第 45 卷第 5 期
2025 年 10 月

振动、测试与诊断
Journal of Vibration, Measurement & Diagnosis

Vol. 45 No. 5
Oct.2025

DOI:10.16450/j.cnki.issn.1004-6801.2025.05.008

响应控制下非线性结构动力学实验研究*

郭　宁[1]，张　欣[2]，段绵超[1,3]，万晓忠[1]，徐　超[1]

（1.西北工业大学航天学院　西安，710072）
（2.北京电子工程总体研究所　北京，100854）
（3.湖北航天飞行器研究所　武汉，430040）

摘要　非线性结构在稳态激励下存在多重响应，采用传统振动实验方法很难直接获得非线性结构的动力学特性。针对此问题，提出了基于加速度响应控制步进正弦扫频实验技术的恒定力动力学特性测试方法。首先，选择激励点处的加速度响应作为控制信号，通过控制其响应幅度恒定进行步进正弦扫频实验；其次，根据不同加速度幅值工况实验获得简谐激励谱和简谐加速度响应谱曲线，并利用线性插值构造平滑的简谐力面；然后，通过从简谐力面中提取恒定力幅值的等值线，即为非线性结构恒定力幅值工况的频响曲线；最后，对典型螺栓连接非线性结构开展动力学特性研究。结果表明，采用本研究方法可以准确测试螺栓连接非线性结构的频响曲线，螺栓连接结构的动力学特性具有非线性的力依赖性，且螺栓预紧力大小和结构重装配对连接结构的动力学特性均有较明显的影响。

关键词　非线性结构；响应控制；动力学特性；简谐力面；实验技术
中图分类号　TH113；O329

引　言

非线性因素广泛存在于各类工程结构中，如摩擦、间隙及螺栓连接等。当结构存在显著的非线性时，将使结构的动力学特性随着激励水平的变化而产生漂移，并且动力学响应也会出现跳变、多解等非线性现象，这些行为可能会引起结构模态失稳或与外激励耦合产生过载等严重问题[1-2]。因此，对于结构的非线性动力学特性的研究受到广泛关注。随着实验技术和分析方法的不断发展，直接通过实验途径来研究非线性结构的动力学特性不仅可以验证理论，而且对一些简单的非线性振动系统能够直接得到规律性的结论[3-5]。

目前，工程结构的非线性动力学实验方法主要有自由振动实验方法和基于外激励的强迫振动实验方法。其中，自由振动实验方法一般采用力锤作为激励方式，可以简便地获取非线性系统的频率和阻尼特性[6]。但是，力锤激励是一种宽带低能量激励形式，导致大部分激励能量不会传递到感兴趣的频率范围内。因此，从自由振动实验中采集的结构响应信号只包含了一个相对较小的模态振幅范围的信息，无法完备表征所关心的结构非线性动力学特性。

基于外激励的强迫振动实验方法，通常采用步进正弦扫频信号作为激励信号，可以保证在关心的频率范围内的能量输入，实现结构非线性动力学特性的有效辨识。实验室中常用的单点激励步进正弦扫频测试方法包括恒定激励电压的步进正弦扫频、力幅值控制的步进正弦扫频和响应幅值控制的步进正弦扫频。恒定激励电压的正弦扫频测试方法可以保证在整个扫频范围内激励电压恒定，但是由于结构和激振器的耦合作用，在整个扫频范围内激励力幅值和响应幅值都是随频率变化的，很难测试得到非线性结构动力学特性与激励幅值的定量关系[7]。Zhang等[8-9]在定频稳态激励下通过连续改变激励电压，研究了电磁激振器与非线性结构的相互作用，解释了使用电磁激振器进行非线性结构强迫振动实验时出现的力降现象，并提出了非线性结构多值响应曲线和多值相位曲线的测试方法。文献[10-11]提出了基于恒定激励电压正弦扫频实验的响应重构法，来测量弱非线性结构和强非线性结构的恒定位移频响函数及恒定速度频响函数，用以辨识结构的非线性特征参数。基于力幅值控制的步进正弦扫频测试方法，是通过控制驱动点的力信号幅值保持恒定来测量结构的频响曲线，但由于共振峰附近的力

---

* 国家自然科学基金资助项目（12072268）
收稿日期：2023-04-12；修回日期：2023-09-26

降行为[12-13]，为保持力幅值恒定，需要急剧升高激励电压，导致共振峰附近控制效果不稳定[14-15]，测试频响曲线在共振峰处存在跳跃等现象，无法辨识得到准确的非线性动力学特性。基于响应幅值控制的步进正弦扫频测试方法是通过控制结构上某一测点的响应幅值恒定来采集结构的动响应，已在基于振动台的动力学测试中得到了广泛应用[16]。Catalfamo 等[15]研究表明，采用加速度响应幅值作为控制信号，可以保证激励电压在共振峰附近平缓变化，达到良好的控制效果。但是，在理论分析非线性系统时，一般假设激励是力幅值恒定，若直接采用基于响应控制的步进正弦扫频测试方法无法获取非线性结构的恒定力幅值频响曲线，使得在进行理论方法的比较验证时产生困难。Karaağaçli 等[17-19]根据单非线性模态理论，结合位移响应控制的步进正弦扫频测试方法，提出了基于简谐力面的非线性特征参数辨识方法，获得了非线性结构的恒定力幅值频响曲线，并研究了导弹结构和舵机结构的非线性特性，但在实验过程中采用的是加速度响应作为控制信号，而在构建响应谱与力谱之间的简谐力面时，直接采用了理想的位移谱，没有考虑实际测试误差，导致共振峰幅值、阻尼特性等辨识不准确。

