life.

nonlinear ultrasound, microcracks, ultrasonic detection, contact acoustic nonlinearity

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