

## 加工颤振检测与抑制研究综述

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**摘要:** 颤振是金属切削过程中一种典型的自激振动现象, 颤振的发生会导致加工表面质量劣化, 具体表现为纹理波动、尺寸误差增大及表面完整性受损。实现颤振的有效检测与抑制对于保障加工效率、提升零件性能具有重要意义。当前研究已形成基于物理模型的离线预测方法、依赖多传感器信号的试验检测方案和融合智能算法的在线监测框架的多维度技术体系, 但现有综述文献缺乏对该领域的深度解构。针对上述不足, 立足该领域研究前沿, 围绕颤振检测与抑制技术开展系统性技术综述与分析。在颤振检测方面, 建立“解析-试验”二重方法论框架, 重点剖析各类技术的适用场景与性能边界; 在颤振抑制方面, 构建“主动-被动-参数调整”三重控制策略分类体系, 对比不同方案的实施成本与减振效果。基于多维技术对比与跨学科方法融合, 探讨了该领域当前存在的问题的潜在解决方案, 为后续研究提供全面的理论支撑与技术参考。

**关键词:** 切削工艺; 颤振检测; 颤振抑制; 智能算法

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## 0 引言

加工过程中的颤振问题已成为制约高精度、高效率制造的核心瓶颈问题, 其动态失稳行为会引发工件表面质量退化、刀具异常磨损甚至机床结构损伤, 已成为航空航天、精密光学、新能源等高端装备制造领域的精密加工亟须解决的技术难题。航空发动机叶片因其薄壁易变形、材料难加工及砂带磨削柔性接触等特征而难实现精密磨削<sup>[1-2]</sup>, 加工颤振导致其型面精度和表面质量受到影响, 进而影响叶片的气动性能和热性能。在光刻机物镜超精密磨削中, 颤振引起的梯度残余应力会导致镜片组装的非均匀形变, 造成投影物镜波前畸变, 直接影响极紫外(Extreme Ultra-Violet, EUV)光刻机的套刻精度。在新能源汽车永磁电动机转子轴硬车削中, 颤振引起的切削力波动会造成直径的尺寸散差, 导致电动机气隙磁场均匀性降低, 进而影响驱动效率。实现智能制造高动态、高效能迭代, 突破颤振实时检测与抑制技术已成为行业共识。

加工过程中的振动可能源于外部激励或内部激励, 而常见的振动形式产生于内部激励, 再生效应被认为是主要原因<sup>[3-4]</sup>, 即源于工件或砂轮表面波与切削系统当前相对振动之间的相位偏移。尽管各国学者

很早就围绕再生效应开展了大量的研究并取得了一些成果, 但预测其发生并使其得到及时有效抑制仍是主要的研究焦点。ALTINTAS等<sup>[5-6]</sup>、TLUSTY等<sup>[7]</sup>、INSPERGER等<sup>[8]</sup>提出了包含频域、时域分析的多种方法, 旨在构建切削系统动力学模型, 通过求解运动方程揭示切削深度与主轴转速的关联规律。为直观表征这两者关系, 研究者开发了稳定性叶瓣图工具, 如图1所示, 通过绘制主轴转速与轴向切深的关系曲线, 将加工参数空间划分为稳定区和不稳定区。其中, 叶瓣下方区域为稳定区, 表示加工参数组合在该区域内加工过程不会发生颤振; 上方区域为不稳定区, 表示加工参数组合在该区域内加工过程中可能发生颤振。传统颤振检测方法多基于时频域分析(如短时傅里叶变换、小波分析)或统计特征提取(如方差峭度等指标), 但在非平稳工况下存在灵敏度不足、实时性受限等瓶颈。随着传感器技术的进步, 凭借其时效性和高精度优势, 逐渐成为主流解决方案。AHRENS等<sup>[9]</sup>、DENKENA等<sup>[10]</sup>融合多传感器, 检测到圆柱形磨削颤振特征, 有效识别了颤振的萌芽状态, 但无法实现在线分析与识别。信号处理技术与特征向量最优化是提升颤振检测精度的关键环节, 通过计算复杂度低、颤振频率分辨率高的算法, 实现在线监测加工过程中

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因材料去除和加工位置移动导致的加工状态和颤振频率变化的研究仍存在不少难点。基于智能监测范式创新,包括多源传感信息融合(振动-声发射-力信号协同分析)、基于深度学习的颤振特征迁移识别以及数字孪生驱动的颤振状态预测等技术,提升复杂工艺条件下的颤振边界辨识精度,采用主动<sup>[11]</sup>、被动<sup>[12]</sup>抑制策略有效阻断或减少颤振对加工过程的影响。

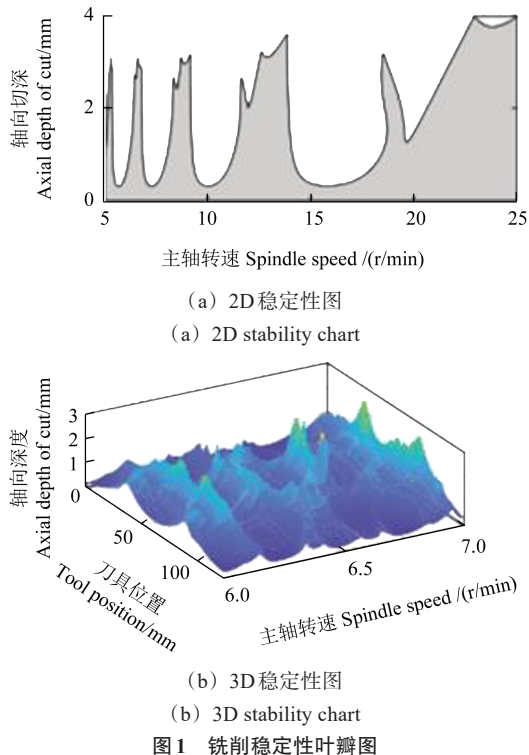


Fig. 1 Stability lobe diagram for milling processes

现有关于铣削、车削和磨削颤振的文献[13-15]对检测与抑制技术的探讨多限于章节性概述,且未能涵盖近年来新兴的检测与抑制方法。基于此,本研究系统梳理了颤振检测领域的各类技术路径,包括基于稳定性叶瓣图、Nyquist判据与极点配置、龙格-库塔法、Newmark- $\beta$ 法和有限元分析的解析方法,涉及涵盖信息采集、信号处理、特征提取与模式分类的试验方法,全面分析各技术路线的局限性,讨论了针对加工过程颤振检测的优化方案。同时,深入探讨了主动、被动和参数调整颤振抑制技术的实施策略,为金属切削加工领域的振动控制提供系统性支撑。

## 1 颤振检测技术

颤振检测研究主要划分为解析法和试验法两大体系。表1通过文献综述形式系统展示了两类技术方法的研究进展与技术特征。

### 1.1 分析技术

颤振稳定性分析预测领域已发展出多种方法论体系。频域法(稳定性叶瓣图、Nyquist判据与极点配

置等)和时域法(龙格-库塔法、Newmark- $\beta$ 法、有限元分析法等)作为主流技术路径,在现有文献中被广泛采用,本文将原理与应用展开论述。

#### 1.1.1 频域解析法

稳定性叶瓣图(Stability Lobe Diagram, SLD)是频域解析法的经典方法,基于再生颤振理论,通过频域传递函数求解临界切削深度与主轴转速的稳定边界,从而划分出切削工艺系统的稳定区域和不稳定区域,继而可以从中选择适当的磨削工艺参数,达到避免颤振和提高切削效率和磨削加工质量的目的。LIU等<sup>[16]</sup>将稳定性叶瓣图临界曲线上部分定义为颤振区域,下部分定义为稳定区域。HASHIMOTO等<sup>[17]</sup>将SLD分为3部分:高工作速度稳定区、低工作速度稳定区和颤振区域。YAN等<sup>[18]</sup>通过特征值确定临界边界,获得了工件旋转周期与接触宽度间的SLD。TOTIS等<sup>[19-20]</sup>将模型参数视为随机变量,分析了不确定动态铣削模型的稳定性,得到了概率SLD,并提出了3种新的基于多项式混沌和克里金代理模型的概率分析方法。ZHANG等<sup>[21]</sup>设计了一种针对参数不确定性的主轴速度优化方法,并将SLD的下界用作优化约束和约束条件。TURKES等<sup>[22]</sup>提出了一种新的解析过程阻尼模型(Process Damping Model, PDM),并针对车削操作中低切削速度的颤振进行了过程阻尼比(Process Damping Ratio, PDR)的计算,利用SLD的反向运行分析计算程序对PDR的变化和数量进行预测,实现对切削系统较为准确的动力学描述。SLD作为预测磨削过程稳定性区域最直接有效的方法,当磨床给定砂轮-工件-夹具等条件时,能获得可保障该磨床实现稳定磨削的砂轮主轴转速-磨削深度等工艺参数匹配。然而,它也存在显著的局限性,SLD特定于其开发过程中所使用的条件和刀具,这限制了其适应不同加工场景、刀具磨损或材料变化的能力;SLD将系统假设为线性时不变系统,忽略非线性阻尼与刀具磨损效应,而切削工艺系统是一个多因素相互耦合的非线性时变系统,导致其与实际加工之间误差较大;此外,SLD主要用作后处理分析工具,这限制了其进行实时预测的能力。

