Manufacturing and uncertainty

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Introduction

Goal

Select processing parameters to achieve the desired outcome for the manufactured product (properties, dimensions, function…)

Obstacles

- Requires input-output relationship between parameters and outcome
- Inputs are not perfectly known
- Input-output relationship includes approximations and omissions
- Outputs cannot be perfectly measured [1, 2]

Situation

- Establish input-output model (materials science, physics, chemistry…)
- Predict output(s) given input(s)
- Incorporate uncertainty

Consider machining as an example manufacturing operation.

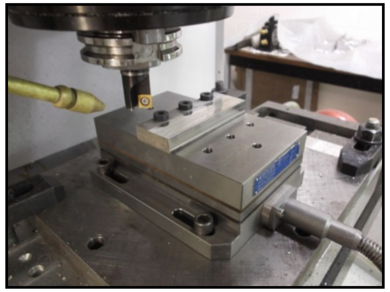
1. ISO, 1993, Guide to the Expression of Uncertainty in Measurement, International Organization for Standardization, Geneva, Switzerland
2. Barry N. Taylor and Chris E. Kuyatt, 2001, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, http://physics.nist.gov/TN1297, National Institute of Standards and Technology, Gaithersburg, MD.

Machining background

Goals for part production by machining

- Dimensionally accurate part
- Desired surface finish
- No chatter (unstable)
- Acceptable tool life

Dynamometer testing

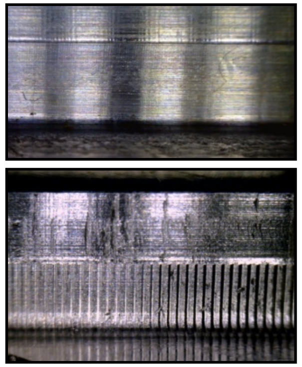


Stability

Surface location error (SLE)

Force model

Stable



Chatter

Time domain simulation

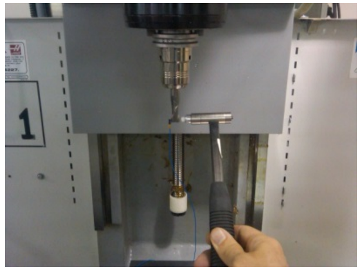
Tool wear

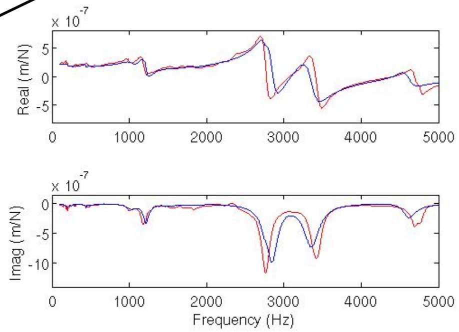
Frequency domain stability

Frequency domain SLE

Modal fitting

Frequency response function (FRF)



