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Hardware-in-the-loop Experiments on an Active Turning Tool with Robust LPV Control of Chatter Vibration

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About Dr. Ziv Brand

Dr. Ziv Brand is the Head of the Control Research Center and a senior lecturer in the Department of Mechanical Engineering at SCE - Shamoon College of Engineering, Be'er Sheva. His research interests include control systems engineering, active vibration control, magnetic bearings, and structural dynamics. His research activities include theoretical, numerical, and experimental work, as well as the adaptation and implementation of control systems for various engineering applications.

Ziv completed his B.Sc. in Electrical Engineering and his M.Sc. and Ph.D. in Mechanical Engineering. He has over 22 years of industry experience as a researcher in control systems and dynamics, as well as in senior management roles.

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Presentation Outline

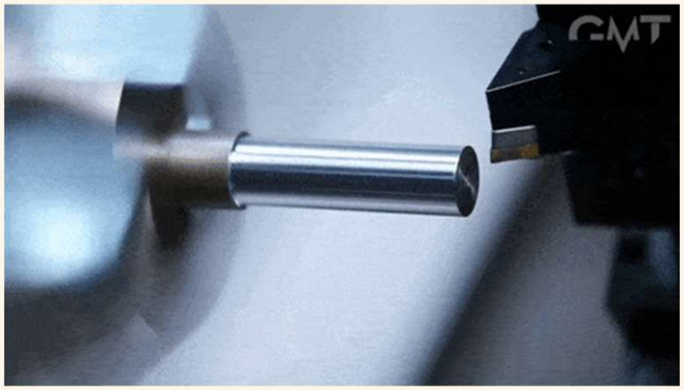
1. Introduction
    - Overview of chatter vibration in turning processes
    - Research motivation and objectives
2. Problem Definition
    - Chatter vibration and its effects
    - Challenges in vibration suppression
3. Robust LPV Control Design
    - LPV framework and control strategy
    - Key features of the proposed method
4. Experimental Setup
    - Hardware-in-the-loop testing 3
    - Measurement and validation methods
5. Experimental Results
    - Vibration reduction analysis
    - Performance evaluation and comparison
6. Conclusions & Future Work
    - Key takeaways from the study
    - Future research directions

Background and Introduction

Turning process

A turning process is a machining operation in which a cutting tool removes material from a rotating workpiece to shape it into the desired form, typically producing cylindrical or conical surfaces.

Classification of Turning Processes



External Turning

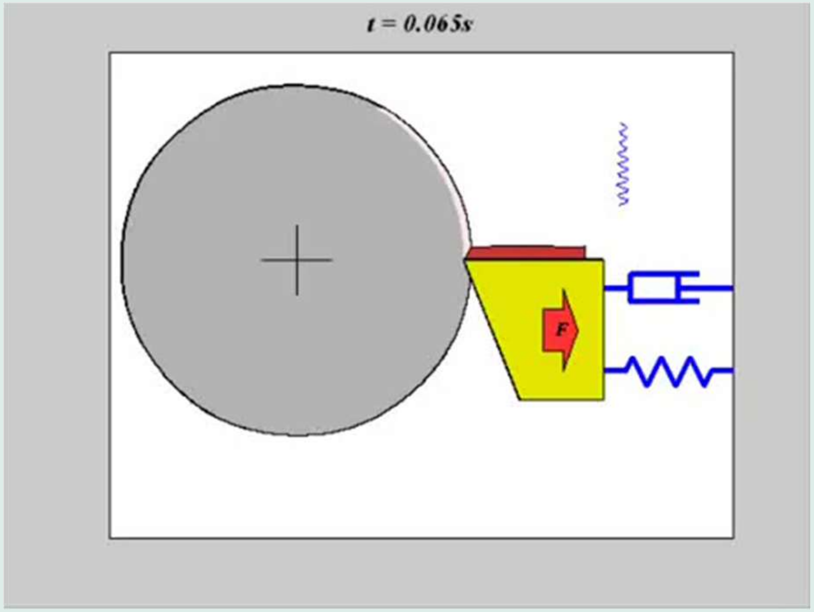
Internal Turning (Boring)

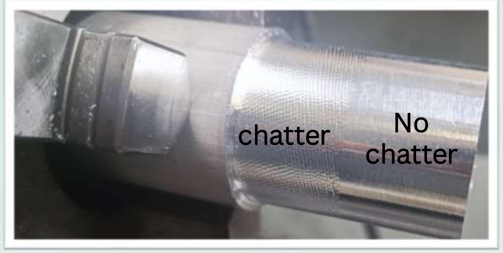
Background and Introduction

Machining vibration

- **Focus on the problem of suppressing vibrations in turning.**
    - Tool interaction involves time-varying forces due to chip formation and removal.

- Vibration affects the workpiece and causes a time-delayed feedback effect that can induce instability, referred to as **"chatter"**.
- Chatter involves a specific vibration frequency and a cycle of periodic deflections, which damages surface quality, increases noise, and accelerates tool wear.





