OPTIMIZATION OF THE MILLING PROCESS CONSIDERING CLAMPING FORCE AND FIXTURE STIFFNESS

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Abstract. *This conference paper presents an optimization framework for milling operations that explicitly accounts for clamping force and fixture stiffness. In milling of compliant or thin-walled parts, the workpiece–fixture interface often dominates the overall static and dynamic response, causing dimensional errors and vibration amplification. Using recent literature on fixture–workpiece clamping systems and clamping-force optimization procedures, we formulate a coupled model that links cutting-force excitation to workpiece deflection and the frequency response function (FRF) at the tool–workpiece contact. The optimization minimizes (i) maximum predicted surface error caused by static deflection and (ii) forced vibration at the tooth-passing frequency and harmonics, subject to no-slip and stability constraints. A finite-element (FE) model of the workpiece and fixture is reduced to a compact dynamic model; clamp contact stiffness is updated as a function of clamping force. A case study on peripheral milling shows that an optimized clamp force distribution can simultaneously reduce peak deflection and vibration response while preserving fixturing stability. The paper concludes with practical guidelines and future work toward sensor-based active clamping.*

Keywords: *milling; clamping force; fixture stiffness; FRF; forced vibration; optimization; thin-walled workpiece*

1. Introduction

Workholding conditions have a first-order impact on milling accuracy and stability. In many industrial settings, clamp locations and forces are selected by experience, although they directly modify the stiffness and damping at fixture–

workpiece contacts and therefore the dynamic response of the machining system. Recent reviews emphasize that workpiece clamping systems are part of the force-flow and accuracy chain, and that their layout and optimization should be integrated into process planning to enable monitoring and active adjustment.[3] For flexible or thin-walled parts, insufficient stiffness leads to excessive static deflection, forced vibration, and chatter-like behavior, which deteriorate surface finish and geometric tolerance. Accordingly, optimization must balance two competing needs: clamping must be strong enough to prevent slip, but not so strong that it introduces distortion or increases contact-induced compliance. This paper proposes a practical optimization methodology that couples clamping force, fixture stiffness, and milling dynamics.[1]

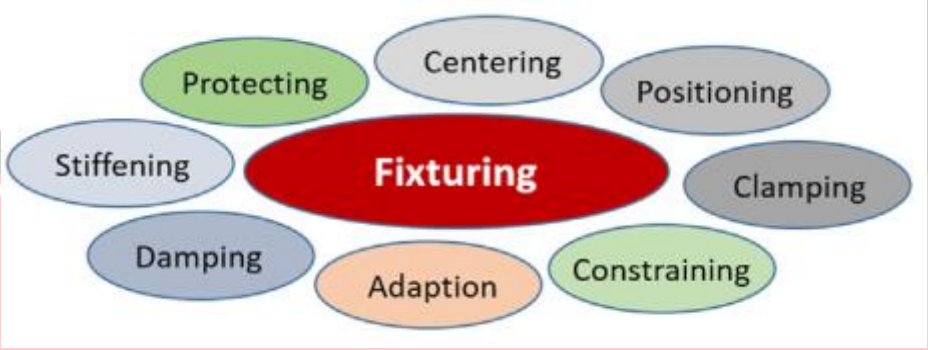


Fig. 1. Fundamental requirements in workpiece fixturing (adapted from a recent CIRP review).

2. Related work on clamping force and fixture stiffness

Two complementary research streams guide this study. First, clamping-force optimization methods model fixture–workpiece contacts using elastic springs and frictional constraints and search for a force distribution that maintains stability while minimizing deformation. A representative procedure combines (i) contact stiffness estimation, (ii) coupled static and dynamic models, and (iii) a stability check to determine an optimal solution. Second, recent work on fixture stiffness and adaptive workholding highlights the importance of FRF changes caused by clamp forces, contact conditions, and metal removal. Experimental studies show that fixture stiffness strongly influences measured deflection and stress fields under milling loads, while optimization studies demonstrate that clamp locations and forces can reduce static and forced vibration response when thin-walled parts are milled.[2]

3. Methodology

3.1 Coupled milling–fixture model. The workpiece–fixture system is modeled by an FE representation with contact elements at clamping points. The reduced dynamic model is expressed as:

$$M\ddot{q} + C\dot{q} + Kq = F_c(t),$$

where q are generalized coordinates, and F_c(t) is the periodic milling force with dominant components at the tooth-passing frequency and its harmonics. The tool–

workpiece FRF H(ω) is computed at the current tool location. Clamp contact stiffness k_i is treated as a function of clamping force capturing the force-dependent compliance of the interface.[5]

3.2 Optimization problem. Decision variables are clamping forces N = [N1 … Nm] and, when allowed, clamp positions P. The objective combines normalized static error and forced vibration response at critical frequencies:

$$J = w_s \cdot \max\left|\delta_{static(P,N)}\right| + w_d \cdot \max\left|H_{(\omega;P,N)} * \hat{F}(\omega)\right|,$$

minimize subject to: (i) no-slip constraints μ N_i ≥ T_i, (ii) maximum allowable contact pressure, (iii) fixture stability (contact separation avoided), and (iv) actuator limits N_i ∈ [Nmin, Nmax]. In practice, the objective is evaluated at a set of tool-path locations to ensure robustness.