Nyquist判据通过开环传递函数的Nyquist图对临界点 $(-1, j_0)$ 的包围情况判断闭环系统稳定性,当Nyquist曲线逆时针包围临界点 $(-1, j_0)$ 的次数等于开环传递函数右半平面极点数时则闭环系统稳定。Nyquist判据具有直观的稳定性裕度量化和多自由度系统适应性,使其在机械加工过程实时稳定性分析中成为一种较为常见的选择。SNOEYS等<sup>[23]</sup>、HASHIMOTO等<sup>[24]</sup>同时考虑了工件和砂轮的再生颤振理论,并结合Nyquist图分析了磨削过程中的颤振。EYNIAN等<sup>[25]</sup>建立了基

表 1 机械加工中颤振检测的解析技术与试验技术对比研究

Tab. 1 Comparative analysis of analytical and test methods for chatter detection in machining operations

维度 Dimension	解析法 Analytical method	试验法 Experimental method
理论基础 Theoretical foundation	基于数学模型和动力学理论,如频域分析、时域分析、稳定性叶瓣图、Nyquist判据与极点配置等 Based on mathematical models and dynamic theories, such as frequency domain analysis, time domain analysis, stability lobe diagrams, Nyquist criteria, and pole placement	基于实际加工数据,如振动信号、声发射信号和切削力信号 Based on actual machining data, such as vibration signals, acoustic emission signals, and cutting force signals
实现方式 Implementation methodology	通过理论建模和数值仿真实现,无需实际加工设备 It is achieved through theoretical modeling and numerical simulation, without the need for actual machining equipment	需要传感器和数据采集设备,如加速度传感器、声发射传感器和力传感器等 Sensors and data acquisition equipment are required, such as accelerometers, acoustic emission sensors, and force sensors
预测精度 Prediction accuracy	依赖于模型的准确性,对复杂系统可能存在误差 It relies on the accuracy of the model and may have errors for complex systems	直接基于实际数据,可靠性较高,但受传感器精度和信号处理技术影响 It is directly based on actual data and has high reliability, but is influenced by the precision of sensors and signal processing techniques
适用场景 Applicability scenarios	适用于加工参数优化和颤振预测,常用于理论研究和新工艺开发 It is applicable to the optimization of machining parameters and the prediction of chatter, and is commonly used in theoretical research and the development of new processes	适用于实际加工过程中的实时监测和颤振检测,常用于工业生产环境 It is suitable for real-time monitoring and chatter detection during actual machining processes, and is commonly used in industrial production environments
实时性 Real-time performance	通常为离线分析,实时性较差 It is typically conducted as offline analysis, with poor real-time performance	可实现实时监测,适用于在线颤振检测 It enables real-time monitoring and is suitable for online chatter detection
成本 Cost	理论建模和仿真计算,成本较低 Theoretical modeling and simulation calculations, lower cost	需要传感器和数据采集设备,成本较高 It requires sensors and data acquisition equipment, resulting in relatively high costs

于再生切屑和再生切屑面积/切削刃接触长度的动态切削力模型,该模型考虑了切削条件和车刀几何形状,并用Nyquist准则对稳定性进行解析预测,最后通过试验验证了稳定性模型的正确性。LI等<sup>[26]</sup>基于Nyquist准则和劳斯准则分析了工艺阻尼对薄壁Ti6Al4V合金铣削系统的影响,提出了改进的干扰区域计算模型,通过试验表明,当主轴转速为1 000 r/min时,利用基于该模型专门设计的立铣刀,最终稳定轴向切削深度从1.2 mm增加到2.7 mm。Nyquist判据与极点配置受线性时不变假设的制约,在实际切削过程中,切削力-位移关系成非线性(如刀具跳刀、材料塑性变形等),导致Nyquist判据的保守性偏差。同时,针对铣削等断续切削过程存在多齿周期性激励,传统Nyquist判据难以直接解析此类高维时滞系统。

### 1.1.2 时域数值法

时域法通过直接求解时变延迟微分方程(Delay Differential Equations, DDEs),可完整保留非线性阻尼、刚度时变效应及再生效应耦合项。相较于频域法基于雅可比矩阵线性化处理的局限性,时域法能准确表征刀具-工件接触区因材料去除导致的动态刚度非线性演化过程。例如,在变切深加工或断续切削中,时域法可捕捉到瞬时冲击载荷引起的亚临界Hopf分岔现象。采用显式、隐式时间积分(如Newmark- $\beta$ 、龙格-库塔法)结合空间离散化策略可处理多自由度系统

及非对称支承条件。GUO等<sup>[27]</sup>综合考虑刀具和薄壁零件的1阶和2阶模态参数以及具体的加工参数,基于铣削动力学模型,采用改进龙格-库塔法的半离散化方法(Semi-Discretization Method based on Improved Runge-Kutta Method, IRKM-SDM)绘制颤振SLD。经仿真与试验验证,在模拟精度与计算效率方面,IRKM-SDM绘制的SLD相较于零阶分析法(Zero-Order Analysis, ZOA)、多频解法(Multi-Frequency Method, MFS)及传统半离散法(Semi-Discrete Method, SDM)更具优势。NIU等<sup>[28]</sup>基于第二类沃尔泰拉(Volterra)积分方程提出了一种广义龙格-库塔方法(Generalized Runge-Kutta Method, GRKM),通过与半离散化方法的比较,GRKM具有更高的收敛速度和计算精度。JIANG等<sup>[29]</sup>基于改进的基函数和隐式Newmark- $\beta$ 方法,提出了一种新的动载荷识别方法,通过数值模拟和载荷识别试验,验证该方法的性能,并分析了噪声和模型误差对负载识别结果的影响。SONG等<sup>[30]</sup>将离散振动速度纳入重构积分矩阵求解过程,并利用状态离散映射判定铣削稳定性,使局部离散误差达到 $o[(\Delta t)^5]$ 量级,较零阶SDM和1阶全离散化法(Full-Discretization Method, FDM)分别提高了3个数量级。在达到相同预测精度要求时,该算法计算时间仅为零阶SDM的11%~14%,为1阶FDM的24%~27%,为实现高效精准的铣削稳定性预测提供了策略。

在切削加工颤振问题的时域数值分析中,高计算成本主要源于大规模动力学方程的迭代求解及全自由度系统的瞬态响应模拟。针对复杂加工场景(如五轴加工)和复杂材料(如钛合金)的切削过程的适配性优化,研究者们提出了多种数学模型,但这些模型通常具有较高的计算复杂度。模型降阶(Model Order Reduction, MOR)技术和图形处理器(Graphics Processing Unit, GPU)并行计算优化技术为降低计算成本、提高仿真效率提供了重要解决方案。MOR通过减小模型的自由度,保留关键动态特性,从而降低计算复杂度。LIU等<sup>[31]</sup>针对微铣削过程中的颤振问题,提出了一种集成了离心力、陀螺力矩和刀具跳动效应的动态模型。该模型通过降阶技术,将复杂的多自由度系统简化为更易处理的低阶模型,显著减少了计算量,同时保持了较高的预测精度。刘宇等<sup>[32]</sup>针对微铣削中的切削力系数时变特性,引入了Gamma过程来描述刀具磨损与切削时间的关系,并建立了时变可靠性模型。通过降阶技术,该模型能够有效预测切削力系数的变化,并提高了颤振预测的准确性。GPU优化技术利用图形处理器的并行计算能力,可加速复杂模型的仿真过程。HEITZ等<sup>[33]</sup>提出了一种基于快速傅里叶变换(Fast Fourier Transform, FFT)的切削力模型优化方法,利用GPU加速FFT计算,显著提高了高频切削力的拟合效率。NIU等<sup>[34]</sup>开发了一种改进的微铣削动态切削力模型,该模型通过GPU加速仿真过程,实现了对金属基复合材料切削力的高效预测。为给切削颤振研究提供更高效率的解决方案,HONG等<sup>[35]</sup>、