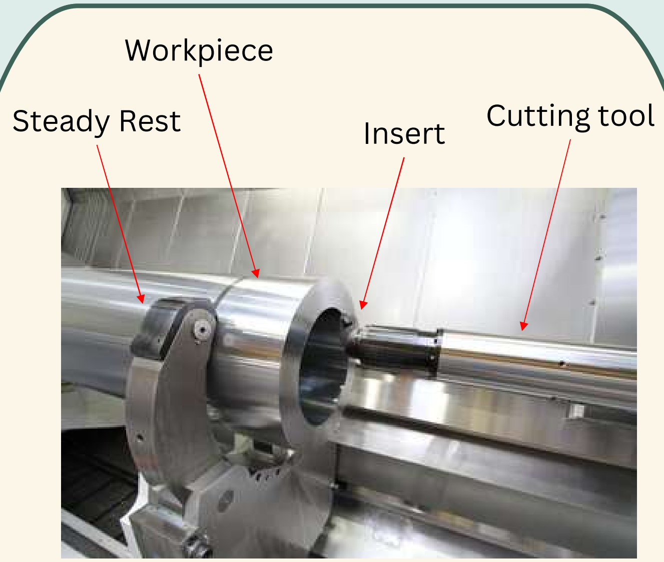
Background and Introduction

Turning Process in machining

- The workpiece rotates around its symmetry axis, mounted on a spindle
- An internal cutting tool acts with the surface to remove material.
- Low stiffness, low resonance frequencies, and low damping in the cutting tool can lead to chatter.

Internal Cutting Tool

- The natural frequencies of flexible modes make the prediction and suppression of vibration challenging.



Internal turning process
(From web: NSH group)

Background and Introduction

Market Demands

- Increasing Overhang-to-Diameter Ratio.
- Improving Surface Finish Quality
- Increase Productivity
- Reducing Component Wear
- Operational Flexibility
- Real-Time Monitoring and Recommendations

VS

Market Supply

Generation Tools

Anti-Vibration Solid Carbide up to 14D

Anti-Vibration Steel Shank up to 10D

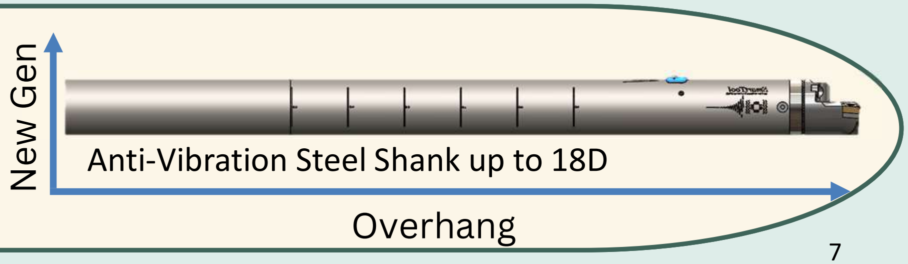
Solid Carbide up to 7D

Steel Shank up to 4D

Overhang

Our Focus

- A New Generation Based on Advanced Technology



New Gen

Anti-Vibration Steel Shank up to 18D

Overhang

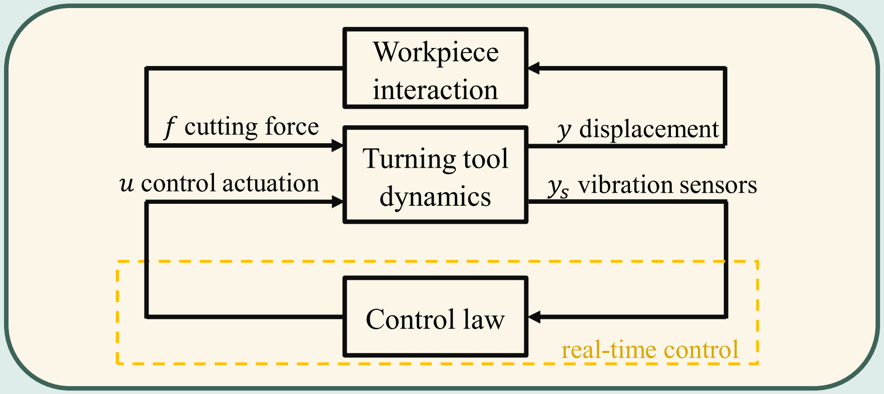
Background and Introduction

Strategies to reduce vibration and prevent chatter

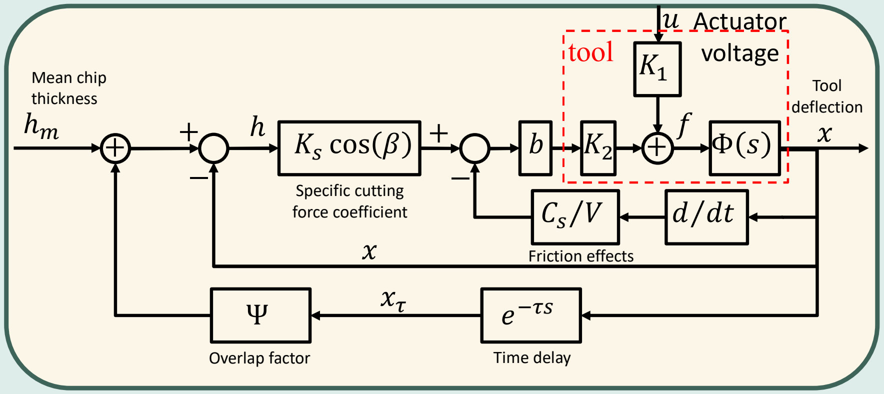
- Based on active control methods.
- Adding actuators and sensors to the system with a feedback control algorithm that modifies the system dynamics.
- For increasing damping levels of the problematic vibration modes.