为了准确研究非线性结构的动力学特性，笔者提出基于加速度响应控制的非线性结构恒定力动力学特性辨识方法，以典型的含局部摩擦非线性的螺栓连接振子结构为对象，研究其动力学特性与装配特征、外激励水平等参量之间的映射关系，并与传统测试方法进行对比，验证了所提非线性结构动力学特性测试方法的有效性。

1　加速度控制恒定力动力学实验方法

本研究通过控制激励点处的结构加速度振动响应幅值恒定，来获取激励点的简谐力谱，结合简谐力面[19]的概念提出非线性结构恒定力动力学特性辨识方法。

根据实验结构动力学理论可知，任意测试频率点f下系统的控制回路传递函数可表示为

$$H(f)=S_c(f)\big/S_d(f) \tag{1}$$

其中：$S_c(f)$为加速度响应控制谱；$S_d(f)$为激励电压谱。

假设实验的预设参考加速度响应谱为$S_{\mathrm{ref}}(f)$，若在频率点f_1处实测加速度响应谱与预设参考加速度响应谱之间存在差异，且大于预设容差ε时，即

$$e=\left|S_c(f_1)-S_{\mathrm{ref}}(f_1)\right|>\varepsilon \tag{2}$$

则需要对频率点f_1的激励电压进行迭代修正，直至满足容差要求。

修正后，频率f_1的激励电压谱值为

$$S_d^*(f_1)=S_{\mathrm{ref}}(f_1)\big/H(f_1) \tag{3}$$

当在频率点f_1处采集获得稳态响应后，进入下一频率点重新进行响应控制测试。加速度响应幅值恒定控制流程如图 1 所示。通过该控制流程，可实现对激励点处加速度振动响应幅值的准确控制。

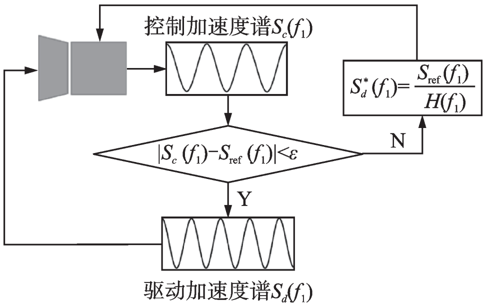


图 1　加速度响应幅值恒定控制流程图

Fig.1　The flow chat for amplitude constant control of accelerator response

根据所关心的激励力幅值范围和激励频率范围，设定一系列的加速度响应幅值控制测试工况，并根据上述方法测试获得相应工况下结构的输入简谐力谱和各测点的简谐加速度响应谱，如图 2 所示。其中：实线为力幅值；虚线为加速度幅值。

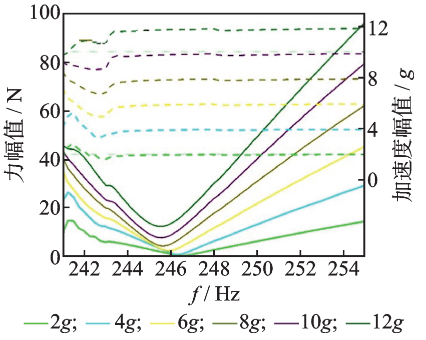


图 2　不同加速度幅值工况下的简谐加速度谱和简谐力谱

Fig.2　Harmonic acceleration spectra and harmonic force spectra for different measurement conditions

对已测量的简谐力谱和简谐加速度响应谱分别进行线性插值，并以频率为x轴、加速度幅值为y轴、力幅值为z轴构建三维曲面，即为非线性结构频率响应的简谐力面，如图 3 所示。

使用某一恒定力平面（如$z=5$ N）来截取简谐力面，提取两者的交线即为该恒定力情况下的非线性结构的频响曲线。恒定力频响曲线提取如图 4 所示，其中红色曲线即为非线性结构的频响曲线。