MALGHAN等<sup>[36]</sup>提出了MOR技术和GPU技术相结合的策略,即先利用降阶技术简化切削力模型,再通过GPU加速优化过程,可以显著提高计算效率,为优化切削参数、提高加工质量提供支持。

时域数值法可直接模拟瞬态响应并提供详细的时间历程数据,这有助于对非线性时变系统颤振机制的理解。但对于高自由度系统,高计算成本和较低参数敏感性限制了其工业级应用。MOR技术和GPU在切削颤振研究中已展现出较为显著的优势,但仍面临一些挑战:降阶模型的精度与计算效率之间的平衡仍需进一步优化;对于复杂材料(如钛合金)的切削过程,现有的降阶模型在预测切削颤振时仍存在一定局限性。未来研究可以进一步探索MOR与GPU优化的深度融合,开发更高效、更精确的切削颤振预测与控制方法。此外,传统时域方法在多物理场耦合问题中的扩展性有限,难以处理热力耦合等复杂情况。未来需结合高效数值算法、不确定性量化及数据驱动技术,构建兼具物理精确性与工程实用性的混合预测框架,以应对智能制造中对颤振在线抑制的迫切需求。

### 1.2 试验技术

#### 1.2.1 数据采集

颤振检测程序的典型流程,如图2所示。其中,信号预处理主要依赖于数字滤波器和信号处理算法(如带通滤波器、移动平均等),计算效率主要取决于滤波器的阶数和信号的长度;颤振检测方法包括基于频谱分析、时频域分析或机器学习的算法,机器学习因模型训练和推理复杂导致颤振检测的复杂度相对较高;

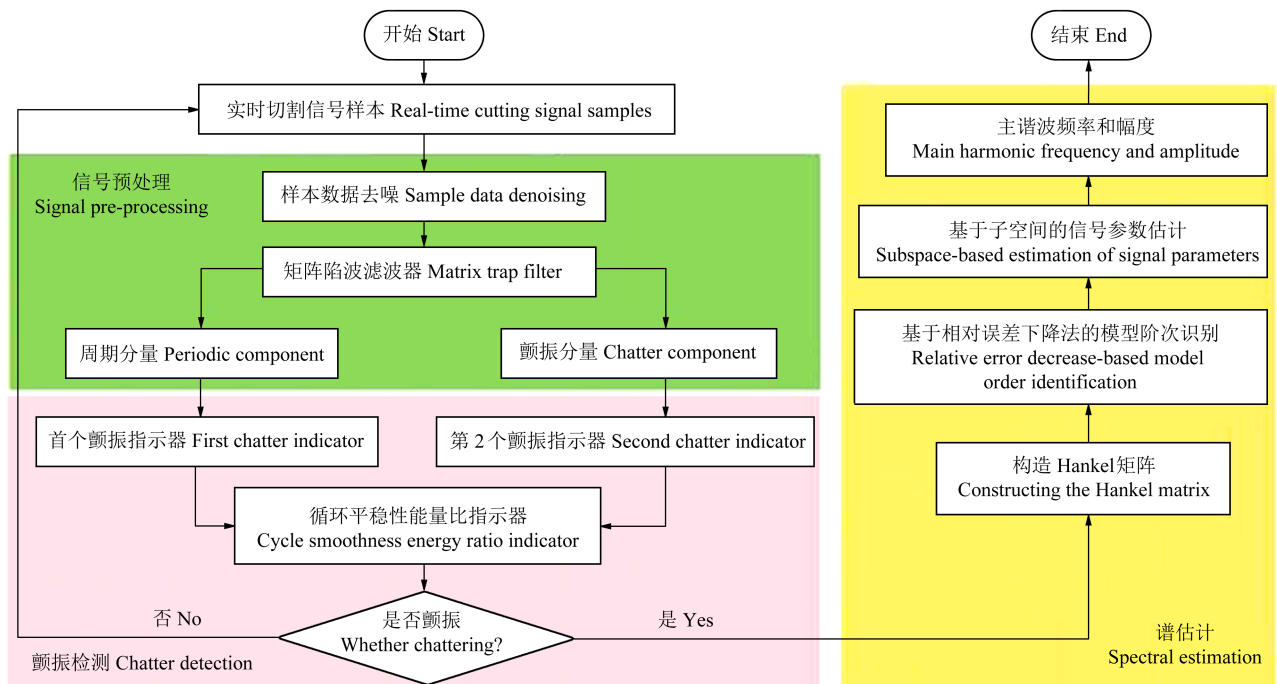


图2 颤振检测流程图

Fig. 2 Flowchart for chatter detection process

谱估计的计算复杂度呈阶数敏感型特征,FFT的复杂度相对较低,而基于高阶统计量或奇异谱分析(Singular Spectrum Analysis, SSA)的方法复杂度更高,若采用变分模态分解(Variational Mode Decomposition, VMD)等自适应方法,复杂度可能进一步增加。数据采集是颤振检测的第一步,具体包括:首先,在切削过程中采集原始信号,并通过滤波器进行预处理以去除不相关成分;其次,利用FFT获得频

率谱;最后,计算能量比作为颤振指标。

为了同时获取稳态和非稳态信号,通常会考虑多种加工条件,包括刀具几何形状<sup>[37]</sup>、主轴转速、切削深度和工件材料<sup>[38-39]</sup>。力信号<sup>[40]</sup>、加速度信号<sup>[41-45]</sup>、声发射信号<sup>[46-47]</sup>作为理想信号常用于表征加工过程中的颤振,除此之外,用于颤振检测的不同信号还包括:电流信号<sup>[48-49]</sup>、图像信号<sup>[50-54]</sup>和位移信号<sup>[55-56]</sup>。不同传感器信号的对比分析如表2所示。

表2 不同传感器信号的对比分析

Tab. 2 Comparative analysis of heterogeneous sensor signal characteristics

种类 Type	有效频带 Effective frequency band/ kHz	信噪比 Signal-to-noise ratio/ dB	实时延迟 Real-time delay/ms	安装复杂程度 Installation complexity	成本 Cost
力信号 Force signal	0~10	45~60	0.1~0.5	高 High	高 High
加速度信号 Acceleration signal	0.5~20	30~50	0.5~2	低 Low	中 Medium
声信号 Acoustic signal	50~300	20~40	0.05~0.2	中 Medium	较高 Relatively high
电流信号 Current signal	0~2	15~30	10~50	无 None	低 Low
图像信号 Image signal	空间域 Spatial domain	10~25	50~200	高 High	高 High

由表2可知,力传感器信号具有高灵敏度和实时性,但其体积相对较大,导致安装困难,并会降低切削系统的刚度进而限制切削参数的选择,且价格昂贵。加速度信号具有有效、抗干扰性强的特点,在加工过程的监测中得到了广泛的应用,但加速度信号依赖于信号处理手段对其进行过滤,影响了信号测量的准确性。声信号传感器较其他传感器具有更宽的频带,因此在大多数情况下更具通用性,但在低频加工中存在准确性不足的问题。电流信号通过伺服驱动器内置的电流环直接采样,无需附加传感器,故经济性最好,但其受带宽限制,无法检测频率不小于2 kHz的高频

颤振。图像信号基于机器视觉的颤振频率提取和模态振型重构,具有物理直观性的特点,图像分辨率是影响检测结果的最重要因素,一般来说图像的分辨率很高,这意味着处理成本高且需要较长的计算时间,使其在识别萌生阶段的颤振更具挑战性。

### 1.2.2 信号处理

信号处理是颤振检测的关键步骤。从加工过程中获取的传感器信号通常无法直接使用,需对信号进行处理,典型的信号处理方法主要包括时域法、频域法和时频域法,表3总结了主要使用的信号处理方法。