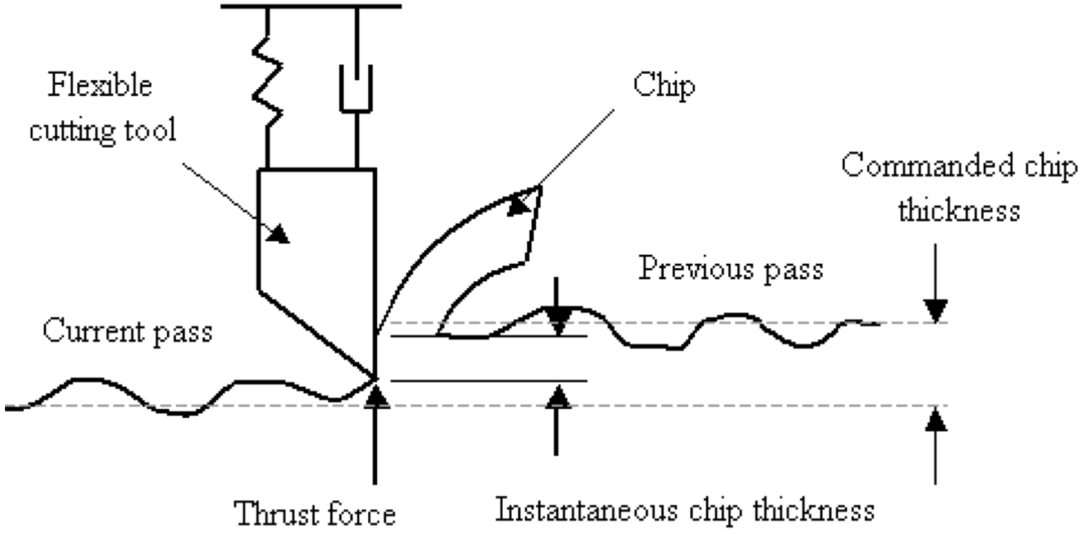


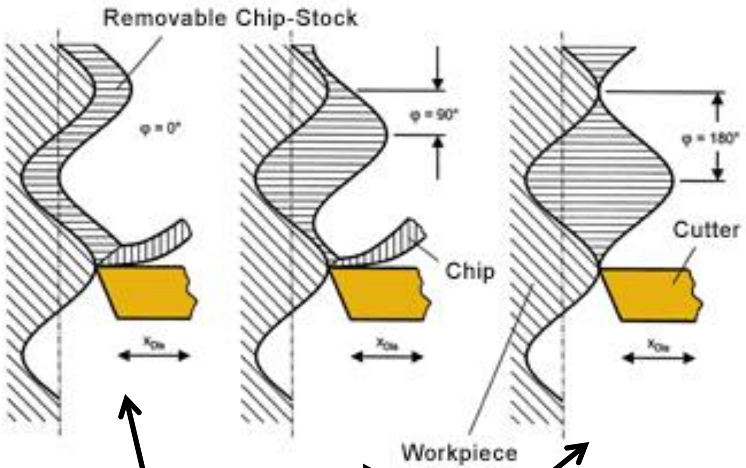
Modal testing

Receptance coupling modeling

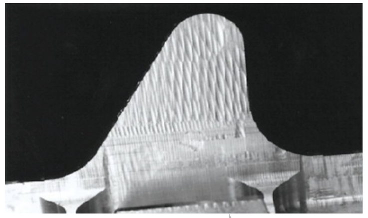
Machining background

Chatter – self-excited vibration that occurs in machining (large forces, poor finish)





Chip thickness varies so force varies → unstable



Regeneration is a primary mechanism for chatter

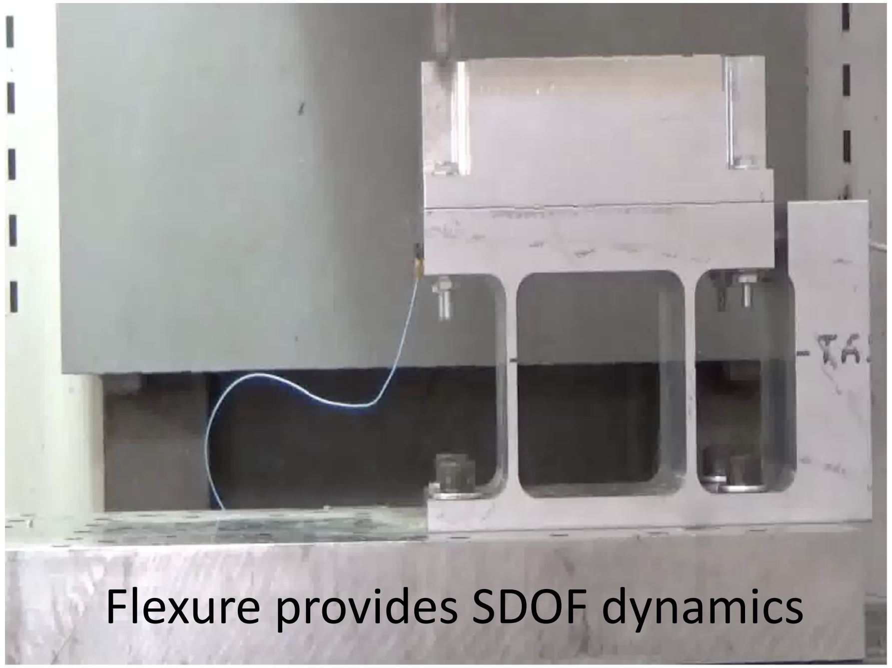
- force depends on chip thickness
- chip thickness depends on current vibration and previous pass
- current vibration depends on force

