Control of Chatter using Active Magnetic Bearings

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Opportunity

- Chatter is a machining process instability that inhibits higher metal removal rates (MRR) and accelerates tool wear.
- The higher MRR achievable through chatter control could yield more than a $10 billion increase in US GDP.

Advantages for Machining

Active magnetic bearings (AMBs) have several advantages for high speed machining:

- stiffer spindles and higher speeds
- adaptive balancing via feedforward control
- increased damping of spindle modes
- ability to adapt bearing properties to cutting conditions via gain scheduled control

Two Efforts

- Design and testing of a 32,000 rpm milling spindle supported by active magnetic bearings (sponsor: Cincinnati Milacron)
- Investigation of new concepts for chatter control (sponsor: NSF)

AMB Spindle

- Design of high speed AMB spindle
- System modeling
- Experimental investigation of advanced control

AMB Spindle

- Design of high speed AMB spindle
  - optimization of rotor / actuator / control
  - rotor loss experiments & thermal modeling
  - dynamic analysis, AMB clearances, tolerances
- System modeling
- Experimental investigation of advanced control

AMB Spindle

- Design of high speed AMB spindle
- System modeling
  - analytical models of rotor & actuator
  - component testing of amplifiers & sensors
  - initial levitation via PID control
  - system ID and model adjustment
- Experimental investigation of advanced control.

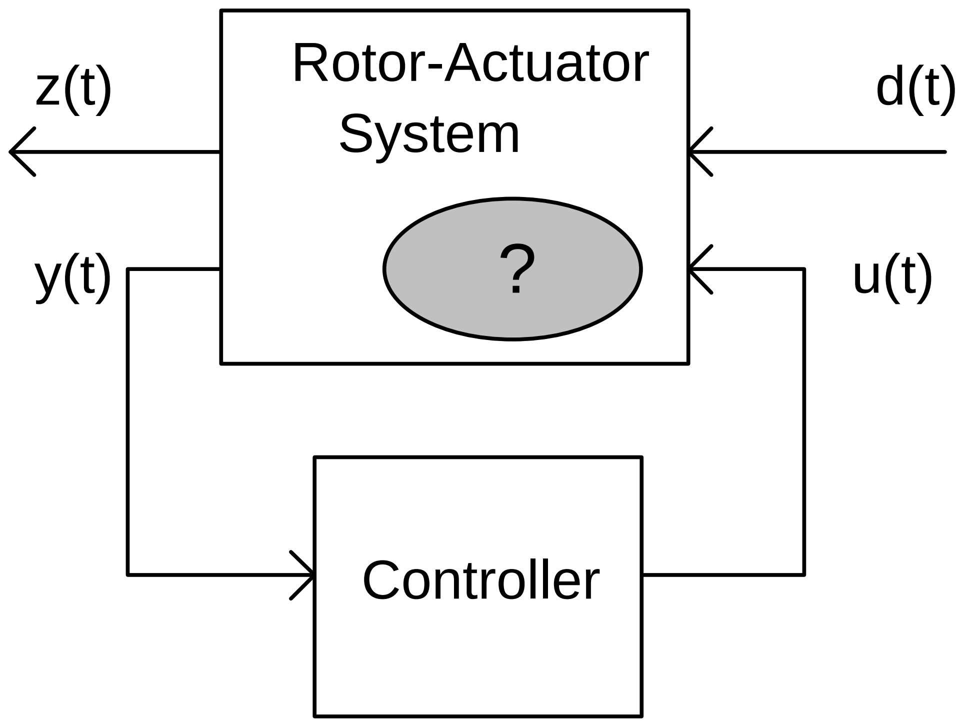
AMB Spindle

- Design of high speed AMB spindle
- System modeling
- Experimental investigation of advanced control
  - assembly coding on parallel controller
  - multivariable control synthesis and reduction
  - testing of over 30 control algorithms
  - adaptive balancing

AMB Spindle Features

- 32,000 rpm, 90 hp, 3 million DN
- 3 radial bearings and 1 thrust bearing
  - 1000 lbf cutting load
- Differential optical sensors
  - 0.25 μm noise
- Parallel processing DSP controller
  - 7 input, 7 output, 75 states at 12 kHz

Modern Control Framework



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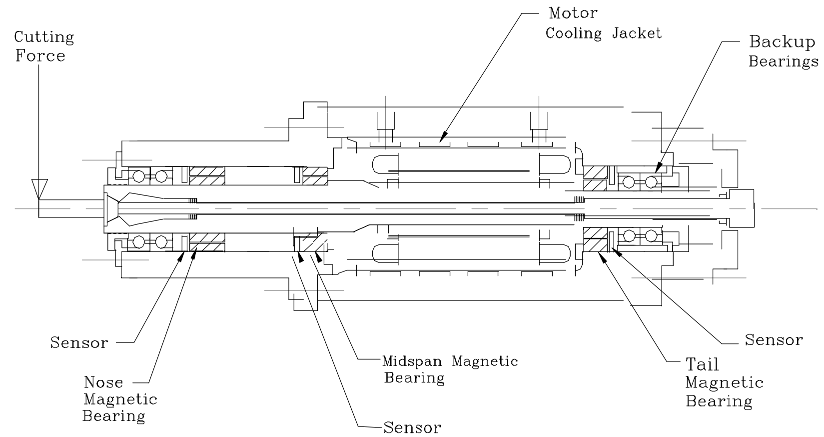
Multivariable Control

- Most AMB systems operate under decentralized PID control.
- Greater performance can be achieved by using all available information to coordinate actions.