Cutting tool model

- **Time-dependent displacements** from previous and current cutting revolutions affect cutting dynamics.
- **Stability boundary equation:** $b_{lim} = \frac{-1}{2\Psi K_s \cdot \cos(\beta) Re[G(j\omega_c)]}$.
- **Friction between the insert and workpiece** introduces damping effects.
- **Key Properties**: Parametric uncertainty, Uncertain time-delayed feedback, unmodeled and Unmodeled and uncertain higher-order modes



The block diagram for vibration control of the turning process



The block diagram for turning process with active tool

Robust LPV Control

Characteristics of Robust LPV Control

- **Adaptive Control:** Adjusts robustness/gain properties in real-time within a workshop environment.
- **Uncertainty Handling:** Designed to mitigate parametric uncertainty in machining processes.
- **Time-Delayed Feedback Compensation:** Accounts for cutting force effects that influence stability.
- **Spillover Prevention:** Reduces instability caused by unmodeled higher-order modes.

Objectives

- ◎ **Stabilize Unstable Machining Processes** → Ensure a smooth and controlled cutting operation.
- ◎ **Improve Surface Quality & Tool Life** → Minimize vibrations that degrade cutting efficiency.
- ◎ **Enhance Real-Time Adaptability** → Enable the system to adjust based on varying cutting conditions.
- ◎ **Validate Control Effectiveness** → Demonstrate performance through lathe experiments and cutting emulation tests.

Key Features

- ☑ **H_∞ Based Controller** → Ensures robust performance under varying conditions.
- ☑ **LPV Framework** → Dynamically adapts control parameters for optimal vibration suppression.
- ☑ **Lab Experimental Validation** → Cutting emulation tests confirm a **65% reduction** in chatter vibration..
- ☑ **Lathe Machine Experiments:**
  - **Unstable cutting: RMS vibration reduced >95%**, peak-to-peak **~90%**, enabling higher material removal and better surface finish.
  - **Stable cutting: Vibration reduction 10%–50%**, depending on cutting parameters.
- ☑ **Practical Implementation** → Designed for **real-world machining applications**.

1-DOF Turning Process Model

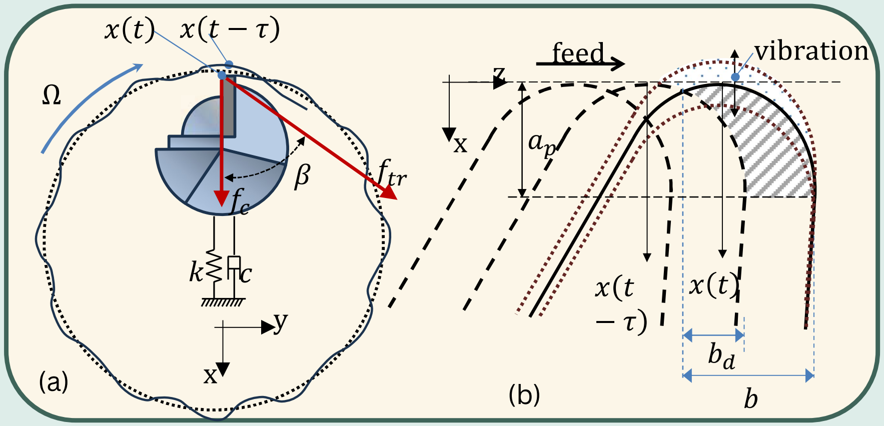
$$m\ddot{x}(t) + \left(c + C_s\frac{b}{V}\right)\dot{x}(t) + (k + K_s b\cos\beta)kx(t) - K_s b\cos\beta\,\Psi x(t-\tau) = Ku(t) + K_s b\cos\beta\, h_m(t)$$

$G_0 = G + \Delta_m G,$

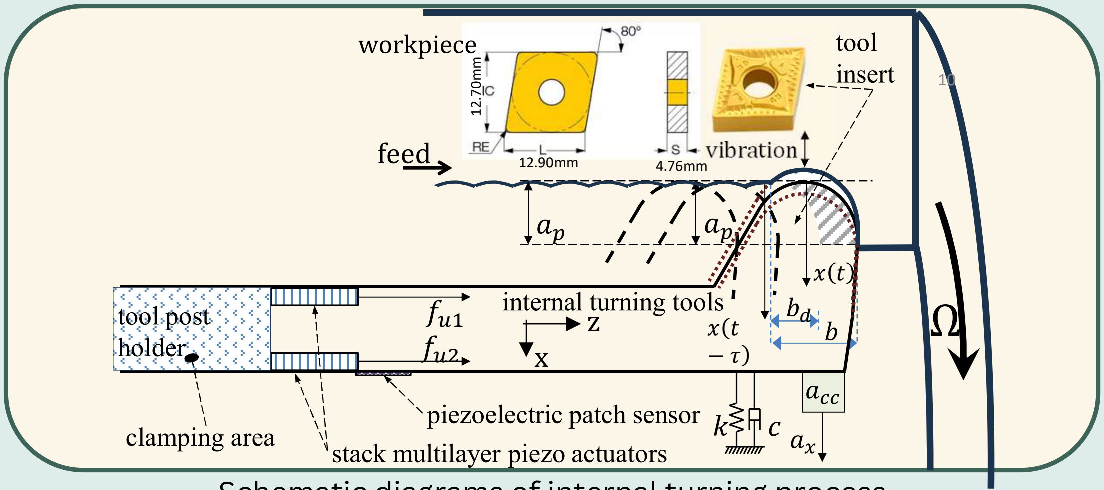
$G_0(s)$ - actual system dynamics, $G(s)$ - model transfer function, and $\Delta_m(s)$ - multiplicative error factor

