MILLING DYNAMICS UNDER LOW STIFFNESS CUTTING CONDITIONS: A BRIEF REVIEW OF MODELING AND ANALYSIS

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Abstract

Dynamic milling system responses change ideal cutting teeth trajectories, decreasing machining accuracy. When milling thin-walled materials or using slender tools, cutting vibrations may reach tens or hundreds of micrometers. Moderate cutting settings reduce cutting loads, milling noise, and dynamic deflections. Productivity plummets. Modeling, evaluating, monitoring, and regulating the dynamic milling process under low-stiffness cutting conditions is tough despite decades of study. This paper summarizes dynamics modeling and response analysis advancements and research challenges.

Keywords: *Milling;* ***Low****-stiffness; Dynamic model; Response analysis; Chatter; machining quality*

Introduction

Milling accuracy depends on cutting teeth motion trajectories, which include machining feed, teeth rotation, and system vibrations 1,2. Vibration amplitudes are usually smaller than the machining tolerance and are not considered when selecting tool path and cutting parameters. If the milling system's dynamic stiffness is low, machining vibrations may reach tens or hundreds of micrometers, which cannot be disregarded. The milling system's flexibility may come from Figure 1's thin cutting tool 5, thin-walled workpiece 5, flexible fixture 6, and/or flexible fixture 6.

Low stiffness has two effects on the dynamics of milling:

Regenerative chatter or mode-coupling chatter limits the chatter-free material removal rate (MRR) and threatens surface roughness and dimension accuracy, increasing the chance of substandard goods. Since the 1950s, academics and industry have studied milling dynamics. 8,9. These studies are grouped by dynamics modeling, response analysis, process monitoring, and vibration control. To understand and optimize milling dynamics in low-stiffness circumstances, the following difficulties must be resolved:

Modeling dynamics. Conventional dynamic model simplifications and assumptions may no longer apply. Since vibration amplitudes approach the nominal chip thickness in low-stiffness circumstances, system responses and cutting loads must be coupled. 10. reaction analysis. Milling chatter prediction and suppression have garnered attention for decades. Chatter-free cutting is not usually high-quality cutting. 11. Quantitative links between cutting parameters, system responses, and cutting quality (deflection error and surface roughness) may be improved.

observe process. High interrupted milling forces under low stiffness generate bifurcations with different signal characteristics. 12. With tool feed and material removal, system dynamics may alter, making non-stationary signals hard to monitor. Vibration control. Controlling milling vibrations has been suggested by optimizing process parameters 14, designing tool geometry 15, using fixtures

16, and other methods, but there are no clear guidelines on how to choose, improve, and tune control schemes 9, especially in low-stiffness cutting conditions where dynamics may change with machine configuration and material removal.

This paper briefly discusses the first two aspects dynamics modeling and response analysis under low-stiffness cutting conditions and current research breakthroughs and difficulties.

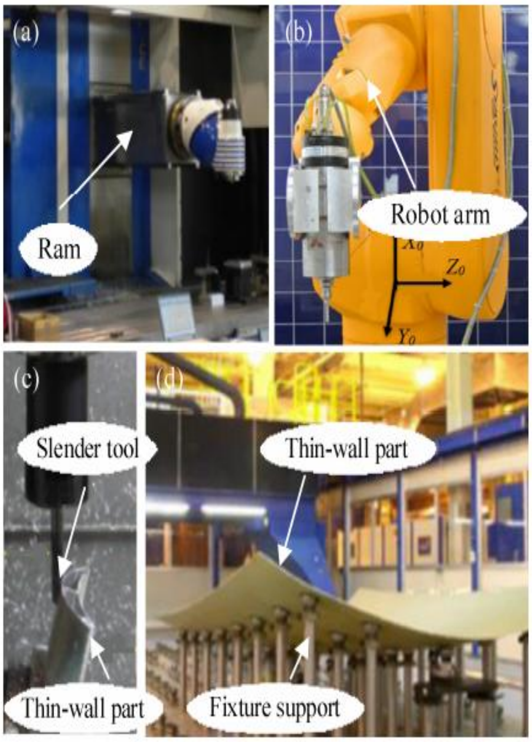


Fig. 1 Sources of flexibility in milling systems 3-6.

2. Dynamics Modeling

Figure 2 shows how the dynamics model maps the relationship between milling inputs (such as tool shape and runout, cutting parameters, cutting force coefficients, and frequency response function) and system responses (such as vibration displacement, velocity, and acceleration).