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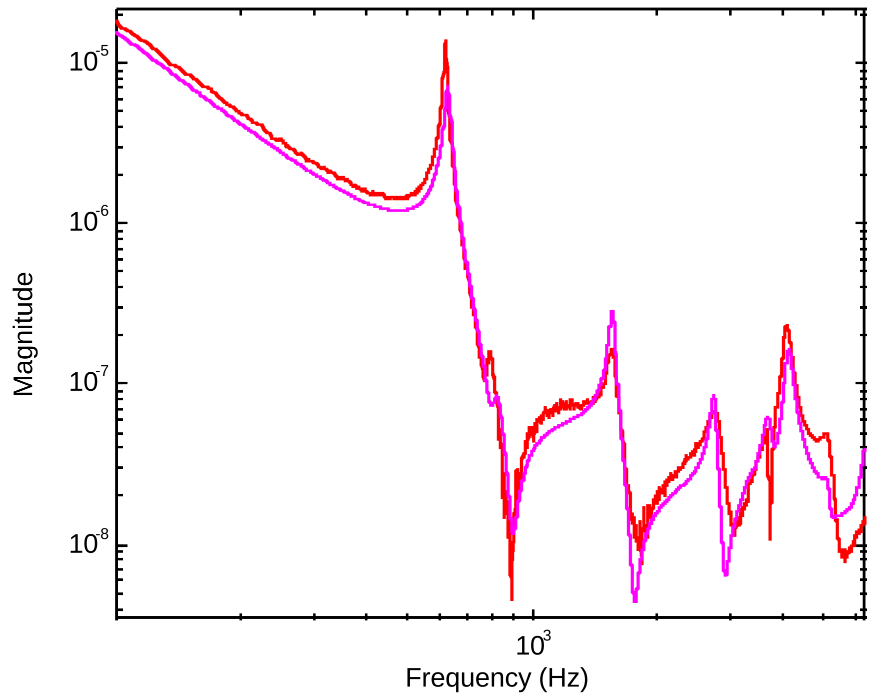
AMB Spindle Modeling

- The control designs are heavily dependent on accurate component models.

The analytically derived rotor model was very accurate up to 3 kHz. Here it's frequency response is compared to experimental data obtained by impact testing.



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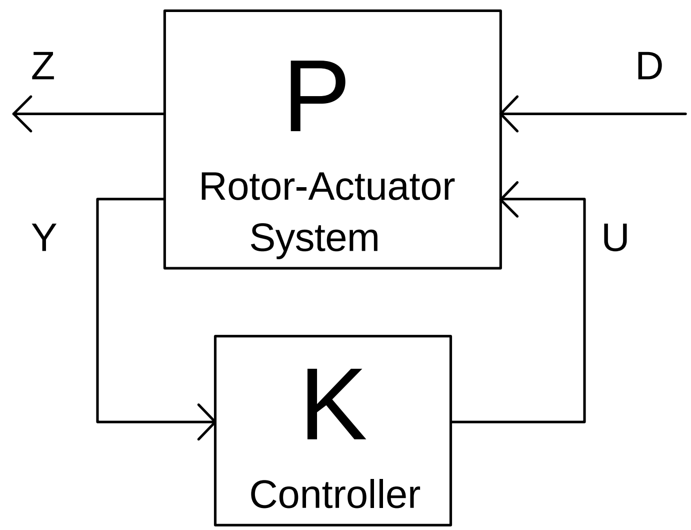
H∞ Formulation

- Minimize $\left\| \frac{Z(jw)}{D(jw)} \right\|$ over all frequencies ω by choice of controller K.
- H∞ performance index equates to worst case 'model' of cutting process



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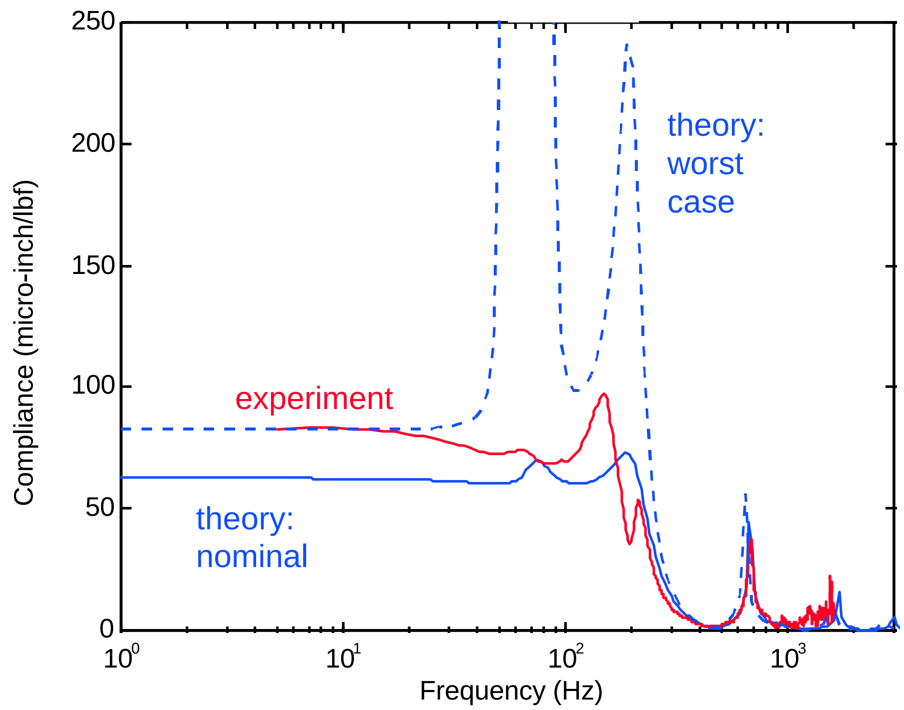
Experimental Results