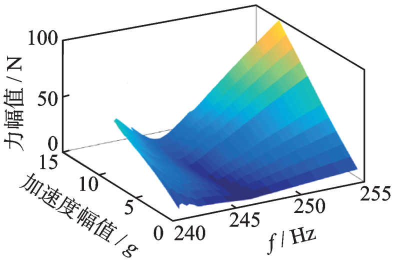


图 3　构造的简谐力面

Fig.3　Construction of the harmonic force surface

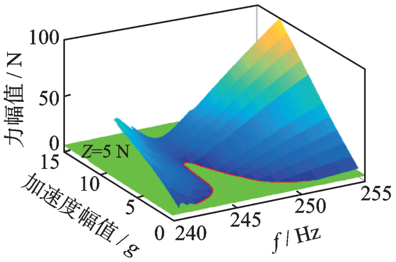


图 4　恒定力频响曲线提取

Fig.4　Extraction of the constant-force frequency response curve

综上所述,本研究所建立的加速度响应控制恒定力动力学实验方法流程如图 5 所示。

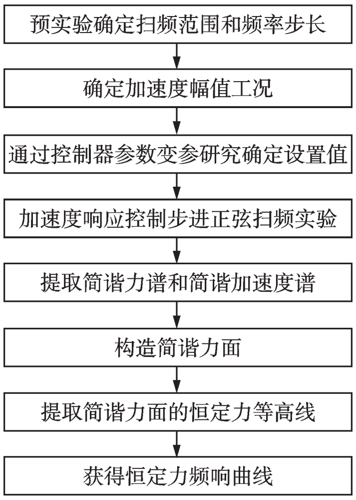


图 5　加速度响应控制恒定力动力学实验方法流程图

Fig.5　The flow chart of the acceleration response-controlled constant-force dynamics test method

2　实验描述

典型的包含局部摩擦非线性的螺栓连接振子结构如图 6 所示。该结构由 2 个集中质量块通过柔性梁和 1 个 M6 螺栓装配组成。螺栓连接振子结构几何尺寸如图 7 所示,其材质均为 304 不锈钢。其中,柔性梁起到激振力动力放大的作用,以达到有效激励螺栓连接接合面间产生相对摩擦运动的目的。此类结构已被广泛用于研究螺栓连接界面的摩擦迟滞特性和非线性动力学响应特性中[20-22]。

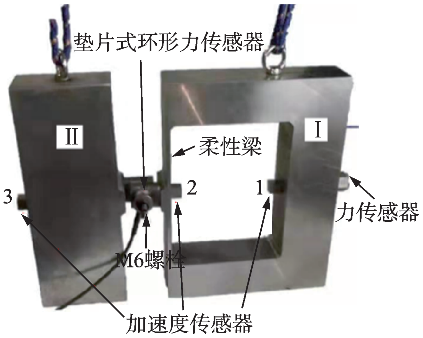


图 6　螺栓连接振子结构

Fig.6　Bolted-joint oscillator

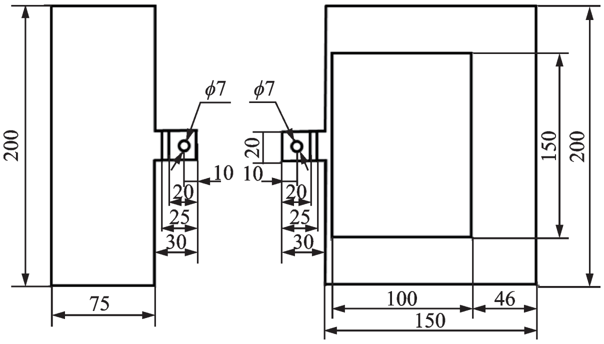


图 7　螺栓连接振子结构几何尺寸(单位:mm)

Fig.7　Geometric dimensions of bolted-joint oscillator (unit: mm)

实验中,螺栓连接结构采用刚性绳悬挂在固定支架上,模拟自由边界条件。在螺栓头侧,安装垫片式环形压力传感器来监测螺栓预紧力。在图 6 所示的 1、2、3 点位置处分别粘贴 ICP 型加速度传感器(其标称灵敏度为 100 mV/g),用于测试结构的加速度振动响应。将数据采集系统的输出通道与功率放大器连接,用以驱动电磁激振器。激振器沿结构中心线方向提供水平激励。为了测量激振器施加到结构的输入载荷,在顶杆末端安装了 1 个力传感器(其标称灵敏度为 11.02 mV/N)。所有信号通过 LMS 数据采集系统和 LMS Test Lab 软件完成实验数据采集和分析。螺栓连接结构非线性动力学特性测试系统如图 8 所示。

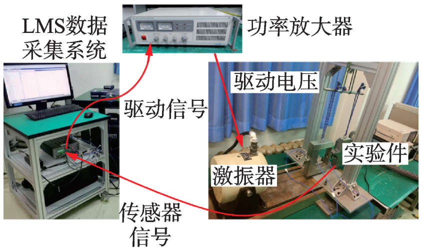


图 8　螺栓连接结构非线性动力学特性测试系统

Fig.8　Test system for nonlinear dynamic characteristics of bolted structures

采用搭建的螺栓连接结构动力学特性实验系统以及建立的恒定力动力学特性实验方法，研究激励幅值、螺栓预紧力等因素对螺栓连接非线性结构动力学特性的影响，具体实验研究工况见表1。

表1　螺栓连接结构动力学特性实验研究工况

Tab.1　Test condition for the experimental study of dynamic characteristics of the bolted structure

工况	外激励力幅值/N	螺栓预紧力/N
1	1	800, 1 200, 1 600
2	5	800, 1 200, 1 600
3	10	800, 1 200, 1 600