Dynamic model

Inputs for milling, such as tool form and runout, cutting parameters, cutting force coefficients, and frequency response function, are mapped to system responses, such as displacement, velocity, and acceleration, in Figure [1,17]:

$$M\ddot{Q}(t)+C\dot{Q}(t)+KQ(t)=F\left(t,Q(t),Q\left(t-\tau(t)\right),\dot{Q}(t)\right)$$

The cutting force F() relies on time t, the present vibration displacement Q(t), the previous vibration displacement Q(t (t)), and the vibration velocity Q t. M, C, and K are the mass, damping, and stiffness matrices, respectively. Vibration displacement Q(t).

Eq.'s size depends on its discrete mass nodes and vibration directions. A concentrated load on the tool's free end describes the cutting force. However, Yang et al. 18 showed that the simplicity of a single node may lead to erroneous stability prediction for peripheral milling of thin-walled components with significant axial depth of cut and recommended the multi-node dynamic model 19.

Modal space is used to analyze reaction to the dynamic model in Eq. Modal mod el size depends on mode count. Wan et al. 20 used a lowest envelop approach to separate the dynamic model into single-mode DDEs, reducing stability prediction computation cost. Zhang et al. noted that the cutting force is closely tied to all modes' dynamic responses, hence unique modes cannot be completely separated. For low-stiffness circumstances, mode coupling worsens milling stability and surface quality with large-amplitude vibrations 22.

Cutting forces

The most popular model is mechanistic model 17, which develops the link between cutting geometry and cutting forces. By dividing the cutting forces into four parts—the quasi-static shearing force F cs, the regenerative shearing force F dc, the edge ploughing force F es, and the process damping force F ed—Kilic and Altintas 23 further increased its precision.

$$\boldsymbol{F}\left(t,\boldsymbol{Q}(t),\boldsymbol{Q}(t-\tau(t)),\dot{\boldsymbol{Q}}\right.$$

$$\boldsymbol{F}^{\mathrm{cs}}(t)+\boldsymbol{F}^{\mathrm{cd}}\left(t,\boldsymbol{Q}(t),\boldsymbol{Q}(t-\tau(t))\right)+\boldsymbol{F}$$

CWE must be determined to estimate cutting forces. Three-axis milling CWEs may be calculated analytically. Five-axis milling CWE depends on tool axis origin. Complex computational methods are required. These approaches include developed modeling 26, solid modeling 25, and concrete modeling 24.

Tool geometry and runout are highly related to CWE. Axial discretization allows CWE determination for any tool shape. Runout changes tooth ECRs. As shown in Fig. 3, there are three runout models: (1) the flute-to-flute model, which has a constant ECR; (2) the radial runout model 29, whose ECR changes with tool axis due to the helix angle; and (3) the tilt runout model, whose ECR changes due to both the tool helix angle and the tilt offset angle. The radial runout model balances model accuracy and identification effectiveness 30.

It's noteworthy that low-stiffness cutting reduces the radial depth of cut and feed per tooth. Thus, the system response's amplitude approaches the nominal instantaneous chip thickness and cannot be ignored when computing CWE.

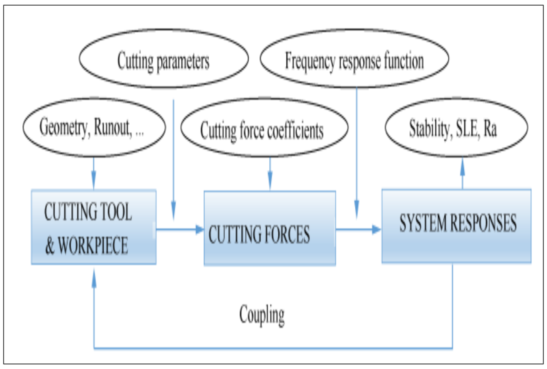
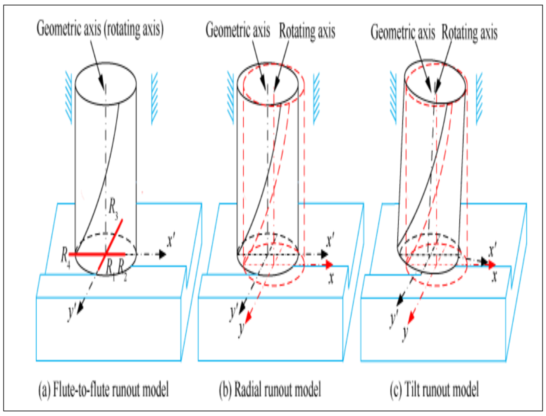


Fig. 2 Schematic of mapping from system inputs to response outputs.