- The H^{∞} controller far outperformed a conventional (but highly optimized) PID controller.
- For example, a 54% reduction in thrust dynamic compliance.

Dynamic Compliance	PID	H^{∞}
Theory - Nominal	22	9
Theory - Worst Case	∞	16
Experiment	28	13

Theoretical and experimental peak dynamic compliances (micro-inch/lbf) for the thrust axis of the AMB spindle.

Radial Compliance w/ PID



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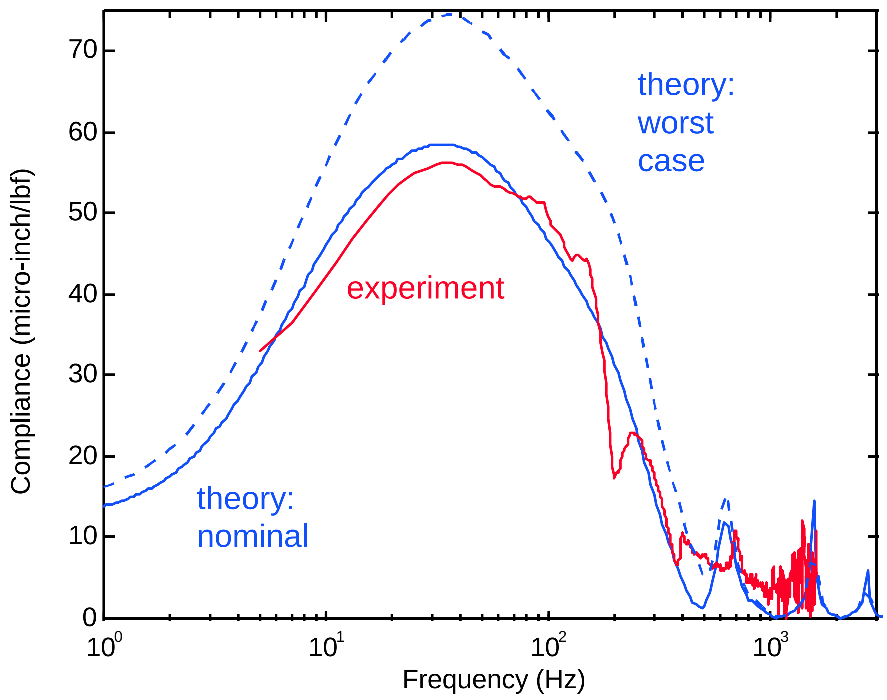
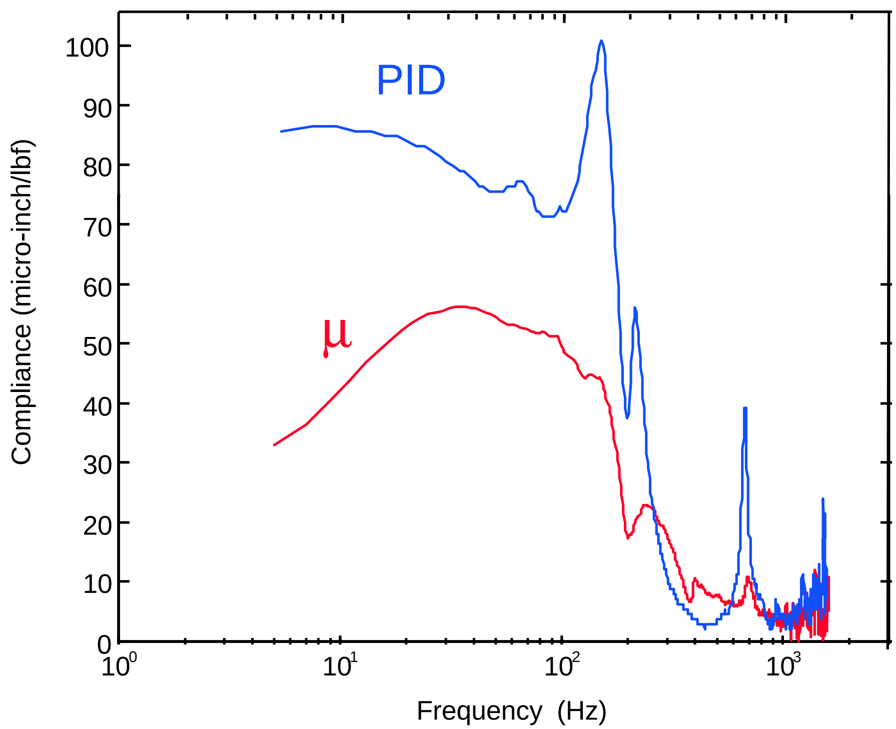
Radial Compliance w/ μ