在信号处理之前,预处理会滤除采集信号中的噪

表3 主要的信号处理技术

Tab. 3 Overview of primary signal processing techniques

方法 Method	优点 Advantages	缺点 Disadvantages	文献 Literature	
时域法 Time-domain method	统计特征分析 Statistical feature analysis	计算简单,实时性强;无需复杂变换,工程实现便捷;对周期性信号敏感 Simple calculation and strong real-time performance; no need for complex transformations, facilitating convenient engineering implementation; sensitive to periodic signals	无法表征频率信息,难以区分非平稳信号的复杂模式;统计量易受噪声干扰;不适用于突变或瞬态信号 Unable to characterize frequency information, making it difficult to distinguish complex patterns in non-stationary signals; statistical measures are susceptible to noise interference; not suitable for abrupt or transient signals	
	过零率 Zero-crossing rate			[57-61]
	自相关函数 Autocorrelation function			
频域法 Frequency-domain method	FFT 功率谱密度 Power spectral density	频率分辨率高;噪声抑制能力强 High frequency resolution; strong noise suppression capability	无法定位时间信息 Unable to locate temporal information	[62-65]
	小波功率谱 Wavelet power spectrum			
时频域法 Time-frequency domain method	STFT	具有非平稳信号适应性,同时能提供时间和频率信息,适合分析颤振的瞬态特征 It has adaptability to non-stationary signals and can provide both time and frequency information simultaneously, making it suitable for analyzing the transient characteristics of flutter	计算复杂程度高;参数选择敏感 High computational complexity; sensitive to parameter selection	[66-71]
	WT			
	HHT			
	VMD			

声成分,将有用成分与噪声完全分离。ZHANG等<sup>[72]</sup>采用同步压缩小波变换(Wavelet Transform, WT)对数据进行预处理,以降低噪声对特征提取的影响。LIU等<sup>[73]</sup>针对信噪比较低的信号快速峭度图(Fast Kurtogram, FK)无法定位颤振的问题,设计了一种带通滤波器,用于找出具有最大谱峭度的频带,通过铣削试验验证了所提方法的合理性。CAO等<sup>[74]</sup>采用梳状滤波器对振动信号进行预处理,以消除旋转频率、刀具通过频率及其谐波产生的干扰。ZHENG等<sup>[75]</sup>采用迭代Vold-Kalman滤波算法和最小均方算法有效滤除信号中的无关成分,实现对颤振成分的准确提取和原位识别,试验结果表明,优化前后的跟踪滤波误差从7.13%降低至0.21%。

时域分析适用于实时监测,但灵敏度有限,频域分析适合稳态信号解析却丢失时间信息,时频域分析虽计算复杂,但为非平稳颤振研究提供关键工具。在实际应用中,需根据信号特性(平稳性、信噪比)、系统资源(计算能力、延迟容忍度)及分析目标(实时预警/机制研究)进行多方法协同优化。

### 1.2.3 特征选取

信号处理通常会进行特征选择,它是颤振检测中的关键步骤,旨在挑选出对颤振敏感的特征,通过捕捉这些指标的变化来揭示相应的加工状态。特征选择可以分为特征生成和特征筛选两个步骤,首先,利用统计方法或其他方法生成大量特征,但并非所有特征都对颤振敏感;其次,为了在计算效率和准确性之间取得平衡,颤振检测过程中需进行特征选择,以获得更高的分类精度。

统计方法是信号处理之后生成相应特征的最常用方法,统计指标可直接基于统计理论进行计算<sup>[76-77]</sup>,常用的统计值包括均值、均方根、方差、标准差、峰度和偏度等。JAUHARI等<sup>[78]</sup>使用加权平均值、方差和偏度作为颤振指标;WU等<sup>[79]</sup>在研究铣削过程的稳定性问题时将标准差作为颤振指标;WANG等<sup>[80]</sup>利用峰度概率密度函数(Kurtosis Probability Density Function, KPDF)评估振动信号的冲击特性。除了统计指标外,能量比<sup>[81-83]</sup>、分形维数<sup>[84]</sup>、近似熵<sup>[85]</sup>和功率谱熵<sup>[86-88]</sup>等特征也用于颤振检测,这些指标主要基于频域和时频域方法计算,且其颤振识别能力已通过不同试验得到证明。

针对不同的加工过程,采用合适的特征提取可获得适用于不同加工过程的敏感特征量。短时傅里叶变换(Short-time Fourier Transform, STFT)通过加入固定窗函数的方式完成局部信号的频谱分析<sup>[89]</sup>,但同时会导致自适应性的缺乏以及对非平稳信号敏感度低等问题<sup>[90]</sup>。WANG等<sup>[91]</sup>提出一种基于小波的去噪方

法,该方法结合了混合阈值函数和依赖于分解层级的通用阈值规则,适用于不同的加工过程,而无需进行二次校准。李欣等<sup>[92]</sup>将经验模态分解(Empirical Mode Decomposition, EMD)和希尔伯特-黄变换(Hilbert-Huang Transform, HHT)引入颤振信号特征提取中,可以在颤振形成之前0.5 s得到颤振爆发的征兆,实现对镗削颤振的快速预报。SHRIVASTAVA等<sup>[93]</sup>利用EMD良好的噪声处理能力建立了刀具颤振与各加工参数的相关性关系,为切削加工预测稳定的加工区域提供了策略。由于切削加工过程通常所采集的信号并不是纯白噪声,因此,在使用EMD时,首个本征模态函数(Intrinsic Mode Function, IMF)中通常会出现频率范围过宽的现象,即模态混叠,进而导致后续的希尔伯特变换(Hilbert Transform, HT)失去实际意义。为解决模态混叠问题,可采用集合经验模态分解(Ensemble Empirical Mode Decomposition, EEMD)。EEMD是一种基于噪声辅助的方法,即在运用EMD方法前,向原始信号中添加有限的白噪声。文献[94-95]已证实,EEMD的效果优于EMD;图3为EMD与EEMD结果的对比,由图3可知,通过EEMD获得的第1个IMF的频带比通过EMD获得的第1个IMF的频带更窄,在第3个IMF中这一效果尤为显著。

LIU等<sup>[96]</sup>提出了一种基于VMD和能量熵的铣削颤振检测方法,可有效监测铣削早期颤振情况。LI等<sup>[97]</sup>提出了一种基于VMD和多尺度熵的铣削过程在线颤振检测方法,可有效检测稳定切削条件和变切削条件下的铣削颤振。然而,VMD须提前确定模态数 $K$ 和惩罚因子 $\alpha$ ,这导致其存在对参数选择敏感、对突发性瞬态信号捕捉能力不足等问题。为缓解上述问题,GUPTA等<sup>[98-100]</sup>采用局部均值分解(Local Mean Decomposition, LMD)分析了车削过程的声音信号,并结合均方根、峰峰值及绝对平均值取得了较好的颤振识别准确率。MISHRA等<sup>[101]</sup>则采用基于样条的局部均值分解(Spline-Based Local Mean Decomposition, SBLMD)技术对不同切削参数下获取的加工声音信号进行处理,改善了传统LMD的固有缺陷,开发了可用于刀具颤振的在线监测系统。CHEN等<sup>[102]</sup>基于三次三角基数样条插值的改进包络算法的C-ELMD,有效提高对合成信号的集合局部均值分解精度,为齿轮和轴承故障诊断提供了策略。

表4为颤振特征提取算法总结。其中,EMD模态混叠和边界效应较为明显,EEMD运算时间成本较高,VMD缺乏自适应性,而LMD算法效率高,自适应良好,综合对比,LMD更适合用于颤振在线监测,然而传统的LMD仍存在一定程度的模态混叠和边界效应等问题。在实际应用中,需结合加工工艺(如切削参数、