(a) Flute-to-flute runout model (b) Radial runout model (c) Tilt runout model

Fig. 3 Schematic of runout models.

With their investigation of the impact of quasi-static deformation on cutting forces, Sun and Jiang 31 were able to predict stability in thin-walled plate milling operations with greater accuracy. In milling conditions with a thin cutting tool, Totis et al. 10 thoroughly examined the coupling relationship between system vibrations and cutting forces. It said that under low-stiffness circumstances, the actual cutting volume varied significantly from the nominal values.

System identification

The geometry of the tool and workpiece, real cutting parameters, cutting force coefficients, and frequency response function (FRF) must be calculated to compute system responses, as shown in

Fig. 2.

Workpiece and tool geometry. Thin-walled blanks may deviate from the CAD geometry due to form error or installation error, thus they must be measured in-situ before machining. Each insert 33 must be measured and oriented to represent the inserted cutting tool properly.

Finding the CWE. Force prediction, response analysis, and error control need accurate CWE computation. As shown in Section 2.2, CWE and system responses are closely related. Reference calculates actual CWE using a tedious simulator. Research is needed to integrate system responses in the dynamic model concisely.

FRF ID. Bravo et al. suggest considering tool and workpiece flexibility when predicting stability. Response analysis with several modes is computationally demanding. The machine-workpiece FRF determines the right mode reduction. Experimental modal analysis (EMA) determines the tool's FRF. Schmitz and Donalson 36 proposed the receptance coupling substructure analysis (RCSA) to semi-analytically predict the FRF at the free end of the instrument to reduce EMA test burden. Ertürk et al. improved RCSA accuracy by Timoshenko beam modulation. RCSA prevents repeated EMA when the tool's overhang length changes. The different multi-axis milling machine configurations impact the tool's FRF, which is hard to predict. 38,39. When the cutting location is altered and material is continually removed, the FRF of a thin-walled workpiece changes, making it difficult to calculate using EMA. Alan et al. pioneered component dynamics prediction via structural change. Budak et al. 41 developed this method to predict thin-walled blade in-process workpiece dynamics. Song et al., Yang et al. 18, Tuysuz and Altintas and others have suggested updating thin-walled workpiece dynamics. The above methods cannot totally replace the experimental modal test. The damping ratio cannot be predicted theoretically. Analytical methods like finite element analysis depend on the quantity of material removed and the boundary conditions, which are difficult to predict.

Runout and cutting force coefficients. Cutting force coefficients affect CWE-cutting force mapping accuracy. First, orthogonal transformation may determine cutting force coefficients. Budak et al., developed a generic oblique cutting analysis method to calculate cutting force coefficients for any tool geometry. Tool geometry and orthogonal data—shear angle, friction coefficient, and shear stress—are used in this method. Linear fitting. Since edge force components are independent of feed rate, cutting tests may linearly calculate cutting force coefficients. This method cannot concurrently identify runout parameters. Nonlinear optimization. Non-linear optimization 30,46 may simultaneously determine cutting force coefficients and runout parameters. Number 4. FEMs can represent cutting forces without expensive dynamometers. However, simulation inputs—including material parameters and tool geometry—determine prediction accuracy.

Response Analysis

Based on the dynamic model, response analysis seeks to evaluate the milling stability (i.e., whether chatter will occur) and machining quality (including dimension inaccuracy and surface roughness).

Chatter stability

Estimating milling stability under low-stiffness cutting is important since stability restrictions are generally low. Stability analysis methods fall into three categories: frequency-domain method. Altintas and Budak (48) only preserved the zero order term (ZOA) using Fourier series to mimic periodic cutting forces to meet analytical stability limits. ZOA quickly and accurately generates stability lobe diagrams (SLDs), but it cannot predict periodic doubling chatter in high-interrupted milling. Budak and Altintas 49, Merdol and Altintas 50 offered multi-frequency solutions with higher-order Fourier series to demonstrate prediction accuracy for low radial depth of cut. Higher frequency components reduce computation efficiency and improve stability forecasts, especially for cutting tools with unequal pitch angles. Frequency domain techniques use measured FRF directly, eliminating modal fitting errors. Time-domain methods. Period doubling chatter 53 accelerated time domain approaches for difficult cutting scenarios. Bayly et al. 54 presented Temporal Finite Element Analysis (TFEA) for interrupted milling operations, dividing one spindle rotation time into many in-cutting and out-cutting times. Insperger and Stépán 55, 56 developed the semi-discretization approach (SDM) for milling stability analysis using Floquet theory. Ding et al. built the full-discretization methodology (FDM) 57 and numerical integration method (NIM) 58 on the direct integration scheme. SDM, FDM, and NIM architecture helped build higher-order SDMs 59, 60, 61, the Generalized Runge-Kutta (GRK) approach 62, and others. Interpolation formulae may be used to analyze stationary milling process stability utilizing differential methods. DQM 64,65 and CCM 63 are examples.