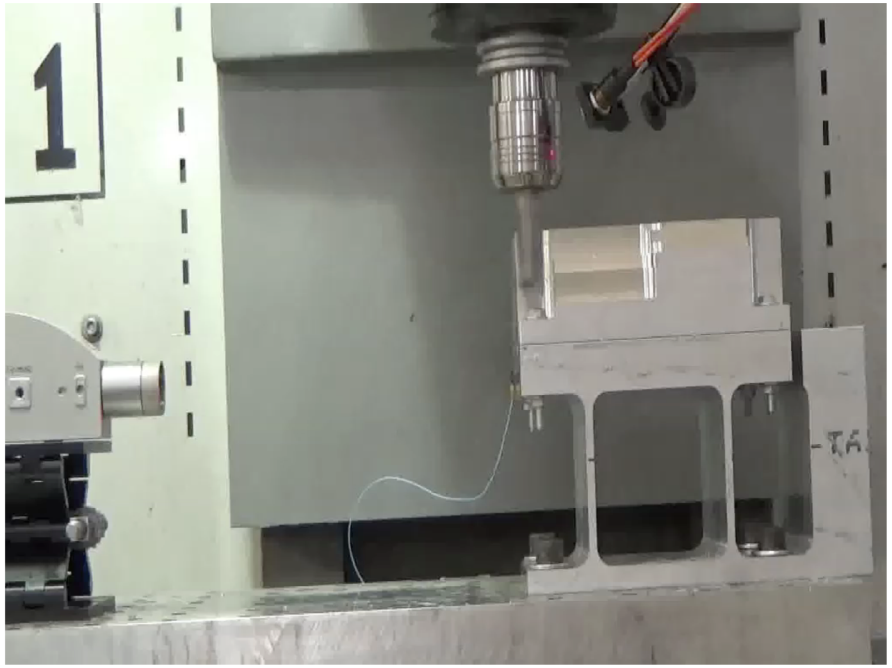
feedback

Chip thickness is nearly constant – small force variation → stable

Machining background

Stable and unstable (chatter) milling examples





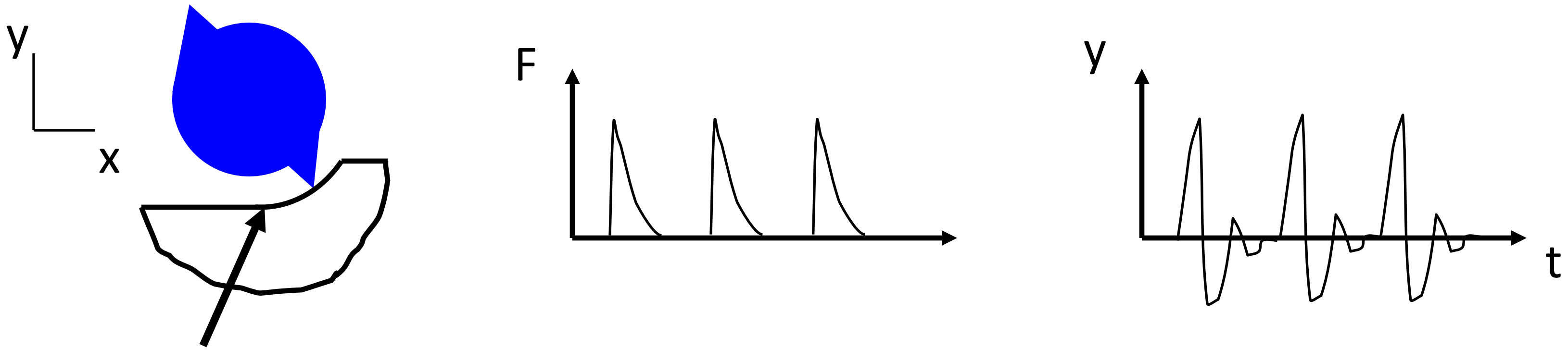
<u>Stable:</u>
Forced vibration
Repeats with each tooth passage
Tooth passing frequency and multiples

<u>Chatter:</u>
Self-excited vibration
Does not repeat each tooth passage
Natural frequency of structure