Radial Comparison



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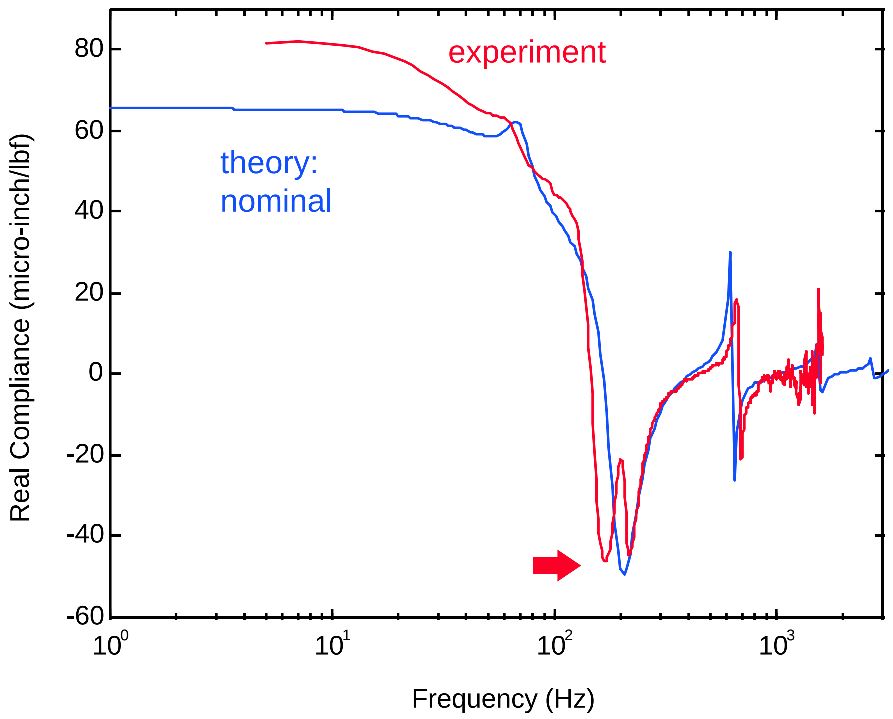
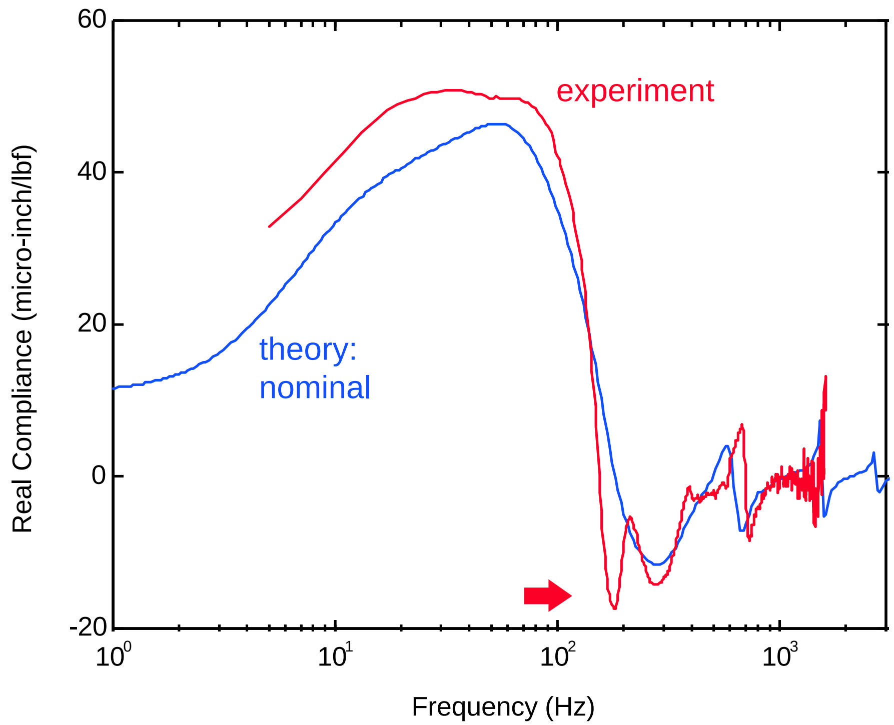
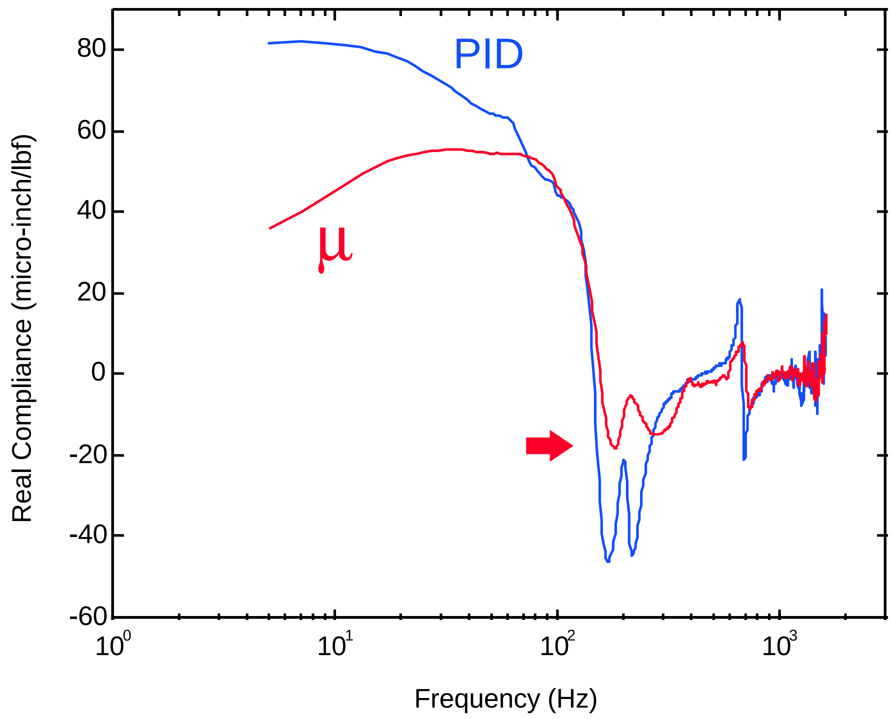
Tool Real Compliance - PID