$$X(s) = \Phi(s)\cdot\left(K_1\cdot U(s) + K_2\cdot F_c(s)\right)$$

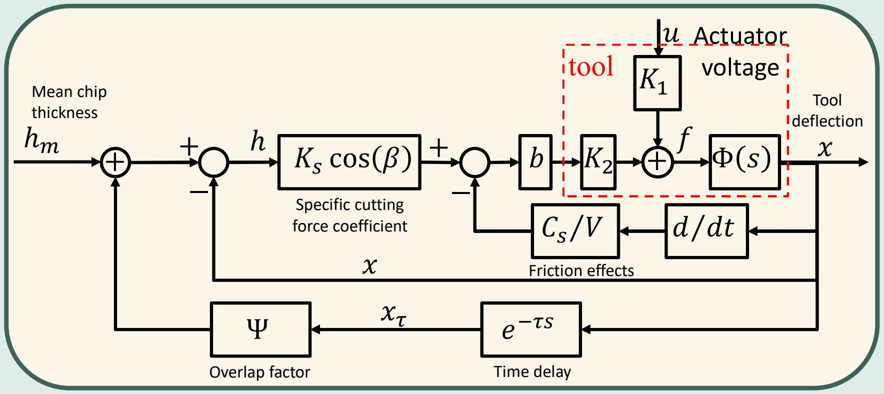
$$\Phi(s) \triangleq \frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$



Schematic diagrams of internal turning process (a) lumped system (b) insert vibration.



Schematic diagrams of internal turning process



The block diagram for turning process with active tool

Robust Control for Cutting with Delayed Feedback

1. Robust Stability under Delayed Feedback:

$$\left\|T_{xx_\tau}(K_c,\kappa)\right\|_\infty < 1 \leftrightarrow \|\kappa T_{xd}(K_c,\kappa)\|_\infty < \Psi^{-1}.$$

where $\kappa = K_2 K_s b \cos\beta / K_1$.

2. Forced Disturbance Attenuation:

$$\left\|W_1 T_{xh_m}(K_c,\kappa)\right\|_\infty < 1 \leftrightarrow \|\kappa W_1 T_{xd}(K_c,\kappa)\|_\infty < 1,$$

$W_1(s)$ - weighting function representing the disturbance spectrum.

3. Robust Stability under Model Error (Δ_m):

$$\left\|\Delta_m T_{fd}(K_c,\kappa)\right\|_\infty < 1 \leftarrow \|W_2 T_{ud}(K_c,\kappa)\|_\infty < 1,$$

$W_2(s)$ - chosen to satisfy $|W_2(j\omega)| > |\Delta_m(j\omega)|\ \forall\ \omega$.

The LPV control synthesis can be formulated using LMIs, solvable through convex optimization techniques.

$$\dot{x} = A(\kappa)x + B_w(\kappa)w + B_u u$$
$$z = C_z(\kappa)x + D_{zw}(\kappa)w + D_{zu}u$$
$$y = C_y x + D_{yw}w + D_{yu}u$$

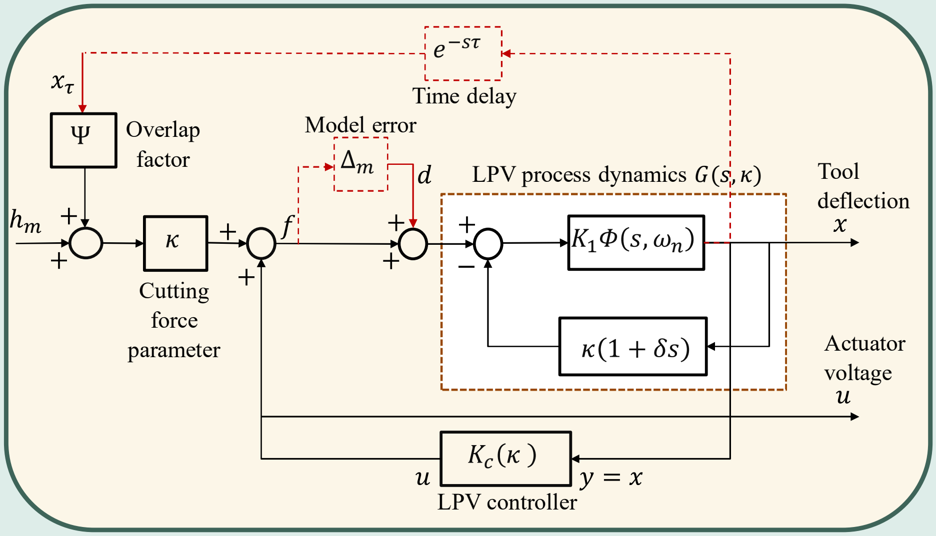
The LPV controller solution is similarly parameter-dependent:

$$K_c(\kappa) = [A_c(\kappa), B_c(\kappa), C_c(\kappa), D_c(\kappa)]$$

The controller is synthesized by solving the LMIs for the set of vertex systems, producing vertex controllers to form the parameter-dependent controller matrices. For this problem, the controller can be expressed as:

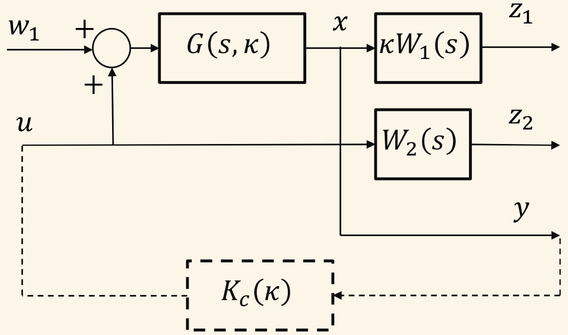
$$K_c(\kappa) = K_c(\underline{\kappa}) + \alpha\left(K_c(\bar{\kappa}) - K_c(\underline{\kappa})\right)$$

where the scheduled parameter is $\alpha = (\kappa - \underline{\kappa})/(\bar{\kappa} - \underline{\kappa}) \in (0,1)$.