螺栓连接振子结构前4阶模态如图9所示。可以看出，结构的第4阶模态振型（模态频率为245.45 Hz）表现为2个质量块的反方向运动，其中柔性梁的振动模态表现为轴向振动放大作用。若选择在第4阶模态的共振区开展实验，可以通过柔性梁的振动放大作用为螺栓连接界面传递更大的切向载荷，可以更有效地研究螺栓连接非线性结构的动力学特性。因此，实验中选择激励频率范围为240～250 Hz，采样频率为800 Hz。测试扫频步长设置见表2。

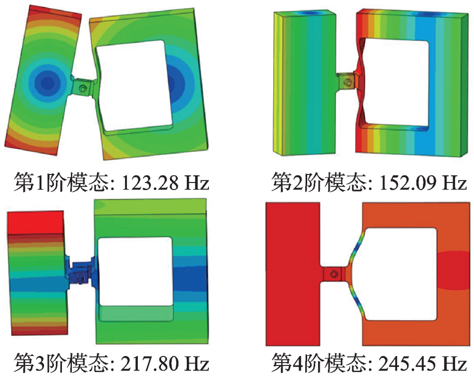

第1阶模态: 123.28 Hz
第2阶模态: 152.09 Hz
第3阶模态: 217.80 Hz
第4阶模态: 245.45 Hz

图9　螺栓连接振子结构前4阶模态

Fig.9　The first four-order vibration modes of the bolted-joint oscillator structure

表2　测试扫频步长设置

Tab.2　Test sweep frequency step setting

扫频范围/Hz	步长/Hz
240～244	0.25
244.1～248.5	0.10
248.75～250	0.25

实验中，采用LMS Test.Lab软件提供的振动响应控制步进正弦扫频测试模块，控制结构上1点位置处的加速度响应使其保持恒定，具体的加速度控制实验工况为0.1g、0.5g、1g、2g、3g、4g、5g、6g、7g、8g、9g、10g、11g、12g、13g、14g和15g。

正式实验之前，通过控制参数的变参实验分析，来确定测试误差校正因子、信号延迟周期、采样周期及控制容差等控制器相关参数。具体实验控制步骤如下：①通过LMS数据采集系统输出第1个频率点（f_1）测试的初始激励电压信号，信号经过功率放大器放大后驱动激振器开始激励，螺栓连接振子结构在激振力作用下产生振动，振动响应信号由加速度传感器采集并传回LMS数据采集系统；②根据加速度响应信号与加速度目标谱之间的差异调整输出的激励电压信号，允许最大调整次数即为信号延迟周期（本实验设置为400）；③当在频率点f_1的测试加速度谱值与加速度目标谱值满足误差要求（即控制容差）时，根据设定的采样周期完成测试；④在下一个频率点重复上述过程。以上1个频率点的最终激励电压信号为初始激励信号。本研究所采用的基于LMS Test.Lab软件的响应控制步进正弦测试的控制参数设置见表3。

表3　响应控制步进正弦测试的控制参数设置

Tab.3　Control parameter settings for response-controlled stepped sine test

控制参数	取值
系统辨识可信度	低
误差校正因子/%	80
延迟周期	400
采样周期	60
控制容差/dB	3/6

3　实验研究

3.1　实验方法验证

以800 N螺栓预紧力的工况为例，将采用本研究方法获得的螺栓连接振子的频响曲线与采用基于LMS Test.Lab软件的直接力控制实验方法测得的频响曲线进行对比，结果如图10所示。由图可以看出，本研究方法获得的螺栓连接非线性结构频响曲

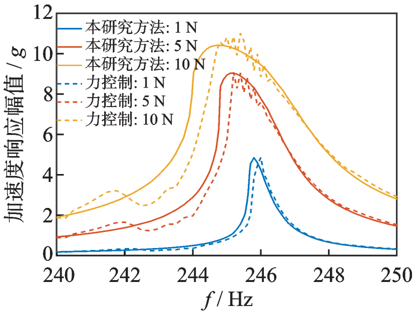


图10　螺栓连接振子频响曲线测试结果

Fig.10　Test results of frequency response for the bolted-joint oscillator

线可以清晰地表征结构的非线性动力学特性,即由于摩擦因素引起的结构刚度软化非线性行为;而采用直接力控制方法测试的频响曲线在共振区左侧与本研究方法具有很好的吻合度,但是在共振峰处存在较大的波动,尤其是在大激励工况下,没有获得有效的非线性动力学特性表征结果。

进一步分析实验中的力控制和响应控制效果,在 800 N 预紧力工况下,实测激励力控制谱和实测加速度振动响应控制谱分别如图 11、12 所示。由图可以看出,直接力控制方法的激励力控制谱在共振区出现了剧烈波动,控制效果较差,最大控制误差达 26%;而基于响应控制的加速度响应谱在共振区未出现明显波动,控制效果良好,最大控制误差仅为 4.85%。文献[8]指出,直接力控制测试方法在共振区出现较大激励控制波动的原因主要是由于激励器和非线性结构的耦合作用,导致在共振区出现明显的激励力降现象,若要保持激振力恒定,则需要多次急剧提高激振器的输入电压,造成控制信号急剧波动。