Tool Real Compliance - μ



Real Part Comparison



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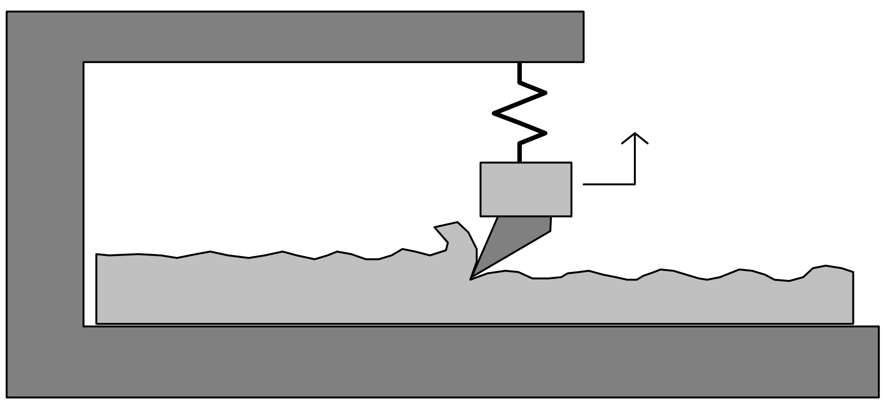
Machining Stability

- Chatter occurs when the chip width is too great. This cutting process instability largely arises from a time-delay in the cutting process.



Chatter is caused by vibration of the tool producing a wavy surface on the workpiece. This waviness then causes greater vibration of the tool in its next pass. The cutting process is thus a dynamic stiffness with a time-delay term. The chip width acts as a gain on this mechanical feedback loop.

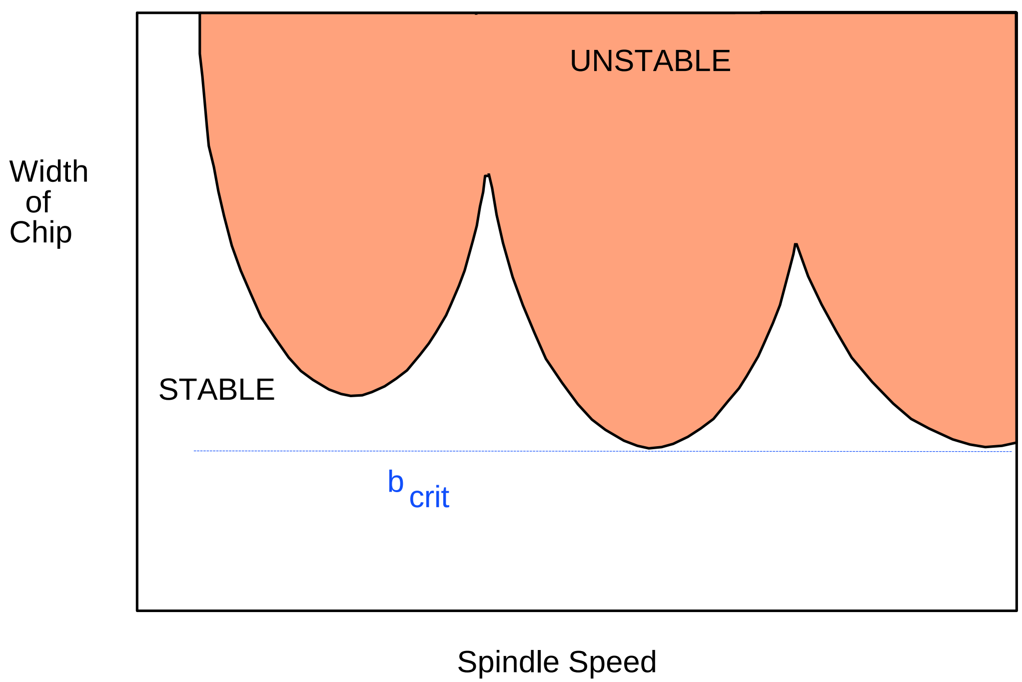
Speed & Chip Width

- Speed & width strongly affects machining stability.