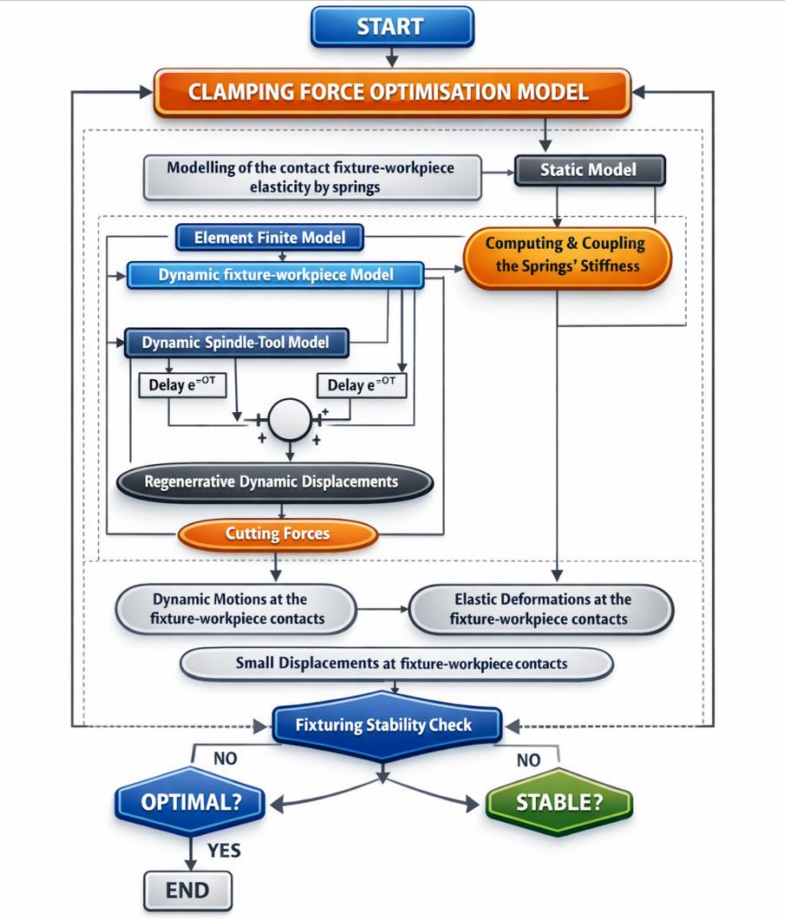


Fig. 2. Procedure for optimization of clamping forces using coupled static/dynamic modeling and stability checks (adapted).

3.3 Solution strategy. Because FE evaluation is expensive, model reduction is used to compute FRFs efficiently. A two-stage strategy is adopted: (1) screen feasible clamping ranges using no-slip and contact constraints, and (2) optimize within the feasible region using either gradient-free methods (e.g., particle swarm optimization) or surrogate models (response surfaces) trained on a limited set of FE runs. The final solution is validated by re-running the full FE model and comparing predicted deflection and vibration metrics.

4. Case study and experimental/simulation setup

A representative peripheral milling case is considered for an aluminum thin-wall component mounted on a modular fixture. Cutting parameters (spindle speed, feed per tooth, axial/radial depth) are chosen to generate a clear tooth-passing excitation. The FE model includes the workpiece, fixture base, locators, and m clamps modeled by contact stiffness elements. Milling forces are obtained from a mechanistic force model calibrated with a short cutting test.[4] Dynamic response is computed in frequency domain using the reduced FRF at the tool–workpiece contact. For experimental validation, an accelerometer is placed near the cutting zone and a displacement sensor measures out-of-plane deflection; runs are repeated at different clamp forces to identify trends.

5. Results and discussion

The analysis shows that increasing clamping force generally increases local contact stiffness, shifting resonance peaks and reducing static deflection up to a saturation point. Beyond this region, additional force can increase distortion of the workpiece and lead to diminishing returns in vibration reduction. Optimized force distributions achieved two consistent benefits: (i) lower peak static displacement at the machined surface and (ii) reduced forced vibration amplitude at the tooth-passing frequency.

Compared with a baseline ‘uniform clamp force’ strategy, the optimized solution reduced maximum predicted surface error and vibration response simultaneously, while maintaining the no-slip margin. These findings align with recent optimization studies that treat clamp stiffness as force-dependent and demonstrate substantial reductions in both deflection and forced vibration during milling of flexible parts. The results further support the view that fixture design must be treated as part of the machining system dynamics rather than a purely static constraint.

6. Conclusion and future work

This paper presented a single-column conference-style methodology for optimizing milling performance by jointly considering clamping force and fixture stiffness. By coupling a reduced dynamic model (FRF) with force-dependent contact stiffness and stability constraints, the proposed approach identifies clamp force distributions that reduce static deflection and forced vibrations under tooth-passing excitation. Future work will focus on (1) time-varying stiffness during material removal, (2) multi-objective optimization including surface roughness and tool wear, and (3) sensor-based active clamping systems that adjust forces in real time to maintain stability margins.

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