System definition for robust LPV control synthesis

$$\bar{\kappa} = K_2 K_s b \cos\beta / K_1$$



LPV plant definition with weighting functions

Experimental Setup in the Lab

Tool

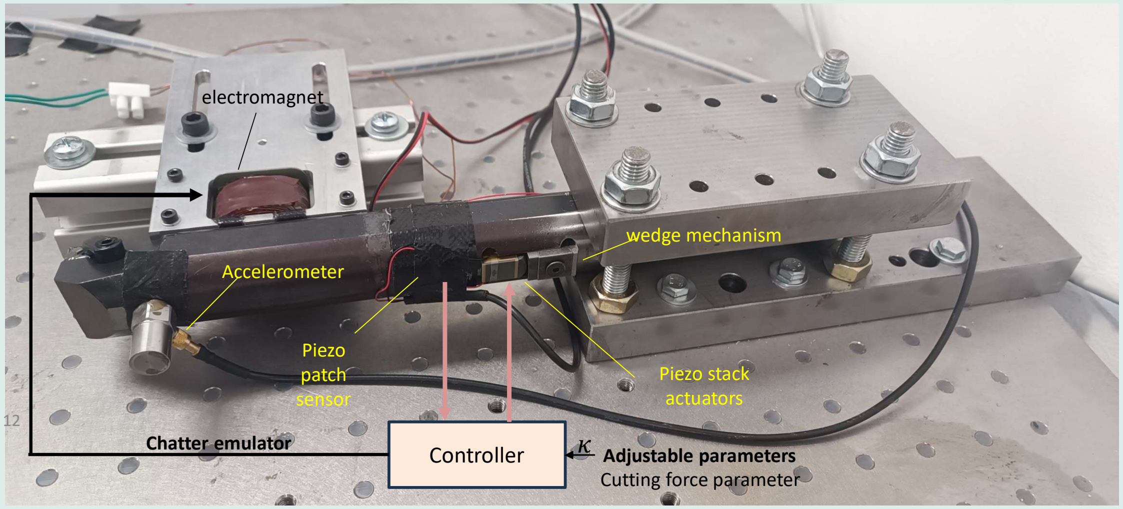
- Commercially available internal tool, D = 32 mm, L = 180 mm, L/D = 5.63
- Driven by piezoceramic stacks.

Emulation

- Non-contact electromagnetic actuator
- Apply force to emulate the cutting force.

Sensing

- Strain sensor used to measure displacement at the tool tip
- Accelerometer used to validate measurement.

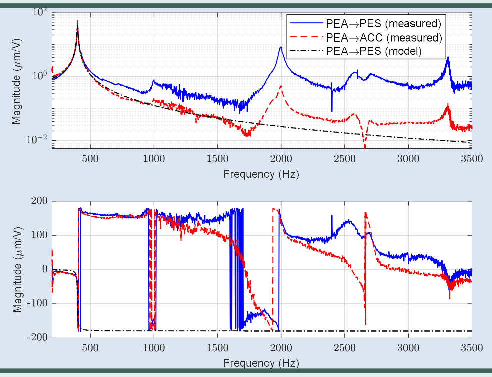


Experimental setup

Robust LPV Control Design

Modal Testing

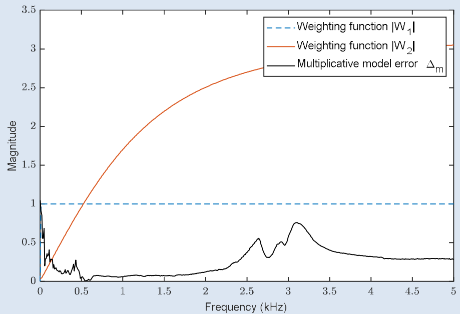
- Sine sweep method for collecting the FRF data.
- Frequency response measurements from sine-sweep tests with PEA excitation, compared with model-based data after tuning.
- Identifying the modal parameters of the first mode using the peak-picking method.



Frequency Response Function (FRF) Measurements.

Design

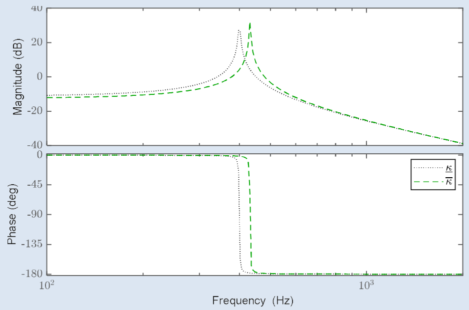
- Develop weighting functions and assess model error in the single-degree-of-freedom dynamic model.
- Compute LPV control parameters.



Weighting Functions and Model Error.

Verification

- Validate robust LPV control synthesis using transfer functions and vertex LPV plant models.

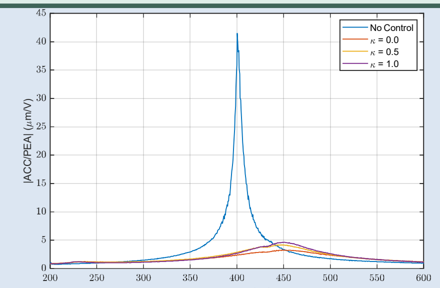


Bode Diagram of LPV Control Transfer Functions.