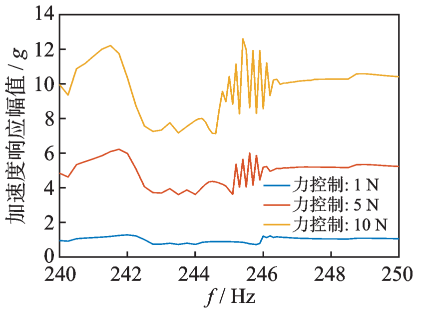


图 11　实测激励力控制谱

Fig.11　Measured excitation force control spectrum

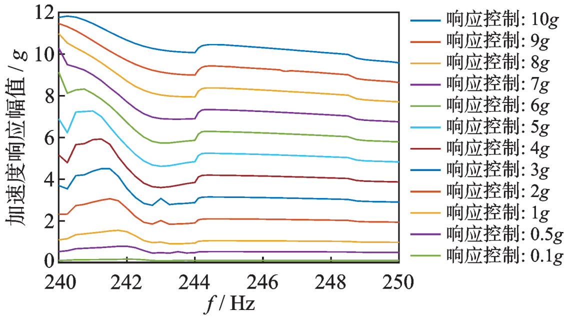


图 12　实测加速度振动响应控制谱

Fig.12　Measured acceleration vibration response control spectrum

3.2　螺栓预紧力和外激励幅值对连接结构动力学特性的影响

根据表 1 的实验研究工况,获得螺栓连接振子在不同工况下的实测恒定力频响曲线,如图 13 所示。由图可以看出,当激励幅值在 1～10 N 之间变化时,螺栓连接振子结构表现出了非线性的力依赖性,频响曲线的“歪头”现象更为明显,共振区也变宽。例如,在螺栓预紧力为 800 N 情况下,共振幅值下降了 5.57g,共振频率下降了 1.1 Hz(0.45%),说明由于摩擦非线性导致螺栓连接结构出现了明显的刚度软化行为。

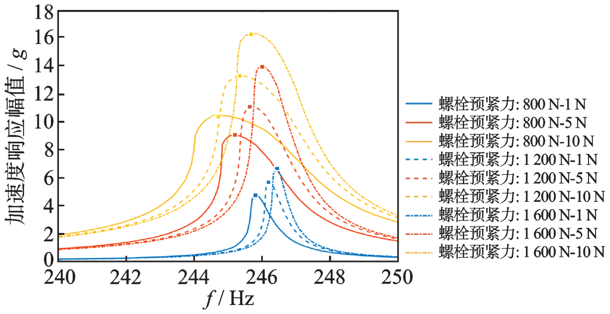
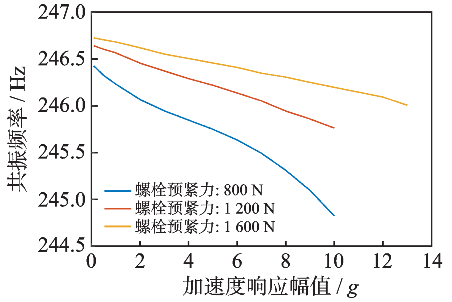


图 13　不同工况下的实测恒定力频响曲线

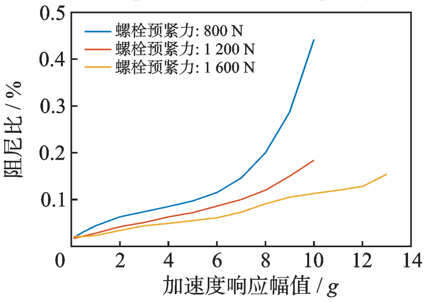
Fig.13　Measured constant-force frequency response curves under different test conditions

进一步提取不同激励幅值下恒定力频响曲线的幅值-共振频率曲线和幅值-阻尼曲线,不同螺栓预紧力工况下动力学特性的变化规律如图 14 所示。由图可以看出,在相同螺栓预紧力情况下,当激励幅值越大,结构的共振频率越小,阻尼比越大。其中,共振频率降低的主要原因是由于摩擦非线性所导致的螺栓连接结构非线性刚度软化,而阻尼比增大的



(a)　幅值-共振频率曲线

(a) Amplitude-resonance frequency curve



(b)　幅值-阻尼比曲线

(b)　Amplitude-damping ratio curve

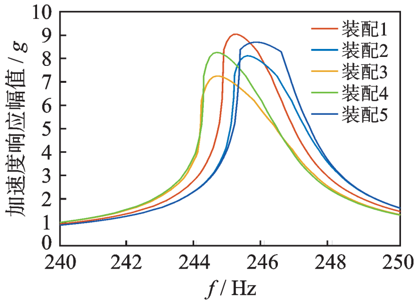
图 14　不同螺栓预紧力工况下动力学特性的变化规律

Fig.14　the variation of dynamic characteristics under different bolt preload conditions