Stability determines the maximum chip width which can be achieved. Certain speeds are much less prone to chatter and thus are advantageous for machining.

Speed directly determines the time delay in the cutting process feedback loop. Chip width acts as a gain in this loop.

Below a certain chip width, b_{crit}, stable cutting results at all speeds. This is delay-independent stability.



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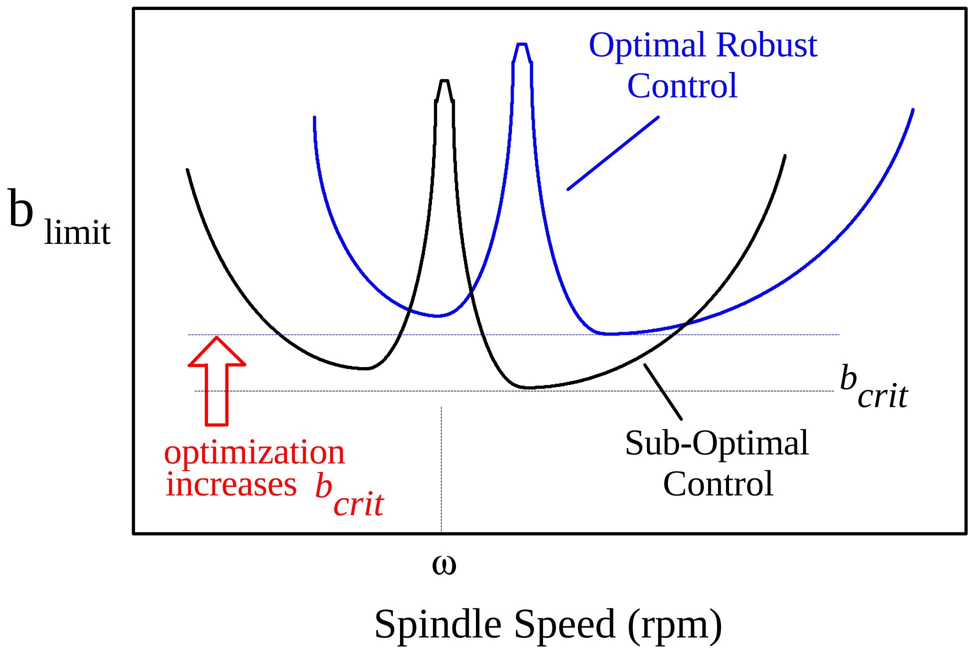
Minimize Tool Compliance

- H^{∞} optimal control improves worst case chip width

This control design procedure has been tested by the PI on the high speed milling spindle.

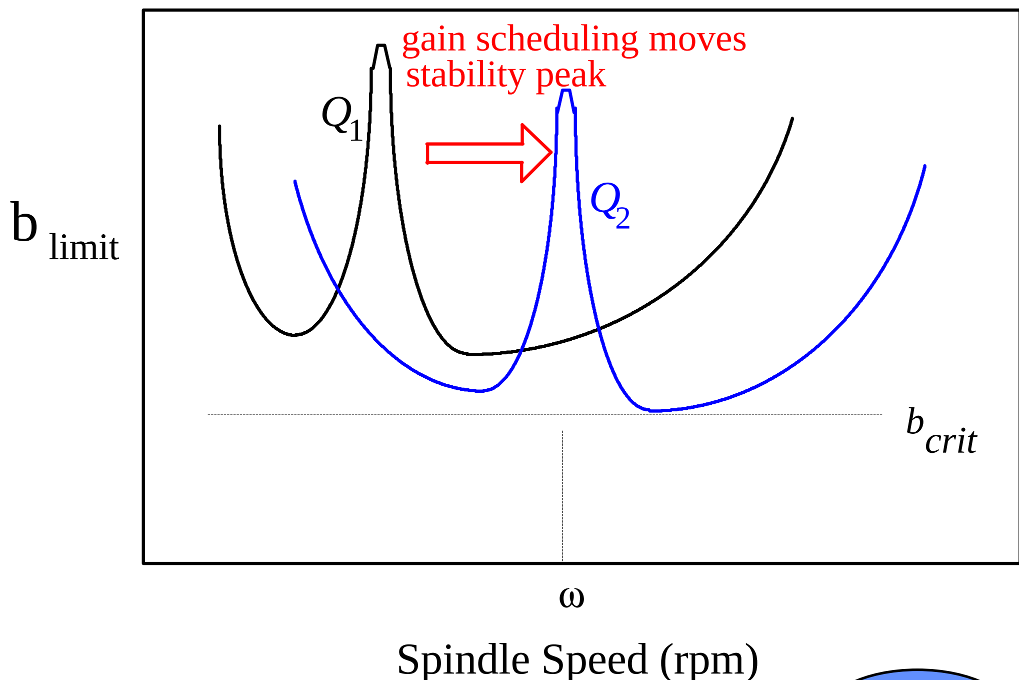
It maximizes the chip width at the worst case speed, b_{crit}, by minimizing the dynamic tool compliance. However, at any given speed, the optimal controller found by this method may have smaller chip width than a sub-optimal controller.