Experiment Results

FRF Analysis

- Measured FRF of the internal cutting tool in an uncontrolled case.
- Three additional cases using robust LPV control with two vertex models and one interpolation case.
- Results confirm high damping in the system's resonant frequency range.



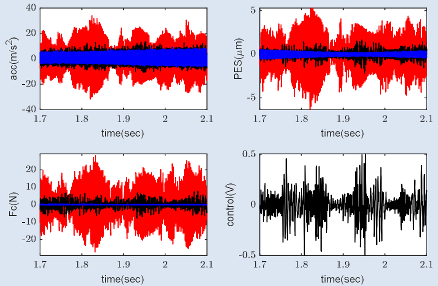
Measured FRF for LPV control with vertex models.

Time-Domain Analysis

❖ Chatter emulator results for three different cases:

- Case 1 (Red): Unstable machining without control.
- Case 2 (Black): Unstable machining with control.
- Case 3 (Blue): Stable machining without control.

❖ Case 4 (without the chatter emulator) shows results similar to Case 3, confirming the absence of chatter in Case 3.



Experimental time-domain results from chatter emulator.

Key Findings

- Chatter Vibration Reduction: 65% reduction in RMS vibration and 47% reduction in peak value.
- Dynamic Chatter Force (f_c): Decreases from Case 1 to Case 2 due to the reduction in the chip thickness parameter (emulated).
- Piezoelectric Actuation: PEA (Piezoelectric Actuator) and PES (Piezoelectric Sensor) validate the control effectiveness

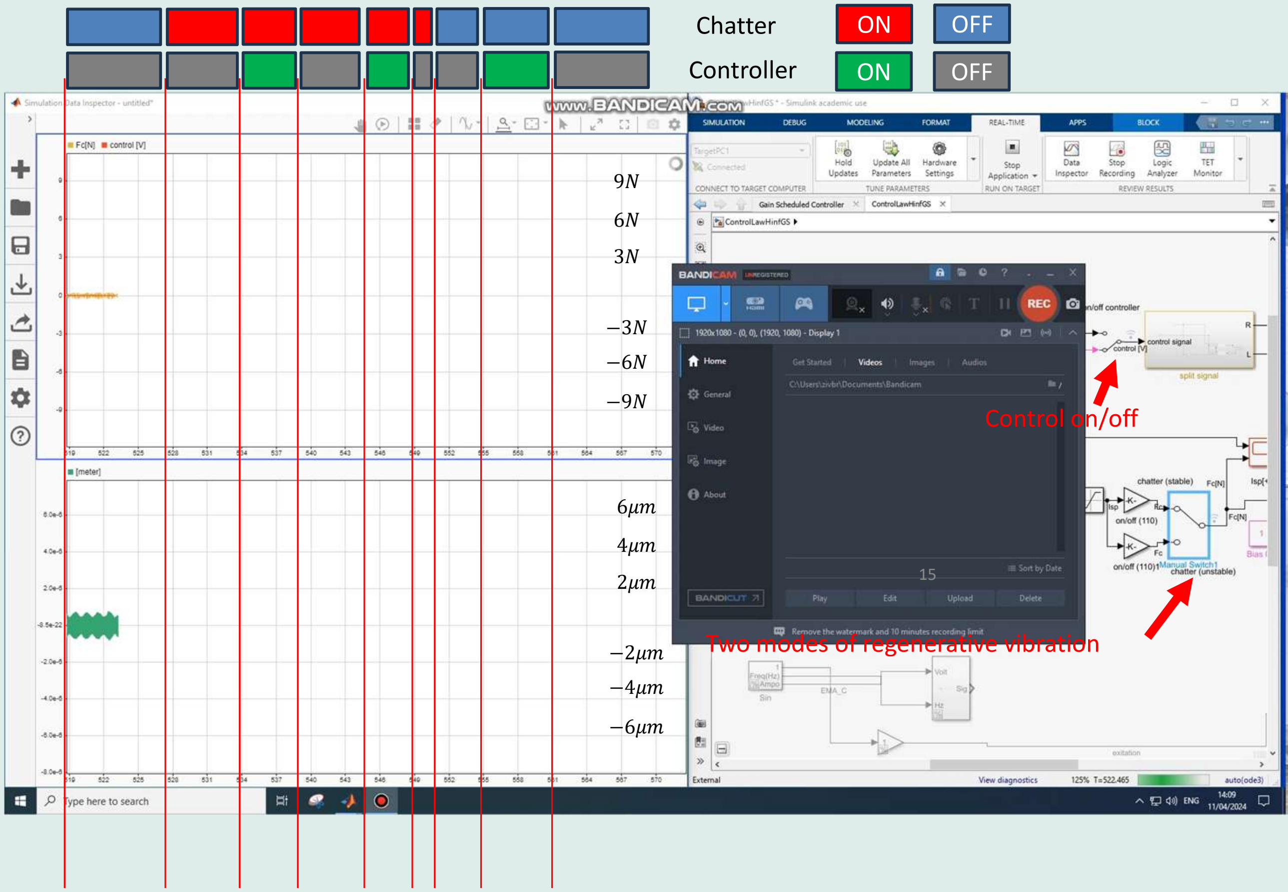
Parameter	Case 1	Case 2	Case 3	Case 4	Units
PES(rms)	1.82	0.63	0.383	0.379	μm
PES(max)	5.88	3.10	0.910	0.855	μm
f_c (rms)	9.34	2.87	0.157	0.000	N
f_c(max)	29.68	13.77	0.633	0.000	N
Control(rms)	0.00	0.32	0.000	0.000	V
Control(max)	0.00	1.19	0.000	0.000	V