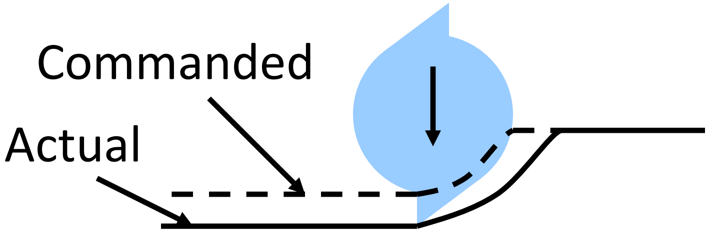
Machining background

Forced vibration during stable cutting can lead to **surface location error**

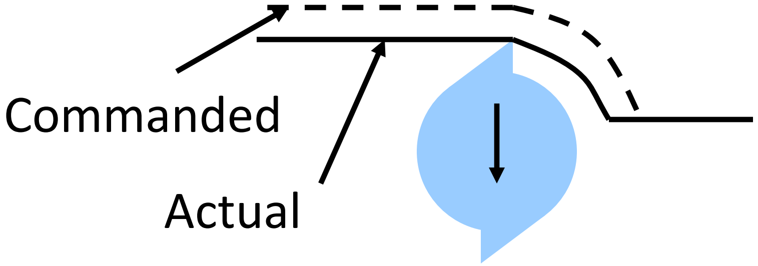
- vibration state of tool when leaving surface defines location
- magnitude and phase of vibration is frequency dependent (tooth passing frequency or spindle speed).



Where is the tool in its vibration cycle when it leaves the surface?

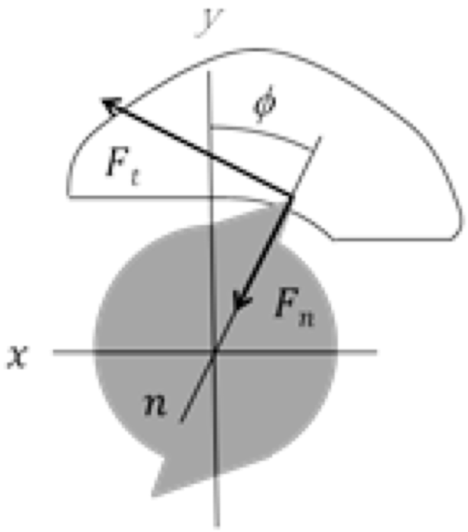


Down-milling: overcut surface



Up-milling: undercut surface

Milling description



Milling – a rotating cutter is used to remove material and leave the desired part geometry.

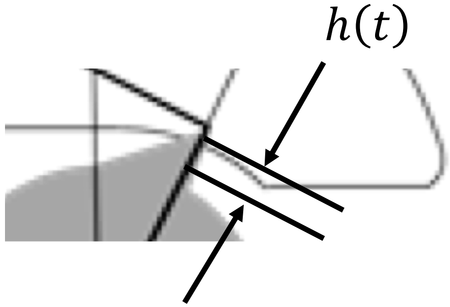
Vibration normal to the cut surface: $n(t) = x(t)\sin\phi(t) - y(t)\cos\phi(t)$

Chip thickness:

$$h(t) = f_t \sin\phi(t) + n(t-\tau) - n(t)$$

Feed per tooth

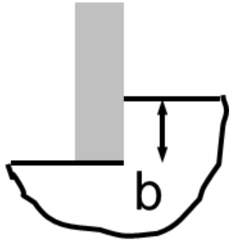
Tooth period



Time-delay term gives feedback (memory) in x and y

Force components: $F_t = k_{tc} b h(t) + k_{te} b$ $\quad F_n = k_{nc} b h(i) + k_{ne} b$

Axial depth of cut



Project into x/y directions:

$$F_x(t) = F_t\cos\phi(t) + F_n\sin\phi(t) \qquad F_y(t) = F_t\sin\phi(t) - F_n\cos\phi(t)$$

Milling description

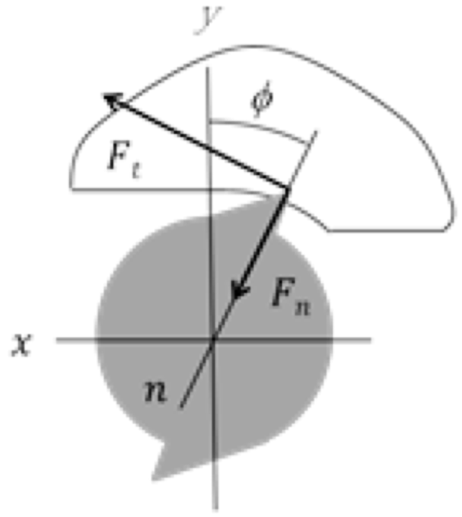
System dynamics are described by a set of **second order time-delay differential equations**.

$$m_x\ddot{x}(t) + c_x\dot{x}(t) + k_x x(t) = F_x(t)$$

$$m_y\ddot{y}(t) + c_y\dot{y}(t) + k_y y(t) = F_y(t)$$

Include x and y time-delay terms.