刀具类型)优化算法参数,并通过交叉验证评估不同算法泛化性能。

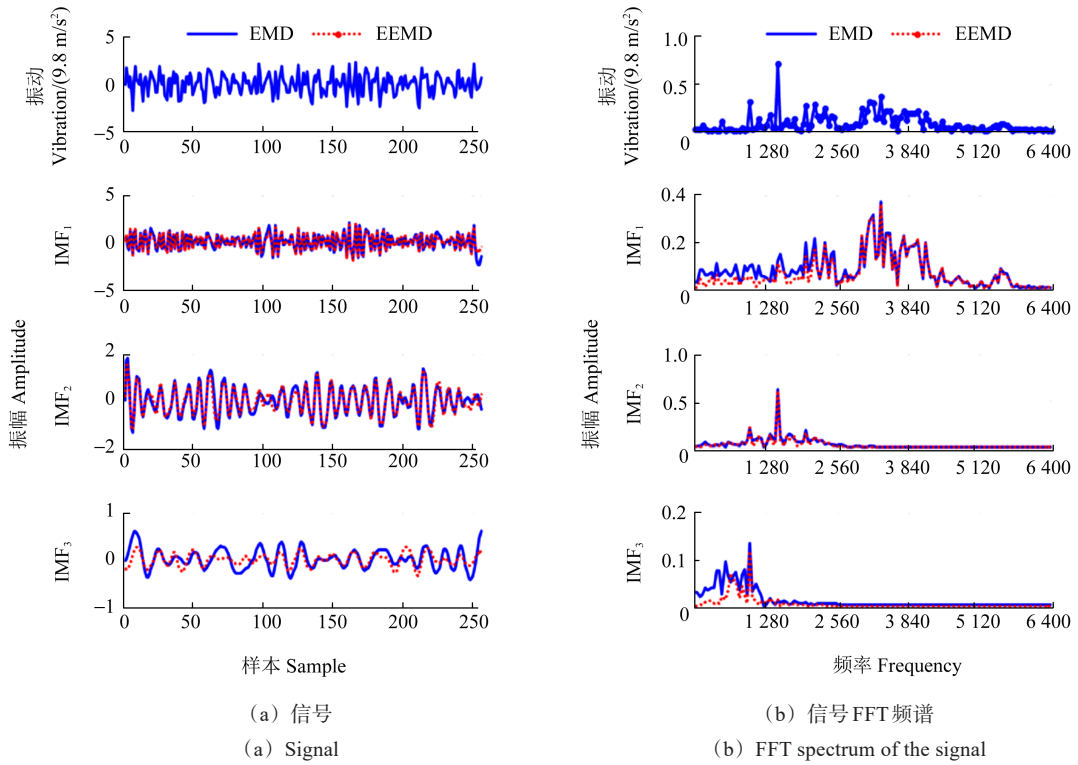


图3 切削过程稳定时EMD与EEMD结果的对比

Fig. 3 Comparative analysis of EMD and EEMD outcomes during stable cutting process

表4 颤振特征提取算法总结

Tab. 4 Comprehensive summary of chatter feature extraction algorithms

方法 Method	基本原理 Fundamental principle	适用范围 Application scope	优点 Advantage	缺点 Disadvantage
短时能量阈值法 Short-time energy threshold method	基于短时能量计算与阈值判定,通过滑动窗口分割信号,统计能量突变特征识别颤振 Based on short-time energy calculation and threshold determination, the signal is segmented using a sliding window, and chatter is identified by statistical energy mutations characteristics	实时性要求高、信号特征显著(如周期性冲击明显)的在线监测场景 Online monitoring scenarios that require high real-time performance and have significant signal characteristics (such as obvious periodic impacts)	计算效率高,实时性强;阈值设定简单,适合在线监测 High computational efficiency and strong real-time performance; simple threshold setting, suitable for online monitoring	对非平稳信号敏感度低;阈值选择依赖先验经验,易误判 Low sensitivity to non-stationary signals; threshold selection relies on prior experience, prone to misjudgment
小波变换 Wavelet transform	利用小波基函数对信号进行多尺度分解,通过时频能量熵或小波系数的模极大值捕捉颤振特征 Utilizing wavelet basis functions to perform multi-scale decomposition of the signal, and capturing chatter characteristics through time-frequency energy entropy or the modulus maxima of wavelet coefficients	非平稳信号分析,适用于中高频颤振(如铣削、车削中的突发性振动等) Non-stationary signal analysis, applicable to medium-to-high frequency chatter (such as sudden vibrations in milling and turning processes)	时频分辨率可调,方向选择性优异;可结合能量熵等多特征融合 Time-frequency resolution is adjustable with excellent directional selectivity; it can be combined with multi-feature fusion such as energy entropy	小波基函数和分解层数需人工设定,缺乏自适应性;高频分量噪声干扰显著 The wavelet basis function and decomposition level need to be manually set, lacking adaptability; noise interference in high-frequency components is significant
经验模态分解 Empirical mode decomposition	自适应将信号分解为IMFs,通过筛选高频IMF分量能量熵或相关性判断颤振 Adaptively decompose the signal into Intrinsic mode functions (IMFs), and determine chatter by screening the energy entropy or correlation of high-frequency IMF components	复杂非线性振动信号分析,适用于多源干扰下的微弱颤振检测 Analysis of complex nonlinear vibration signals, suitable for detecting weak chatter under multi-source interference	自适应分解信号,无需预设参数;适用于非线性和非平稳信号 Adaptive signal decomposition without preset parameters; suitable for nonlinear and non-stationary signals	模态混叠现象严重;端点效应和计算耗时限制其工程应用 Severe mode mixing phenomenon; endpoint effects and computational time consumption limit its engineering applications

续表 Continued table

方法 Method	基本原理 Fundamental principle	适用范围 Application scope	优点 Advantage	缺点 Disadvantage
集合经验模态分解 Ensemble empirical mode decomposition	在 EMD 基础上添加白噪声抑制模态混叠,通过集合平均重构信号后提取 IMF 特征 On the basis of empirical mode decomposition (EMD), white noise is added to suppress mode mixing, and after reconstructing the signal through ensemble averaging, the Intrinsic mode function (IMF) features are extracted	高噪声环境下(如重切削)的颤振特征提取,需平衡噪声抑制与计算效率 Feature extraction of chatter in high-noise environments (such as heavy cutting) requires balancing noise suppression and computational efficiency	抑制模态混叠,提升分解稳定性;通过噪声辅助增强特征鲁棒性 Suppress mode mixing and enhance decomposition stability; improve feature robustness through noise-assisted techniques	计算复杂度高(需多次 EMD 迭代);白噪声引入可能影响高频特征准确性 High computational complexity (requiring multiple iterations of EMD); the introduction of white noise may affect the accuracy of high-frequency features
变分模态分解 Variational mode decomposition	基于变分优化理论分离信号为多个 IMFs,通过中心频率和带宽参数约束分解过程 Based on the theory of variational optimization, the signal is separated into multiple Intrinsic mode functions (IMFs), and the decomposition process is constrained by center frequency and bandwidth parameters	高精度时频特征提取,适用于多分量耦合振动信号(如多刀具协同加工) High-precision time-frequency feature extraction, applicable to multi-component coupled vibration signals (such as those arising from multi-tool collaborative machining)	分解参数可控(中心频率、带宽),模态分离效果好;支持并行计算 The decomposition parameters (center frequency, bandwidth) are controllable, resulting in good modal separation; parallel computing is supported	需预设模态数和惩罚因子,参数选择敏感;对突发性瞬态信号捕捉能力不足 The number of modes and penalty factors need to be preset, and parameter selection is sensitive; there is insufficient ability to capture sudden transient signals
局部均值分解 Local mean decomposition	通过迭代分解信号为乘积函数(PFs),提取瞬时幅值和频率特征,结合 PF 分量的非平稳性判据识别颤振 By iteratively decomposing the signal into product functions (PFs), extracting the instantaneous amplitude and frequency characteristics, and combining the non-stationarity criteria of the PF components to identify chatter	瞬态信号分析(如断刀伴随颤振),需处理端点效应和模态混叠问题 Transient signal analysis (such as tool breakage accompanied by chatter) requires addressing endpoint effects and mode mixing issues	分解效率高,瞬时频率和幅值表征直观;适用于非平稳信号快速分析 High decomposition efficiency with intuitive representation of instantaneous frequency and amplitude; suitable for rapid analysis of non-stationary signals	端点效应导致边界失真;模态混叠问题未完全解决,需结合其他方法优化 Endpoint effects lead to boundary distortion; mode mixing issues are not fully resolved and require optimization in combination with other methods

1.2.4 分类

试验技术通过多传感器数据采集获取原始数据,并利用信号处理方法进行特征提取,从而为后续的分类算法提供高质量的特征输入。在此基础上,通常利用阈值法或基于机器学习的分类算法通过对

这些特征进行学习和分类,实现从试验数据到颤振状态识别的无缝衔接,为切削过程的稳定性和质量控制提供了可靠的技术支持。表 5 归纳总结了不同机器学习算法的特点及应用情况。

表 5 多种颤振识别法优缺点及应用总结

Tab. 5 Summary of the advantages, disadvantages and applications of various chatter identification methods