Adapting to Spindle Speed

- Gain scheduled control achieves larger chip width by changing control algorithm with spindle speed.

This research investigates the use of controllers that change with machining conditions such as spindle speed. This can be considered as shifting the peak of the stability lobe diagram to the current operating speed. Since it does not optimize for the worst case speed, greater metal removal rate can be achieved.



Gain Scheduling Theory

- Recent breakthroughs in control theory allow the synthesis of controllers that are functionally dependent on time-varying parameters.
- These gain scheduled controllers are designed via the use of parameter-dependent storage functions and Linear Matrix Inequalities (LMIs).
- Such controllers are very advantageous for chatter control.

Analysis LMIs

- The LPV system given by [A,B,C,D] is stable with an induced L_2 norm of γ if the following LMIs are satisfied

$$\begin{bmatrix} A^T P + PA & PB & C^T \\ B^T P & -g\ I & D^T \\ C & D & -g\ I \end{bmatrix} < 0 \qquad\qquad P > 0$$

Analysis yields Synthesis

- If an analysis problem can be formulated in terms of LMIs, then the corresponding synthesis equations can be directly found by:
  - writing the analysis problem for the closed loop system
  - projecting out the controller state space matrices $[A_c, B_c, C_c, D_c]$
- The controller can then be found by solution of the LMIs followed by a reconstruction step
- For this reason, our efforts have concentrated on the analysis problem.

Uncertain Delay Systems

- Results for the analysis of uncertain delay systems fall into two categories:
  - delay-independent stability - the system is analyzed to determine if it is stable for any amount of delay.
  - delay-dependent stability - the system is analyzed to determine if it is stable for delays $0<\tau<\tau_{max}$.

Implications for Machining

- Delay-Independent Stability
  - Corresponds to stability at all speeds.
  - In synthesis, this corresponds to maximizing b_{crit}.
  - PIs have demonstrated equivalency to H^{∞} analysis.
- Delay-Dependent Stability
  - Corresponds to stability over a speed range.
  - In synthesis, this shifts stability lobe peaks.

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Prior Stability Results

- Delay-Independent
  - based on Lyapunov-Krasovskii functionals
  - yields LMIs for analysis
- Delay-Dependent
  - based on Lyapunov-Krasovskii functionals
  - yields τ_{max}-dependent LMIs for analysis

Lyapunov framework results are very difficult to interpret or improve.

A Unified Theory

- Previous results for the system

$$\dot{x}(t) = Ax(t) + A_d x(t-\tau) \qquad 0 \le \tau \le \tau_{\max}$$

correspond to a stability robustness analysis of the comparison system

$$\dot{x} = (A + MA_d)x + \Delta_1 (I - M)A_d x + \Delta_2 \tau_{\max} MA_d Ax + \Delta_1 \Delta_2 \tau_{\max} MA_d A_d x$$

via the scaled small gain theorem

Here $\overline{\tau}_{max}$ is the maximum delay, Δ_1 and Δ_2 are unit gain 'uncertainties', and M is a matrix that may be freely chosen. This theory unifies delay-independent and delay-dependent results and provides a new interpretation of them.

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A Unified Theory (contd.)

- In the scaled small gain formulation:
  - results are much easier to understand and to extend than in Lyapunov framework
  - robustness to model uncertainties is easily added
  - less conservatism in synthesis than Lyapunov

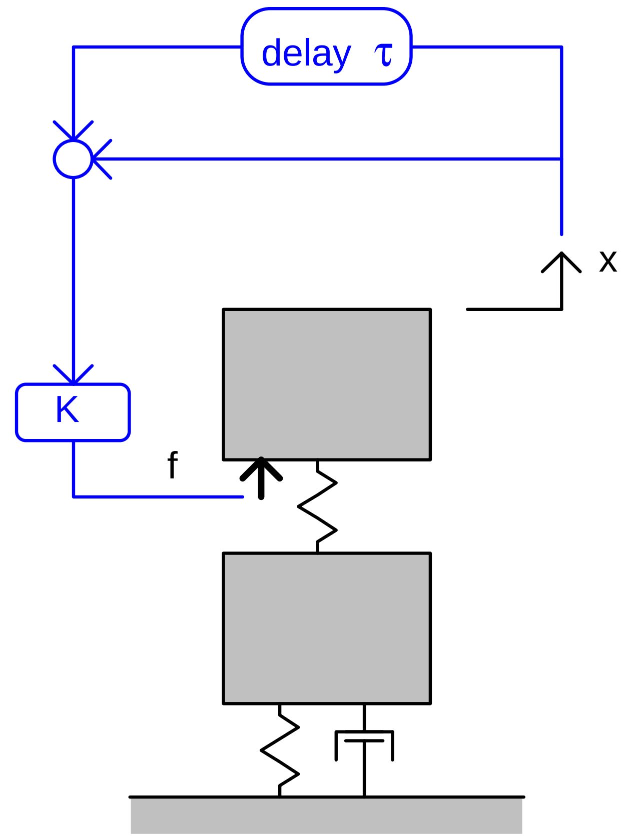
We have already made several important extensions to theory using insights gained.