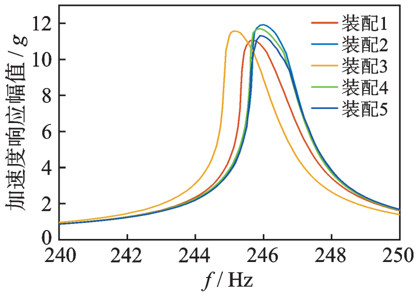
主要原因是由于激励幅值越大，导致螺栓连接界面间发生相对滑移的区域越大，摩擦耗散能量越多，因此阻尼特性更大。此外，在激励幅值相同时，当螺栓预紧力增加，则结构的连接刚度增大，因此在相同激励幅值下，共振频率更大。

3.3　重装配对螺栓连接结构动力学特性的影响

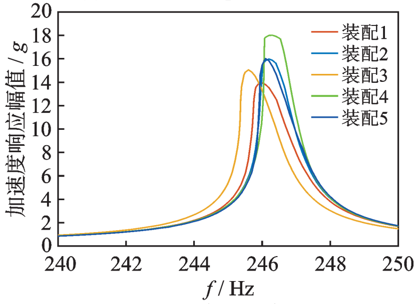
为进一步研究结构重装配对螺栓连接结构动力学特性的影响，每种实验工况均开展了5次重复实验。每次实验中，先将螺栓完全拧松，再将螺栓预紧力拧紧至实验目标值，达到结构重装配的目的。实验过程中，由于螺栓预紧力不能精确施加，因此要保证每次装配时施加的螺栓预紧力的绝对误差在40 N以内，且实验过程中螺栓预紧力变化不超过2%。以5 N激励工况为例，螺栓连接结构5次重装配的实验频响曲线如图15所示。由图可以看出，螺栓连接结构每次重装配后的动力学特性都会发生变化。



(a) 800 N螺栓预紧力工况
(a) 800 N bolt preload condition



(b) 1 200 N螺栓预紧力工况
(b) 1 200 N bolt preload condition



(c) 1 600 N螺栓预紧力工况
(c) 1 600 N bolt preload condition

图15　螺栓连接结构5次重装配的实验频响曲线

Fig.15　Test frequency response of 5 times reassembly of bolted structure

以5 N激励工况为例，不同螺栓预紧力下重装配5次的共振频率分散性如图16所示。由图可以看出，小螺栓预紧力情况下，重装配对连接结构动力学特征影响较大，约有1.2 Hz的变化范围。随着螺栓预紧力的增大，重装配的影响变小，重装配引起共振频率变化的变异系数均小于1%。

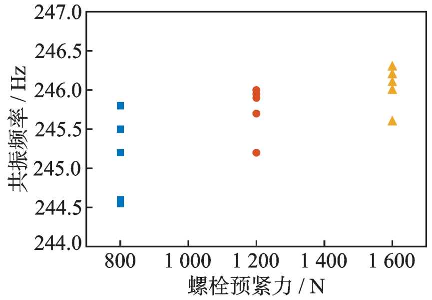


图16　不同螺栓预紧力下重装配5次的共振频率分散性

Fig.16　Resonance frequency dispersion of 5 times reassembly of bolted structure with different bolt preload forces

4　结　论

1）相比直接力控制方法，采用加速度响应作为控制信号来进行步进正弦扫频测试，在共振区（244～248 Hz）具有更好的控制效果，最大控制误差小于5%。

2）采用基于简谐力面的恒定力频响曲线辨识方法获得的结果可以清晰地表征结构的非线性动力学特性，即由于摩擦因素引起的结构刚度软化非线性行为。

3）实验结果表明，螺栓连接结构的动力学特性具有非线性的力依赖性，并且螺栓预紧力大小和结构重装配均会对螺栓连接结构的动力学特性产生影响。

参　考　文　献

[1]　NOËL J P, KERSCHEN G. Nonlinear system identification in structural dynamics: 10 more years of progress[J]. Mechanical Systems and Signal Processing, 2017, 83: 2-35.

[2]　史阳旭，李明，杜晓蕾．艏摇运动下船用转子系统的非线性动力学特性[J]．振动、测试与诊断，2022，42(6)：1189-1197.

SHI Yangxu, LI Ming, DU Xiaolei. Nonlinear dynamics of marine rotor-bearing system under yawing motion [J]. Journal of Vibration, Measurement & Diagnosis, 2022, 42(6): 1189-1197.(in Chinese)

[3]　姜万录，朱勇，郑直，等．电液伺服系统非线性振动机

理及实验研究[J]. 机械工程学报, 2015, 51(4): 175-184.
JIANG Wanlu, ZHU Yong, ZHENG Zhi, et al. Nonlinear vibration mechanism of electro-hydraulic servo system and its experimental verification[J]. Journal of Mechanical Engineering, 2015, 51(4): 175-184. (in Chinese)

[4] 陆飞, 曹芝腑, 姜东, 等. 基于非线性动响应的夹持松动特性研究[J]. 振动、测试与诊断, 2018, 38(4): 712-718.
LU Fei, CAO Zhifu, JIANG Dong, et al. Study on the characteristic of clamped looseness based on nonlinear dynamic response[J]. Journal of Vibration, Measurement & Diagnosis, 2018, 38(4): 712-718. (in Chinese)

[5] 倪德, 邹亚晨, 王平, 等. 某直升机尾传动轴系非线性振动特性的实验研究[J]. 机械制造与自动化, 2021, 50(4): 56-59, 85.
NI De, ZOU Yachen, WANG Ping, et al. Experimental study on nonlinear vibration characteristics of helicopter tail drive shafting[J]. Machine Building & Automation, 2021, 50(4): 56-59, 85.(in Chinese)

[6] JIN M S, BRAKE M R W, SONG H W. Comparison of nonlinear system identification methods for free decay measurements with application to jointed structures[J]. Journal of Sound and Vibration, 2019, 453: 268-293.