颤振识别算法 Chatter detection algorithm	基本原理 Fundamental principle	精度范围 Accuracy range	适用范围 Applicable scope	优点 Advantage	缺点 Disadvantage	文献 Literature
支持向量机 Support vector machine	基于结构风险最小化原理,通过核函数映射至高维空间构建最优分类超平面,解决小样本非线性问题 Based on the principle of structural risk minimisation, the optimal classification hyperplane is constructed by mapping the kernel function to a high-dimensional space to solve the small-sample nonlinear problem	85%~95%	小样本数据;非线性振动信号分类;实时性要求中等的场景 Small sample data; classification of nonlinear vibration signals; scenarios with moderate real-time requirements	高维数据适应性强,泛化性能好;核函数可处理非线性问题 Strong adaptability to high-dimensional data and good generalization performance; kernel functions can handle nonlinear problems	对大规模数据训练效率低;参数选择敏感 Low training efficiency for large-scale data; sensitive to parameter selection	[103-106]

续表 Continued table

颤振识别算法 Chatter detection algorithm	基本原理 Fundamental principle	精度范围 Accuracy range	适用范围 Applicable scope	优点 Advantage	缺点 Disadvantage	文献 Literature
随机森林 Random forest	集成学习框架,通过 Bagging 生成多棵决策树,基于特征子集与样本子集并行训练,通过投票机制聚合结果 An integrated learning framework that generates multiple decision trees through Bagging, trains in parallel with a subset of samples based on a subset of features, and aggregates results through a voting mechanism	90%~98%	高维特征数据(如多传感器融合信号);噪声鲁棒性要求高的复杂工况 High-dimensional feature data (such as multi-sensor fusion signals); complex working conditions with high requirements for noise robustness	抗过拟合能力强,支持并行计算;特征重要性评估直观 Strong resistance to overfitting, support for parallel computing; intuitive evaluation of feature importance	模型复杂度高,解释性弱;对噪声敏感时易导致冗余树生成 High model complexity and weak interpretability; prone to generating redundant trees when sensitive to noise.	[107]
神经网络 Neural network	基于多层感知机与反向传播算法,通过非线性激活函数实现特征自动解耦与高阶抽象表征学习 Automatic feature decoupling and higher-order abstract representation learning via nonlinear activation function based on multilayer perceptron and backpropagation algorithm	92%~99%	非线性;高维度;时序依赖性强的振动信号模式识别,需大量训练数据 Nonlinear, high-dimensional vibration signal pattern recognition with strong temporal dependencies, requiring large amounts of training data	非线性建模能力极强,适用于大规模复杂数据;端到端学习减少人工干预 Extremely strong nonlinear modeling capabilities, suitable for large-scale complex data; end-to-end learning reduces human intervention	训练依赖大量标注数据;计算资源消耗大;模型黑箱特性影响可解释性 Training relies on a large amount of labeled data; consumes significant computational resources; the black-box nature of the model affects interpretability	[108-111]
决策树 Decision tree	基于信息增益或基尼指数递归分割特征空间,生成树状规则集,通过叶节点类别投票实现分类 Recursively partitioning the feature space based on information gain or Gini index, generating a tree-like rule set, and achieving classification through leaf node category voting	80%~90%	实时监测;可解释性需求高的场景,适用于低复杂度振动信号分类 Real-time monitoring; scenarios with high demand for interpretability, suitable for low-complexity vibration signal classification	模型结构简单,训练和预测速度快;特征重要性可视化易于理解 Simple model structure, fast training and prediction speeds; visualization of feature importance is easy to understand	易过拟合,需剪枝优化;对连续特征敏感度低 Prone to overfitting, requires pruning optimization; low sensitivity to continuous features	[112-113]
K近邻 K-nearest neighbors	基于局部密度假设,通过计算待测样本与训练集的欧氏距离(或马氏距离)进行多数投票分类 Based on the local density assumption, majority voting classification is performed by calculating the Euclidean distance (or the Mars distance) between the samples to be tested and the training set	75%~88%	低维特征;样本分布规律明显的场景,适用于在线监测系统 Low-dimensional features; scenarios with obvious sample distribution patterns, suitable for online monitoring systems	无需训练过程,实现简单;对噪声数据鲁棒性较好 No training process required, simple to implement; good robustness to noisy data	计算复杂度高;高维数据性能骤降 High computational complexity; performance plummets with high-dimensional data	[114]
隐马尔可夫模型 Hidden Markov model	基于状态空间建模,假设系统状态服从马尔可夫链,观测序列与状态条件独立,通过 Baum-Welch 算法迭代优化参数 Based on state-space modelling, the system state is assumed to obey a Markov chain, the observation sequence is independent of the state conditions, and the parameters are optimised iteratively by the Baum-Welch algorithm	83%~94%	具有显著时序特征的振动信号(如周期性强、状态转移明确的颤振事件) Vibration signals with significant temporal characteristics (such as chatter events with strong periodicity and clear state transition)	对时序动态特性建模能力强;支持状态转移概率的物理意义解释 Strong modeling capability for temporal dynamic characteristics; supports physical interpretation of state transition probabilities	状态数目需预先设定,可能引入主观偏差;训练复杂度高 The number of states needs to be preset, which may introduce subjective bias; high training complexity	[115]

续表 Continued table

颤振识别算法 Chatter detection algorithm	基本原理 Fundamental principle	精度范围 Accuracy range	适用范围 Applicable scope	优点 Advantage	缺点 Disadvantage	文献 Literature
变压器 Transformer	基于自注意力机制与多头并行编码,通过位置编码捕捉长程序依赖,实现动态特征的全局关联建模 Global association modelling of dynamic features based on self-attention mechanism with multi-head parallel coding, capturing long-range temporal dependencies through positional coding	95%~99%	长时序依赖、多传感器融合 Long-term temporal dependencies, multi-sensor fusion	全局上下文建模、并行计算 Global context modeling, parallel computation	计算复杂度高、数据需求大 High computational complexity, large data requirements	[116-119]

阈值法与智能算法在切削状态识别中呈现互补特性。阈值法凭借超低延迟与强解释性,适用于实时嵌入式监测;智能算法通过高阶特征映射与非线性决策,在高精度诊断与复杂颤振模式识别中占优。为提升分类精度,不少学者已在探索多传感器融合在智能算法中的应用,聚焦阈值-智能混合系统与物理引导的边缘学习框架,结合联邦学习<sup>[120]</sup>解决全局协作与隐私约束问题,打破跨工厂/多设备颤振监测数据孤岛,实

现分布式数据协同与知识共享,提升模型泛化能力。

## 2 颤振抑制技术

在机械加工中,颤振的抑制与控制是亟待解决的难题。近年来国内外学者已开展了众多旨在控制颤振的研究。颤振抑制技术目前主要分为主动颤振抑制、被动颤振抑制和参数调整抑制三大类,如图4所示。表6为不同颤振抑制策略的特点及应用情况。