Time domain techniques, rather than frequency domain methods, are better for complicated milling circumstances such using cutting tools with distinct geometries (66–68), runout (66,69), spindle speed change schemes (70), etc. Time domain techniques are computationally accurate even for low-stiffness cutting because they do not truncate the cutting force term. However, computation efficiency declines with discretizations. Time domain techniques were advised for stationary milling operation stability, not transient response studies. High-amplitude vibrations under low-stiffness cutting may halt cutting teeth. Fly-over or loss-of-contact nonlinear problems cannot be solved by frequency or time domain techniques.

Time marching beginning values. Step-by-step integrating the dynamic equation under an initial state yields time-history system responses including vibration placement, velocity, acceleration, and dynamic forces. Examine milling stability using response outputs. Tlusty and Ismail 73 used the peak-to-peak force indicator and time marching to study machining chatter's basic nonlinearity. Campomanes and Altintas improved time marching accuracy by using trochoid tooth trajectories and dynamic to nominal chip thickness as the chatter indicator. Schmitz et al. investigated how runout affects chatter stability, surface location error (SLE), and surface roughness using time marching. Sims proposed the self-excitation damping ratio as a chatter indicator to enhance time marching calculation.

Starting value time marching allows stability analysis to incorporate nonlinear factors. Time marching approaches give full time-history responses, making them suited for milling system transient behavior studies. Step-by-step integration adds computer cost, which prevents its broad usage.

Surface topography

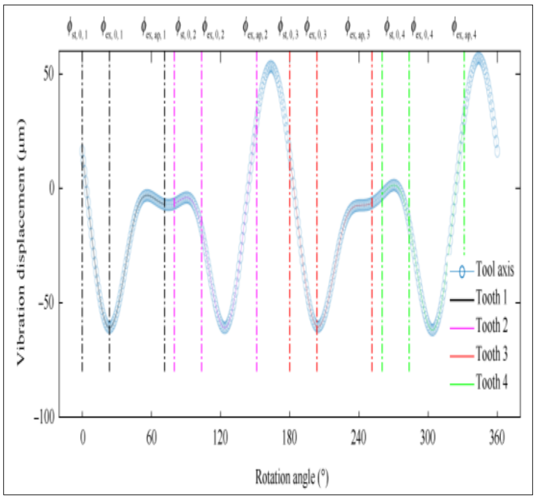
Milling stability research is overemphasized. Steady cutting doesn't necessarily mean good cutting. Cutting force-induced vibrations may also produce SLE and poor surface roughness. Cutting vibrations cause most machining flaws, especially when cutting low-strength metals. Boolean subtraction between the workpiece geometry and the teeth trajectories, which are the kinematic synthesis of the machining feed, teeth rotation, and system vibrations 2, yields the milled surface profile (Fig. 4).

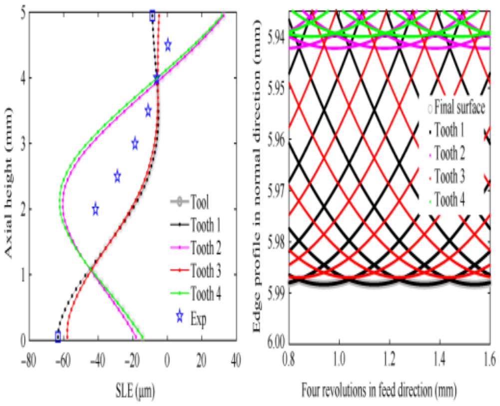
During multi-axis milling, the feed rate may change, resulting in varied cutting forces, system responses, and surface topographies. Xu et al. 81 recently shown that ball-end milling dynamic feed rates significantly affect surface roughness. The milling system in Ref. 81 has high dynamic stiffness, therefore system responses were ignored. Under low-stiffness multi-axis cutting, dynamic feed rate affects surface roughness more complexly. In Section 2.2, runout impacts each cutting element's feed. Runout models explore runout.