Describe tool/workpiece mass, damping, and stiffness in x/y directions.



Closed-form solution for set of delay differential equations is not available. Solution techniques include:

- analytical – approximate solution used to determine stability limit as a function of operating parameters (spindle speed, axial depth of cut)
- numerical – time domain simulation.

Time domain simulation

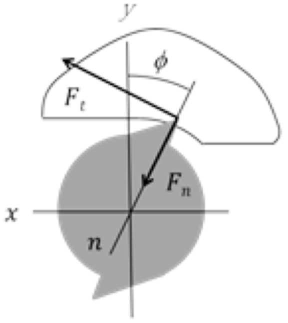
Solve set of second order time-delay differential equations using numerical integration.

Simulation steps per tooth period $S = \dfrac{2\pi}{N_t \cdot d\phi}$

$$n(i) = x(i-1)\sin\phi(i) - y(i-1)\cos\phi(i)$$

$$h(i) = f_t \sin\phi(i) + n(i-S) - n(i)$$

$$F_t = k_{tc} b h(i) + k_{te} b \qquad F_n = k_{nc} b h(i) + k_{ne} b$$



$d\phi$

$$F_x(i) = F_t \cos\phi(i) + F_n \sin\phi(i) \qquad F_y(i) = F_t \sin\phi(i) - F_n \cos\phi(i)$$

$$\ddot{x}(i) = \frac{F_x(i) - c_x \dot{x}(i-1) - k_x x(i-1)}{m_x} \qquad \ddot{y}(i) = \frac{F_y(i) - c_y \dot{y}(i-1) - k_y y(i-1)}{m_y}$$

$$\dot{x}(i) = \dot{x}(i-1) + \ddot{x}(i) \cdot dt \qquad \dot{y}(i) = \dot{y}(i-1) + \ddot{y}(i) \cdot dt$$

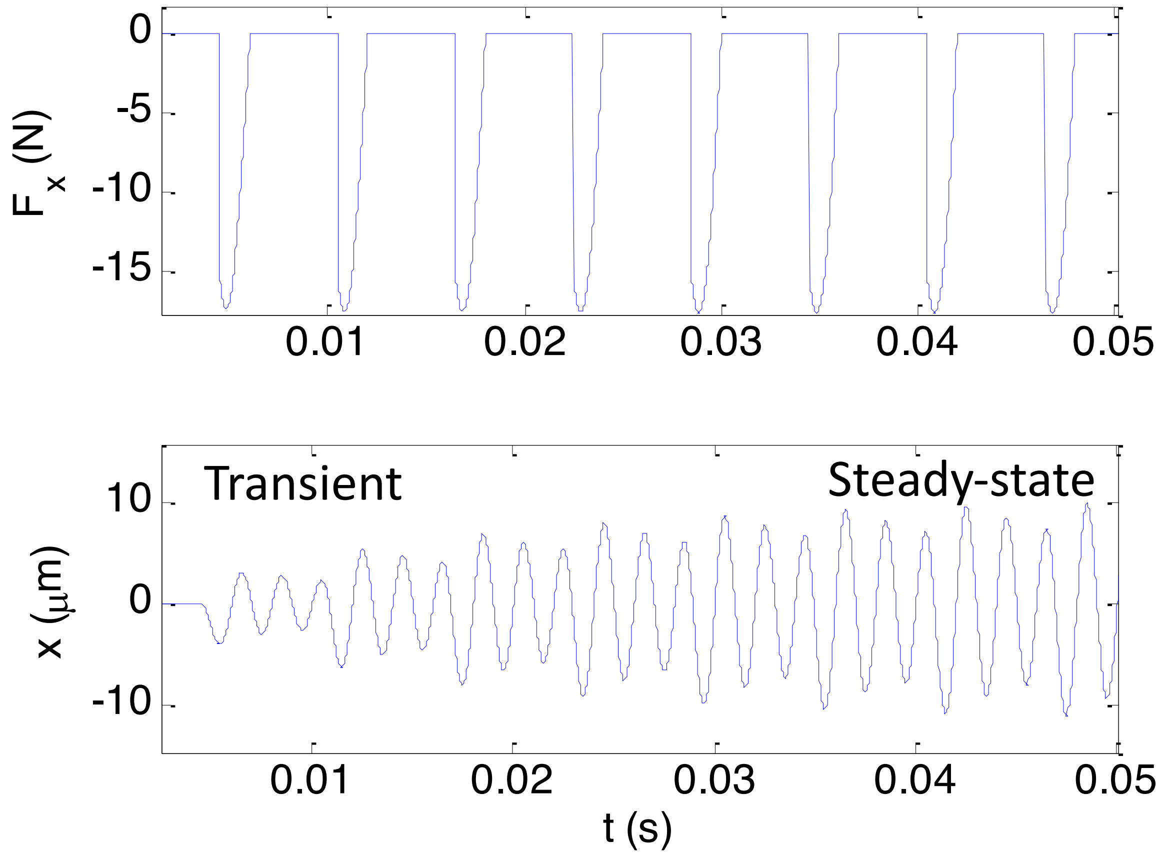
$$x(i) = x(i-1) + \dot{x}(i) \cdot dt \qquad y(i) = y(i-1) + \dot{y}(i) \cdot dt$$