Quantitative measures for different cases

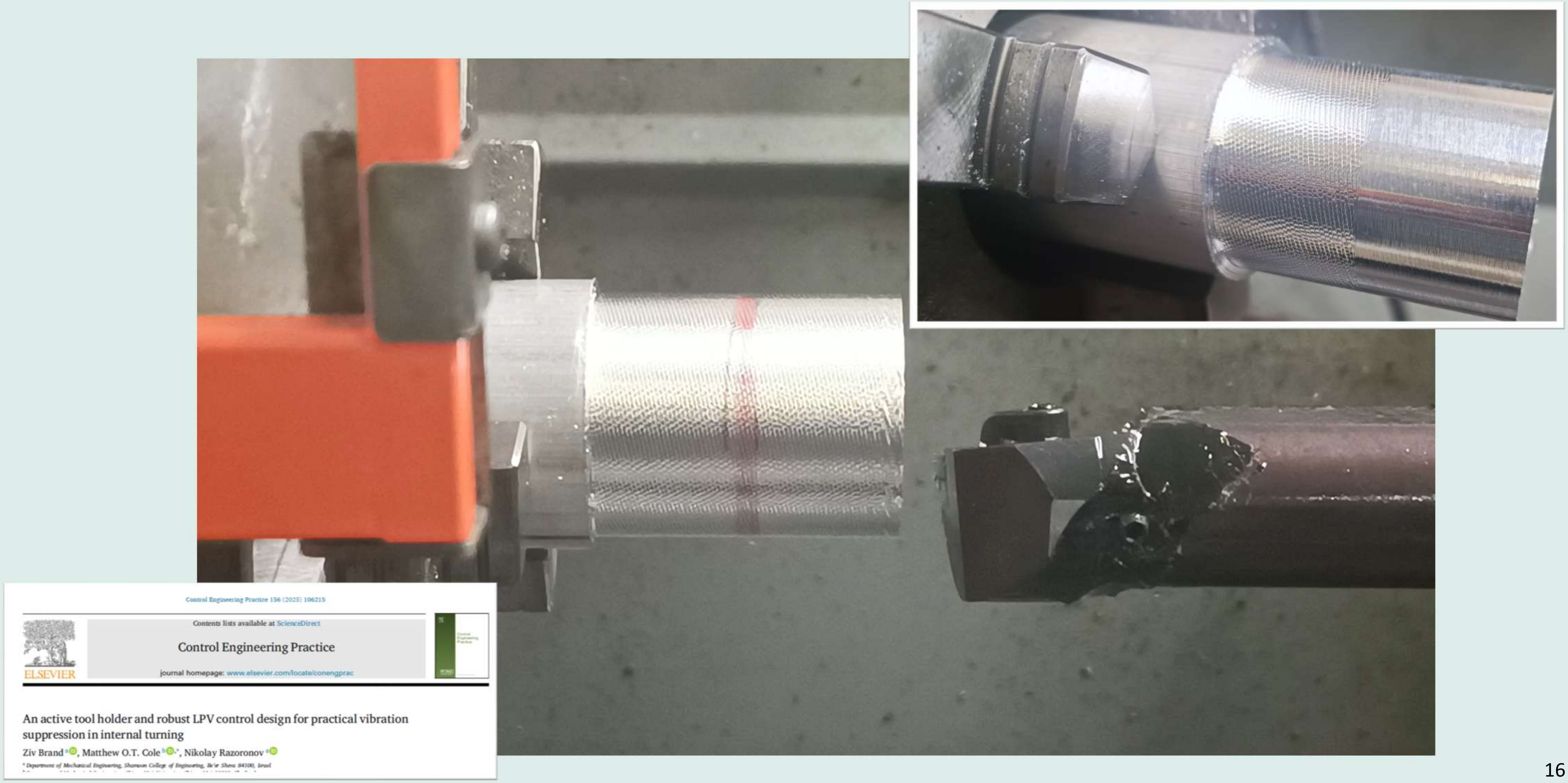
Experiment Results

Chatter ON OFF

Controller ON OFF



Lathe Machine Experiments



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An active tool holder and robust LPV control design for practical vibration suppression in internal turning

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Lathe Experiment Results

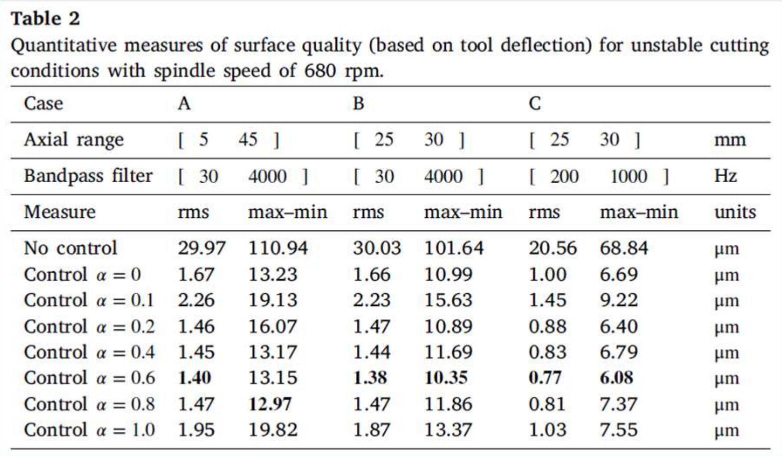


Table 2
Quantitative measures of surface quality (based on tool deflection) for unstable cutting conditions with spindle speed of 680 rpm.