[7] 单卫东. 基于频响函数的某直升机尾传动轴系非线性模态分析[D]. 南京: 南京航空航天大学, 2019.

[8] ZHANG G B, ZANG C P, FRISWELL M I. Measurement of multivalued response curves of a strongly nonlinear system by exploiting exciter dynamics[J]. Mechanical Systems and Signal Processing, 2020, 140: 106474.

[9] ZHANG G B, ZANG C P, FRISWELL M I. Measurement of the multivalued phase curves of a strongly nonlinear system by fixed frequency tests[J]. Archive of Applied Mechanics, 2020, 90(11): 2543-2560.

[10] ZHANG G B, ZANG C P, FRISWELL M I. Identification of weak nonlinearities in MDOF systems based on reconstructed constant response tests[J]. Archive of Applied Mechanics, 2019, 89(10): 2053-2074.

[11] ZHANG G, ZANG C, FRISWELL M I. Parameter identification of a strongly nonlinear rotor-bearing system based on reconstructed constant response tests[J]. Journal of Engineering for Gas Turbines and Power, 2020, 142(8): 081004.

[12] VAROTO P S, DE OLIVEIRA L P R. On the force drop off phenomenon in shaker testing in experimental modal analysis[J]. Shock and Vibration, 2002, 9(4/5): 165-175.

[13] VAROTO P S, OLIVEIRA L. On the interaction between the vibration exciter and the structure under test in vibration testing[J]. Proceedings of SPIE: the International Society for Optical Engineering, 2001, 4359: 640-647.

[14] MONTALVÃO D, FONTUL M. Harmonica: stepped- sine spectrum analyzer for transfer function measurement and non-linear experimental assessment [C]//5th International Conference on Mechanics and Materials in Design. Ponta Delgada, Azores, Portugal: INEGI-Instituto de Engenharia Mecânica e Gestão Industrial, 2006: 1-11

[15] CATALFAMO S, SMITH S A, MORLOCK F, et al. Effects of experimental methods on the measurements of a nonlinear structure[J]. Dynamics of Coupled Structures, 2016, 4: 491-500.

[16] GAO C H, YUAN X B, WANG J Q, et al. Recent progress on control techniques of shaking table and array systems in China: an overview[J]. American Journal of Civil Engineering and Architecture, 2020, 8(3): 119-130.

[17] KARAAĞAÇLI T, ÖZGÜVEN H N. Experimental modal analysis of nonlinear systems by using response-controlled stepped-sine testing[J]. Mechanical Systems and Signal Processing, 2021, 146: 107023.

[18] KARAAĞAÇLI T, ÖZGÜVEN H N. Experimental identification of backbone curves of strongly nonlinear systems by using response-controlled stepped-sine testing(RCT)[J]. Vibration, 2020, 3(3): 266-280.

[19] KARAAĞAÇLI T, ÖZGÜVEN H N. A frequency domain nonparametric identification method for nonlinear structures: describing surface method[J]. Mechanical Systems and Signal Processing, 2020, 144: 106872.

[20] GAUL L, LENZ J. Nonlinear dynamics of structures assembled by bolted joints[J]. Acta Mechanica, 1997, 125:169-181.

[21] BOGRAD S, REUSS P, SCHMIDT A, et al. Modeling the dynamics of mechanical joints[J]. Mechanical Systems and Signal Processing, 2011, 25(8): 2801-2826.

[22] SÜß D, WILLNER K. Investigation of a jointed friction oscillator using the multiharmonic balance method[J]. Mechanical Systems and Signal Processing, 2015(52/53): 73-87.

第一作者简介:郭宁,男,1986 年 12 月生,博士、副研究员。主要研究方向为飞行器结构动力学。
E-mail: guoning@nwpu.edu.cn

damage, a database comprising 3 500 samples of damage signals is generated through iteratively running the numerical model. Subsequently, a one-dimensional convolutional neural network imaging model is constructed. The model is trained using the generated database to establish a mapping relationship between thickness maps and reception signals, and inputting the reception signals into the imaging model yields corresponding thickness maps. Finally, the feasibility of the proposed method is experimentally validated. The mean square error between experimental imaging results and actual values is 8.6048×10^{-4}, the correlation coefficient is 0.711 6, and the imaging model runtime is 0.538 5 seconds. The results indicate that the proposed method can achieve quantitative imaging of corrosion damage thickness within pipelines with high imaging efficiency.