Extensions

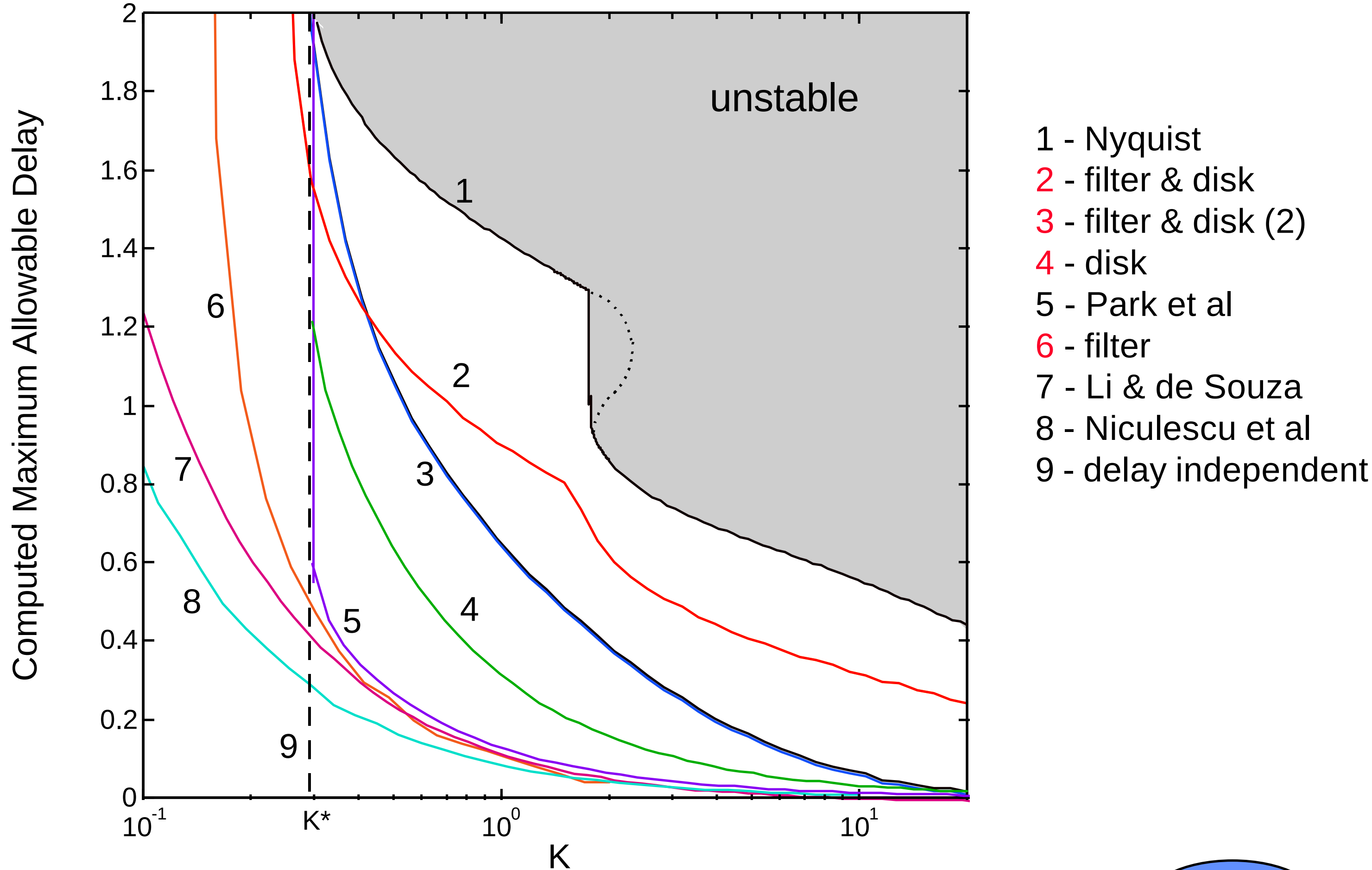
- Connections to Integral-Quadratic-Constraint (IQC) approaches, normalizing filters.
- Use of loop transformations for off-origin disk coverings of delay uncertainty.
- Exploitation of rank-one and nilpotent properties of delay matrix in chatter problems.

Example Problem

- For examining the conservatism of various analysis techniques, a simple two resonance example problem was considered.



Analysis Results



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Publications

- J. Zhang, C. Knospe, and P. Tsiotras, "A Unified Approach to Time-Delay System Stability via Scaled Small Gain", Proceedings of the 1999 American Control Conference, San Diego, June 2-4. *
- J. Zhang, C. Knospe, and P. Tsiotras, "Toward Less Conservative Stability Analysis of Time-Delay Systems", submitted to 1999 Conference on Decision and Control.

* An extended version in preparation for IEEE Transactions on Automatic Control.

Conclusions

- The control of chatter using AMBs may greatly increase metal removal rate.
- Gain scheduled controllers can significantly improve the performance of AMB spindles.
- Our new unified framework lends helpful insight into the stability of time-delay systems and has yielded important theoretical advancements.

Acknowledgments

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- Previous AMB milling spindle research supported by Cincinnati Milacron Inc.