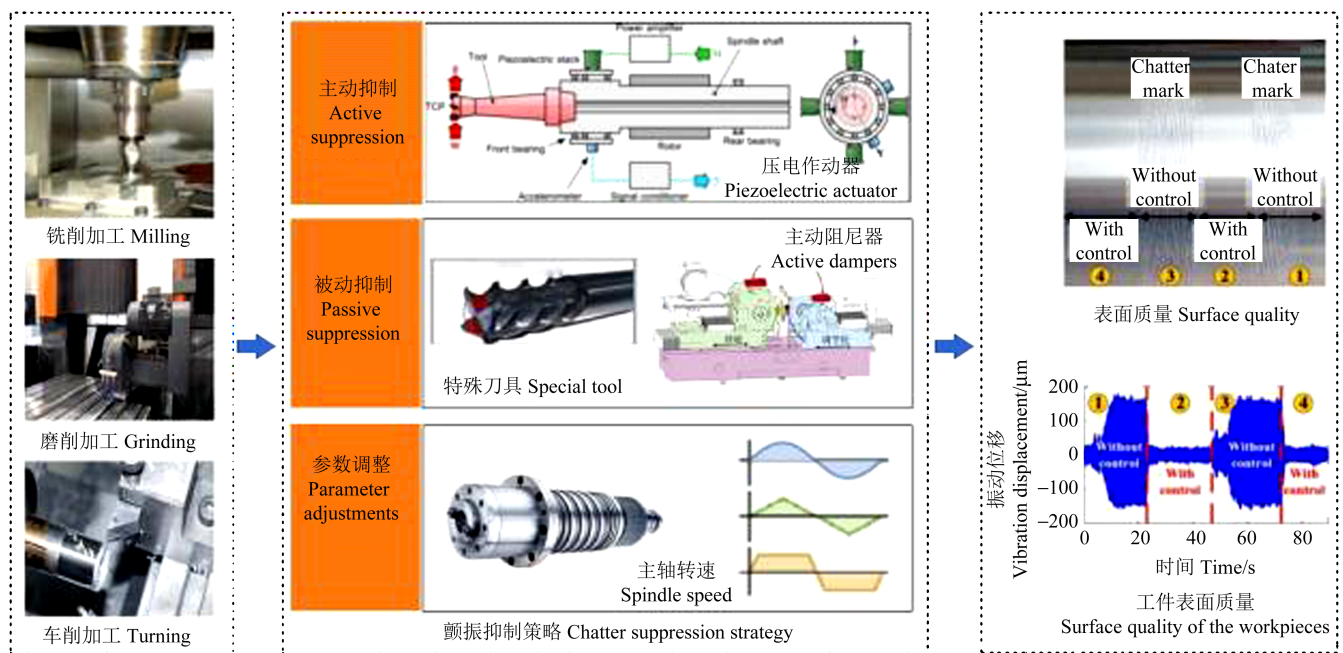


图4 颤振抑制策略

Fig. 4 Chatter suppression strategy

主动抑制基于闭环控制系统,利用传感器(如加速度计、力传感器等)采集振动信号,经控制器(如PID、自适应算法等)计算后驱动作动器(如压电陶瓷、电磁驱动器等)生成反相位振动波。LI等<sup>[121]</sup>通过将压电执行器和位移传感器集成到刀柄中,构建了一种主动控制结构,并开发了相应的控制系统模型。通过不同的铣削试验验证表明,该方法不仅能有效抑制颤振还显著降低了执行器的控制能耗。CUI等<sup>[122]</sup>通过将位移传感器与嵌入式电磁执行器(Embedded Electromagnetic Actuator,

EEA)集成,构建了一个全面的主动控制结构,利用冲击和铣削力识别测试数据的数值模拟进行了验证,使主轴-刀具系统的颤振得到了显著抑制。LI等<sup>[123]</sup>开发了一种基于线性矩阵不等式(Linear Matrix Inequality, LMI)的离散输出反馈鲁棒控制器,显著扩大了铣削过程的无颤振边界。WAN等<sup>[124]</sup>采用滑模控制与电磁执行器构建了主动铣削颤振控制系统的模型,通过仿真与铣削试验结果表明,采用所提方法与系统,铣削颤振得到了有效抑制并显示出良好的鲁棒性和实用性。

表 6 不同颤振抑制策略优缺点及应用总结

Tab. 6 Summary of the advantages, disadvantages and application of different chatter suppression strategy

颤振抑制策略 Chatter suppression strategy	优点 Advantage	缺点 Disadvantage	适用场景 Applicable scenarios	
主动抑制 Active suppression	压电主动阻尼 Piezoelectric active damping 电磁作动器 Electromagnetic actuator	适应性强,可抑制宽频带颤振;动态响应快,适合高精度加工 High adaptive capacity for wide-band chatter suppression; rapid dynamic response suitable for high-precision machining	系统复杂,成本高;依赖高精度传感器与控制器 Complex and costly system; relies on high-precision sensors and controllers	高精度、高动态响应加工 High precision, high dynamic response machining
被动抑制 Passive suppression	调谐质量阻尼器 Tuned mass damper 减振刀具柄 Vibration-reducing tool holder	结构简单、可靠性高;维护成本低 Simple structure, high reliability; low maintenance costs	抑制带宽有限,仅对特定频率有效;可能增加系统质量或体积 Limited rejection bandwidth, effective only at specific frequencies; may increase system mass or size	常规加工环境或固定工况 Regular processing environments or stationary conditions
参数调整抑制 Suppression through parameter adjustment	稳定性叶瓣在线优化 Online optimization of stability lobes 自适应进给 Adaptive feed	无需硬件改动,成本低;适用于复杂工况 No hardware modification is required and cost is low, suitable for complex working conditions	可能牺牲加工效率;依赖精确模型与实时计算能力 May sacrifice machining efficiency; relies on accurate modelling and real-time computational capabilities	多品种、方便参数加工 Multi-species, easy parameter processing

被动抑制利用物理阻尼(如黏弹性材料、调谐质量阻尼器等)或结构动力学优化(如刀具刚度增强、机床模态分离)降低系统谐振峰值,无需外部能量输入。LIU等<sup>[125]</sup>通过优化约束层阻尼(Constrained Layer Damping, CLD)刀杆结构的动力学特性,提升了车削加工过程的稳定性。YANG等<sup>[126]</sup>提出一种集成式单自由度被动阻尼铣刀,通过在刀体内部配置嵌入式阻尼器以实现减振。经模态分析表明,该阻尼铣刀(长径比 $\approx 8$ )在全方位角下可实现75%的振幅衰减,能有效抵御随旋转角度周期性变化的铣削力激励。MA等<sup>[127]</sup>针对微铣削过程中的颤振问题,设计了一种两自由度调谐质量阻尼器用以同步抑制微铣刀在2个正交方向的振动,通过模态试验与微铣削试验验证表明,该调谐质量阻尼器(Tuned Mass Damper, TMD)使临界切削深度提升13倍并满足微铣削系统对紧凑化设计的严苛要求。YANG<sup>[128]</sup>以最大化频响函数最小负实部为目标,提出一种面向最大颤振稳定性提升的TMD参数优化方法,与传统等峰法进行量化对比,所提方法使临界切削深度提升37%。WANG等<sup>[129]</sup>提出了一种含非线性元件的新型TMD结构,区别于传统线性TMD,该非线性TMD在质量块与主系统间增设串联摩擦-弹簧单元,通过非线性刚度特性实现宽频减振。通过构建非线性TMD阻尼工件铣削过程的SLD量化分析表明:该非线性TMD可使临界极限切削深度提升超过30%。

参数调整抑制基于SLD,调整参数至稳定加工区域,避免再生效应或模态耦合引发颤振。MORITA等<sup>[130]</sup>通过引起颤振的结构固有频率、颤振频率,计算了消除颤振的最佳主轴转速。李茂月等<sup>[131]</sup>研究了颤

振频率与主轴转速的关系,并建立了对应的模型,并依据颤振频率自适应调整主轴转速来抑制颤振。BARRENETXEA等<sup>[132]</sup>构建了工件旋转速度连续变化的动态时域模型来避免磨削加工颤振的产生。LIN等<sup>[133]</sup>将车削加工的变速策略应用到面铣削加工中,并利用计算机仿真技术验证了变转速铣削抑制颤振的可行性。

主动抑制适用于对精度和动态性能要求极高的场景,但需权衡成本与复杂性;被动抑制以低成本实现可靠抑制,但受限于频带和结构约束;参数调整抑制通过智能算法平衡效率与稳定性,是数字化制造的优选方案。为适应日益增长的高精、高效加工需求,可将3种策略协同应用。如:“被动阻尼+在线参数优化”策略<sup>[134]</sup>是工业界关注热点,被动阻尼通过吸收高频振动能量,降低系统的整体振动水平,为在线参数优化提供更稳定的加工环境。同时,在线参数优化通过动态调整切削参数,进一步抑制剩余低频振动,弥补被动阻尼的不足。该策略具体实施路径:①建立包含被动阻尼、主动阻尼和切削参数的动态系统模型,分析其振动特性和稳定性边界;②选择合适的高阻尼材料或结构(如磁流变弹性体或晶格结构),并将其集成到加工系统中;③部署振动传感器和切削力传感器,实时采集加工过程中的动态数据;④结合优化算法(如遗传算法、神经网络等)和主动控制策略,动态调整切削参数以抑制颤振;⑤通过试验验证综合应用策略的有效性,评估其对加工质量、工具寿命和生产效率的提升效果。综合应用主动颤振抑制、被动颤振抑制和参数调整抑制策略,通过多层级动态耦合与跨尺度协同机制,充分发挥各自的优势,弥补单一策略

的不足,可显著提升切削加工的稳定性和效率,为智能制造提供重要技术支撑。

### 3 讨论

尽管颤振检测与抑制领域已得到广泛研究,但由于切削过程的复杂性,该问题尚未得到系统性解决。因此,有必要进一步深化研究,现将现存挑战与未来发展方向归纳如下:

1)复杂非线性动力学建模的局限性。加工系统涉及机床-刀具-工件-切削过程的强非线性耦合,包括时变切削刚度、材料本构非线性(如应变率效应、热软化效应等)以及界面摩擦的非光滑特性。传统线性频域分析法(如稳定性叶瓣图理论)难以准确表征高阶模态耦合与分岔行为,而高维非线性微分方程的解析求解面临计算复杂性和参数敏感性问题。对此,可结合微观切削机制与宏观系统动力学构建跨尺度颤振模型,采用模型降阶技术(如本征正交分解法)降低高维非线性系统计算复杂度,同时引入数据驱动方法(如神经网络代理模型)补偿物理模型未建模动态特性。

2)多物理场耦合机制的解耦难题。颤振本质上是机械振动、热力学效应(切削热诱导的材料相变)、流体阻尼(切削液作用)等多物理场交互作用的结果。现有模型多基于单一物理场假设,忽略了热-机耦合变形对刀具动态特性的影响,导致预测精度受限。例如,高速切削中切削热引起的刀具热膨胀会显著改变刀具-工件接触刚度,但此类多场耦合效应尚未被充分量化。亟须开发集成机械振动、热传导、流体动力学的全耦合数值模型,利用有限元-光滑粒子流体动力学(Finite Element Method-Smoothed Particle Hydrodynamics, FEM-SPH)混合算法模拟材料去除与颤振的相互作用。结合数字孪生技术,实现加工系统物理模型与实时监测数据的闭环反馈。

3)材料去除过程的动态不确定性。工件材料的动态力学行为(如动态屈服强度、断裂韧性等)受切削参数(切削速度、进给量等)和微观组织(晶粒取向、缺陷分布等)的显著影响。现有本构模型在极端变形条件下的适用性不足,且难以嵌入连续介质力学框架下的颤振动力学模型,导致颤振临界条件预测存在偏差。需进一步开展不确定性量化与鲁棒稳定性分析研究,探索智能材料(如压电致动器)与拓扑优化结构在被动减振中的应用潜力。

4)传感器信号优选问题。当前尚未形成关于何种传感器信号最适合颤振检测的终极结论,导致多种传感器信号被用于颤振检测辨识。值得注意的是,现有研究多基于单一信号开展分析,而实际加工过程中

信号易受污染且可能伴随突发损伤,这些因素会降低试验数据的可信度并导致决策偏差。为此,多信号融合技术展现出应用潜力,但由于加工条件的时变性与复杂性,传感器组合(包括类型与数量)的选择难以同时保证检测精度与系统鲁棒性。

5)实时信号处理方法创新。信号处理的本质是从原始信号中提取有效特征信息。如第2节所述,现有方法均存在局限性。基于此,可首先将原始信号分解为若干子信号,筛选对颤振敏感的子信号进行重构,再对重构信号进行特征提取。该思路在在线颤振检测中具有开发价值。为实现实时检测目标,亟须开发快速有效的原始信号处理方法,以显著降低计算耗时。

6)特征选择机制优化。特征选择对分类精度具有决定性影响。与传感器信号选择类似,特定特征难以适配不同切削工况,因此多特征融合已成为提升分类精度的主流方案。但随着特征数量的增加,特征空间维度与计算复杂度呈同步增长趋势。此时,特征选择算法对于消除冗余特征、提升辨识性能至关重要。针对此问题,通过组合2种及以上特征选择方法对特征进行排序、评分,开发多准则融合算法,解决特征选择鲁棒性与准确性问题。

7)数据库创建需求。无论是阈值法还是智能识别算法(如支持向量机、卷积神经网络等),充足的数据样本都是保证分类精度的前提。基于此,需创建包含切削过程数据的专用数据库,可有效缩短训练时间并提高分类精度。此外,实时检测系统的实现还需依赖大容量存储设备、高性能计算单元以及更快速的智能识别算法。

8)颤振抑制策略创新。现有研究基于不同加工方式已提出了诸多行之有效的颤振抑制方法,但面向工程化和智能化的颤振抑制技术还不成熟。通过多学科融合(如材料科学、控制理论、人工智能等)与动态自适应技术,构建“感知-分析-决策-执行”全链路智能抑制体系,突破传统单一方法的局限性。同时,面向高精度、高柔性、绿色制造需求,颤振抑制将从“事后补偿”转向“事前预测-事中控制-事后优化”的全生命周期管理。

### 4 结论

加工过程中颤振问题会影响工件的表面质量与轮廓精度,制约精密零部件加工水平。为实时揭示切削状态并减轻其影响,针对颤振检测与抑制已开展了大量研究。本文从信息感知、信号处理、特征提取与模式分类4个维度,系统综述了传统分析与试验方法及最新人工智能(Artificial Intelligence, AI)在颤振检

测中的应用现状。围绕主动颤振抑制、被动颤振抑制和参数调整抑制三大策略,分别介绍了其在加工过程中解决颤振问题的应用成果。此外,还讨论了当前存在的问题和潜在的解决方案。根据现有文献,可得出以下结论:

1)频域法受线性时不变假设的制约,只能通过线性逼近求解非线性模型。时域法能处理非线性和时变系统,可以直接模拟瞬态响应,但对于高自由度系统,高计算成本和较低参数敏感性限制了其工业级应用。针对非线性时变切削工艺系统,时频域法更适用于颤振识别。

2)尽管力信号和加速度信号在颤振检测中被认为更为可靠,但由于测力仪体积大、成本高及加速度计安装技术复杂,限制了其工业应用。多传感器融合获取颤振特征已成为一种趋势,合理地选择和布置传感器显得尤为重要。

3)阈值法虽具有直观性和计算效率高等优势,但其鲁棒性与自适应能力显著弱于智能识别系统。以阈值-智能混合系统与物理引导的边缘学习框架可较好地平衡效率、精度与泛化性。

4)当前AI模型(卷积神经网络、深度神经网络等)存在“黑箱”特性,其决策机制难以解释,限制了其在工业场景的信任度。基于融合物理模型与数据驱动方法,通过数字孪生技术实现虚实映射的颤振预测,可推动加工过程颤振检测从单一算法应用向“数据-机制-控制”协同的智能系统演进。

5)减少甚至避免颤振是研究颤振的目标,揭示颤振的产生机制,判断不同类别颤振的起始与占比情况,确定颤振产生的源头,进而采取对应方法进行抑制。因此,可建立颤振检测-抑制协同机制,通过模型预测控制实现动态参数优化,形成智能机床的闭环生态系统。

尽管颤振检测与抑制研究已取得显著进展,但在传感器信号融合、实时信号处理架构、高判别性特征设计、跨工况数据库创建及多传感器系统集成等方面仍面临诸多挑战。未来的研究应着重于开发更加灵敏、可靠的检测方法,如多传感器信息融合技术和先进的智能算法。在抑制技术方面,需进一步探索高效、经济的主动控制策略,结合数字孪生和工业互联网等新兴技术,强调检测与抑制技术之间的协同作用,特别是通过在线系统和自适应控制策略,有望实现切削过程的智能监测和优化控制,提高加工稳定性和生产率。

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## A review of machining chatter detection and suppression research

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**Abstract:** As a typical self-excited vibration phenomenon in metal cutting processes, chatter leads to deteriorated machining surface quality, manifested by texture fluctuations, increased dimensional errors, and compromised surface integrity. Effective detection and suppression of chatter is crucial for ensuring machining efficiency and enhancing component performance. Current research has established a multi-dimensional technical framework encompassing physics-model-based offline prediction methods, multi-sensor signal-dependent experimental detection schemes, and intelligent algorithm-integrated online monitoring frameworks. However, existing review literature lacks in-depth dissection of this domain. Addressing this gap, this study conducts a systematic technical review and analysis focusing on chatter detection and suppression technologies. For chatter detection, an analytical-experimental dual methodological framework is established, emphasizing the dissection of applicability scenarios and performance boundaries of various techniques. In terms of chatter suppression, a triple control strategy classification system integrating active-passive-parameter adjustment is constructed, comparing implementation costs and vibration attenuation effects of different solutions. Based on multi-dimensional technical comparisons and cross-disciplinary method integration, existing challenges and potential solutions in this field are explored, providing comprehensive theoretical support and technical references for subsequent research.

**Key words:** Cutting process; Chatter detection; Chatter suppression; Intelligent algorithm

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