Keywords ultrasonic guided wave; pipeline structure; damage imaging; finite difference method; convolutional neural network

Reliability Analysis of Hypersonic Vehicle Based on Kriging Model

OU Mengqun, *WANG Yuhui*
(School of Automation, Nanjing University of Aeronautics and Astronautics Nanjing, 211106, China)

Abstract In order to analyze the reliablility of hypersonic flight vehicles, the longitudinal model of the vehicle is simplified as a cantilever beam structure, and a limit state function is formulated. To address the uncertainty of variable parameters within the limit state function, a hybrid reliability analysis method based on a two-stage Kriging model is proposed. For the first stage, initial sample points are selected to construct an initial Kriging model centered on potential failure points meeting specified accuracy requirements, ensuring the model satisfies this accuracy criterion. For the second stage, a hybrid reliability analysis of the flight vehicle is performed using the initial Kriging model and the first-order reliability method. The Kriging model is adaptively updated by incorporating learning functions, thereby enhancing the efficiency and accuracy of reliability calculations. Comparing the results with existing methods under different parameters of ultimate strength, cantilever beam height, and width, it is demonstrated that the proposed method can meet the requirements for real-time and accurate reliability analysis of the hypersonic vehicle.

Keywords hypersonic vehicle; equivalent cantilever beam; hybrid reliability analysis; Kriging model

Experimental Study on Nonlinear Structure Dynamics Based on Response-Controlled

GUO Ning[1], *ZHANG Xin*[2], *DUAN Mianchao*[1,3], *WAN Xiaozhong*[1], *XU Chao*[1]
(1. School of Astronautics, Northwestern Polytechnical University Xi′an, 710072, China)
(2. Beijing Institute of Electronic System Engineering Beijing,1 00854, China)
(3. Hubei Aerospace Flight Vehicle Institute Wuhan, 430040, China)

Abstract Nonlinear structures exhibit multiple responses under steady-state excitation, making it challenging to directly obtain their dynamic characteristics using traditional vibration test methods. To address this issue, a constant-force dynamic characteristics testing method based on acceleration-response-controlled step-sine frequency sweep test technology is proposed. First, the acceleration response at the excitation point is selected as the control signal, and a step-sine frequency sweep experiment is performed by maintaining a constant response amplitude. Secondly, the resulting simple harmonic excitation spectrum and acceleration response spectrum are obtained through experiments under various acceleration amplitude conditions, and a smooth simple harmonic force surface is constructed using linear interpolation. Then, by extracting the contour lines corresponding to constant force amplitude from this surface, the frequency response curve of the nonlinear structure under constant-force conditions is derived. Finally, the dynamic characteristics of a typical bolted nonlinear structure are investigated. The results show that the proposed approach can accurately capture the frequency response characteristics of bolted nonlinear structures, revealing the pronounced nonlinear dependence on force amplitude. Furthermore, bolt preload and structural reassembly are found to significantly influence the dynamic characteristics of the connection structure.

Keywords nonlinear structure ; response-controlled; dynamics characteristic; harmonic force surface; experimental technology

Mechanical Fault Diagnosis of In-wheel Motor Based on Weibull Kernel Function and MCSVDD

LIU Bingchen, *XUE Hongtao*, *DING Dianyong*

(School of Automotive and Traffic Engineering, Jiangsu University Zhenjiang, 212013, China)

Abstract In order to monitor the operation state of each wheel motor in distributed drive electric vehicle and ensure the safety of the vehicle, a fault diagnosis method of in-wheel motor based on improved multi-class support vector data description (MCSVDD) is proposed. The method incorporates two major improvements. First, a classification judgment rule based on the minimum distance to the cluster center within the class is proposed using the affinity propagation (AP) clustering algorithm to enhance MCSVDD. Second, a Weibull kernel function is constructed from the Weibull distribution to optimize data description model. Meanwhile, a dimensionality reduction method based on minimum-distance propagation discriminant projection (MPDP) is proposed for the multi-dimensional feature set of in-wheel motor operating state, which improves the separability of in-wheel motor fault states under different working conditions. Finally, in-wheel motors with typical bearing faults are customized respectively to collect vibration signals under 7 rotating speeds for verifying the effectiveness of the proposed method. The results show that the reduced dimension data's separability of observed samples of in-wheel motor operating state based on MPDP is better than that of linear discriminant analysis (LDA), minimum-distance discriminant projection (MDP) and locality preserving projection (LPP), and the recognition accuracy of MCSVDD's state recognition system based on Weibull kernel function is higher than that of polynomial and Gaussian kernel function.

Keywords in-wheel motor; vibration signal; fault diagnosis; minimum-distance propagation discrimination projection; multi-class support vector data description; Weibull kernel function

Design and Parameter Optimization of LLCC Resonant Network for Linear Ultrasonic Motors

GUO Pengtao[1], *LI Xiang*[1], *ZHOU Lifeng*[2], *YAO Zhiyuan*[3]

(1. School of Electrical Engineering and Automation, Hefei University of Technology Hefei, 230009, China)
(2. Industrial Center/School of Innovation and Entrepreneurship, Nanjing Institute of Technology Nanjing, 211167, China)
(3. College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics Nanjing, 210016, China)

Abstract Aiming to address the operation stability affected by the parameter time-variation of the ultrasonic