Case	A		B		C		
Axial range	[5 45]		[25 30]		[25 30]		mm
Bandpass filter	[30 4000]		[30 4000]		[200 1000]		Hz
Measure	rms	max–min	rms	max–min	rms	max–min	units
No control	29.97	110.94	30.03	101.64	20.56	68.84	μm
Control $\alpha = 0$	1.67	13.23	1.66	10.99	1.00	6.69	μm
Control $\alpha = 0.1$	2.26	19.13	2.23	15.63	1.45	9.22	μm
Control $\alpha = 0.2$	1.46	16.07	1.47	10.89	0.88	6.40	μm
Control $\alpha = 0.4$	1.45	13.17	1.44	11.69	0.83	6.79	μm
Control $\alpha = 0.6$	**1.40**	13.15	**1.38**	**10.35**	**0.77**	**6.08**	μm
Control $\alpha = 0.8$	1.47	**12.97**	1.47	11.86	0.81	7.37	μm
Control $\alpha = 1.0$	1.95	19.82	1.87	13.37	1.03	7.55	μm

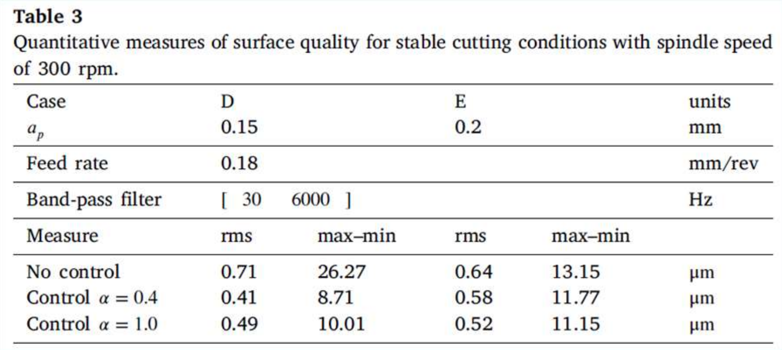
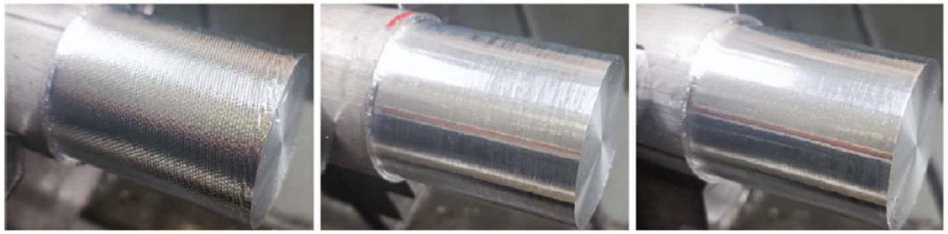


Table 3
Quantitative measures of surface quality for stable cutting conditions with spindle speed of 300 rpm.

Case	D		E		units
a_p	0.15		0.2		mm
Feed rate	0.18				mm/rev
Band-pass filter	[30 6000]				Hz
Measure	rms	max–min	rms	max–min	
No control	0.71	26.27	0.64	13.15	μm
Control $\alpha = 0.4$	0.41	8.71	0.58	11.77	μm
Control $\alpha = 1.0$	0.49	10.01	0.52	11.15	μm

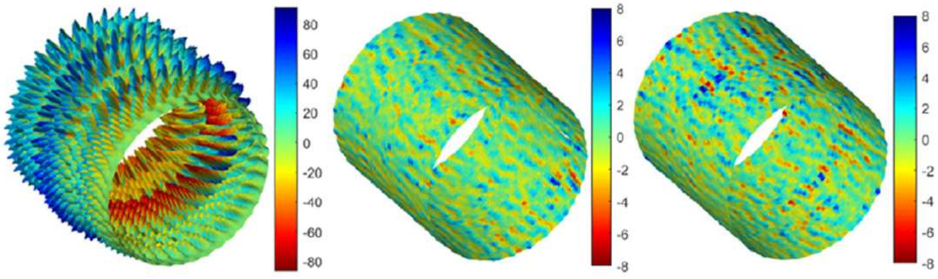


No Control

Control $\alpha = 0.6$

Control $\alpha = 1.0$

Fig. 15. Appearance of workpieces after machining, with and without control.



No Control

Control $\alpha = 0.6$

Control $\alpha = 1.0$

Fig. 16. Machined surface of workpiece: height variation calculated from measured tool deflection during cutting (Axial range is 0 to 6 mm).

Conclusion

01

Effective Vibration Suppression

The proposed robust LPV controller effectively reduces chatter vibration, achieving up to 95% reduction in RMS vibration and 90% reduction in peak-to-peak values in unstable cutting conditions, enabling higher material removal rates with improved surface finish..

02

Adaptability and Robustness

The LPV-based control strategy adapts to varying machining conditions in real-time, addressing parametric uncertainties and time-delayed feedback effects, making it a practical solution for industrial applications.

03

Experimental Validation

Both cutting emulation and lathe machine experiments confirm the controller's effectiveness in stabilizing the turning process. The system transitions from unstable to stable operation, ensuring enhanced machining performance.

Future Work and Industrial Application

The control algorithm will be further developed for real-world applications, particularly when the turning tool is integrated into CNC machines with varying lengths, affecting resonance frequencies. This enhancement will improve adaptability and effectiveness in industrial machining..

thank for listening

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