Since tooth trajectories transfer to surface topography (Fig. 4), system vibration calculation becomes the main concern. 2. Fourier series-based analytical approaches. Fourier series can compute system frequency domain vibrations from periodic cutting forces. Schmitz and Mann 82 suggested two closed-form SLE computations using harmonic balancing schemes and Fourier series. Bachrathy et al. 83 examined milled surface metrics including SLE and surface roughness using Fourier series. This method is efficient but cannot predict chatter stability since it lacks the regeneration force term.

floquet-based methods. Using established mapping points between two close main periods, Floquet theory-based stability prediction methods may simultaneously calculate the SLE. SLE is calculated using TFEA, SDM, NIM, and DQM. Only Niu et al.'s recent work has used Floquet theory to predict surface roughness. These techniques cannot account for nonlinear occurrences like fly-over or loss-of-contact under low-stiffness cutting.

Time marching beginning values. Time-history dynamic responses may define SLE and surface roughness. Quantifying process parameters, tool geometry, runout values, and system dynamics is also conceivable. Schmitz et al. analyze time marches.





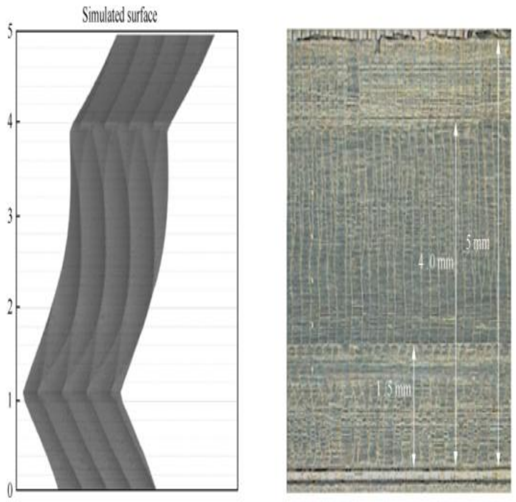


Fig. 4 Mapping from system responses to milled surface 2.

14 looked at how runout affected SLD, SLE, and surface roughness. The surface topography for thin-walled turbine blades was effectively modelled by Biermann et al., as shown in Fig. 5. Initial value time marching approaches' poor computing efficiency is the key issue.

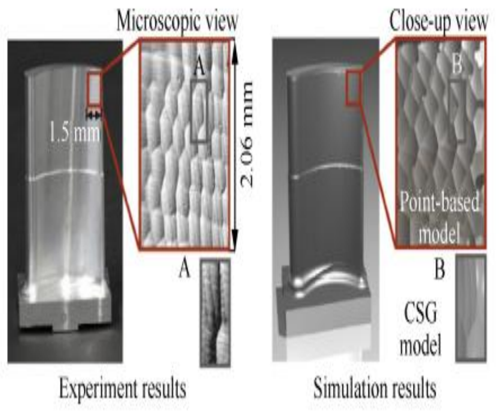


Fig. 5 Simulated and measured surface topographies for turbine blades 78.

Conclusions

Previous works covered the basics of milling dynamics under low-stiffness cutting conditions. This paper's examination of recent advancements suggests the following areas deserve more investigation:

System dynamics precise and effective. Machining may change the milling system's frequency response function. Material removal in milling thin-walled components, spindle speed in high-speed milling, and tool alignment in multi-axis milling all affect FRF. How to integrate EMA and FEM to accurately estimate instantaneous FRF is a research challenge.

An accurate CWE determination. Large-amplitude vibrations affect low-stiffness cutting CWE. CWE lacks analytical expressions. In multi-axis milling, new CWE calculation methods are worth developing.

Fixture effect. Fixtures may control thin-walled component milling vibrations by increasing dynamic stiffness. However, few studies included fixture effects in the dynamics model.

balancing accuracy and efficacy. Response analysis and dynamics model accuracy and efficiency vary. Milling dynamics requires a precision-efficiency tradeoff.

System inputs and machining quality quantified. Milling dynamics aims to generate high-quality, productive, and affordable machined commodities. Chatter-free cutting does not mean high-quality cutting, although milling noise modeling and analysis have received too much research. System inputs like cutting parameters, tool geometry, and fixture setup are not quantitatively mapped to machining quality like SLE and surface roughness.

Due of uncertainty, dynamics modeling and reaction analysis cannot ensure chatter-free high-quality milling. Process optimization cannot expand chatter-free zones. Thus, process monitoring plans and vibration control measures need more study, as detailed in the following article.

Acknowledgements

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