Time domain simulation

Simulation inputs

- Cutting conditions: spindle speed, radial/axial depth, feed per tooth, cutting force coefficients.
- Tool geometry: number of teeth, diameter, helix angle.
- Tool point modal parameters: *m*, *c*, *k* in the *x* and *y* directions.

Simulation outputs



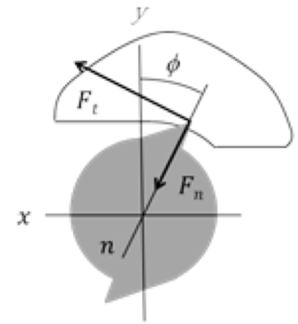
Bifurcation prediction

For dynamic systems, a *bifurcation is a dramatic change in the system state, or behavior*.

Milling exhibits various bifurcation (instability) types.

- A powerful interrogation tool for milling dynamics is **periodic sampling at the tooth period**.
- This sampling establishes the synchronicity of the motion (response) with the cutting force (excitation).
- For stable cutting conditions, only **forced vibration** is present and the sampled point repeats for each tooth passage (stable).
- For unstable cutting, on the other hand, the repetition of a single point is not observed and the character of the sampled points identifies the type of instability (chatter): secondary **Hopf** or period-n **bifurcations**.

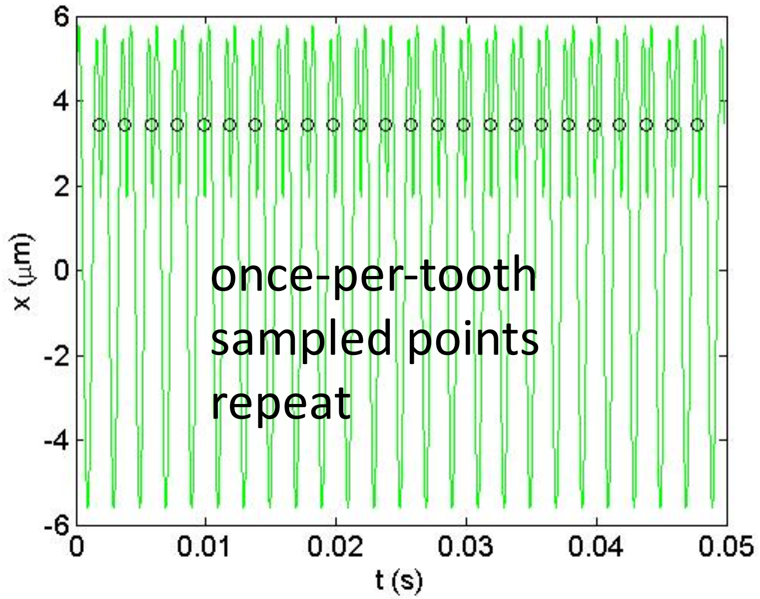
Bifurcation prediction



Example

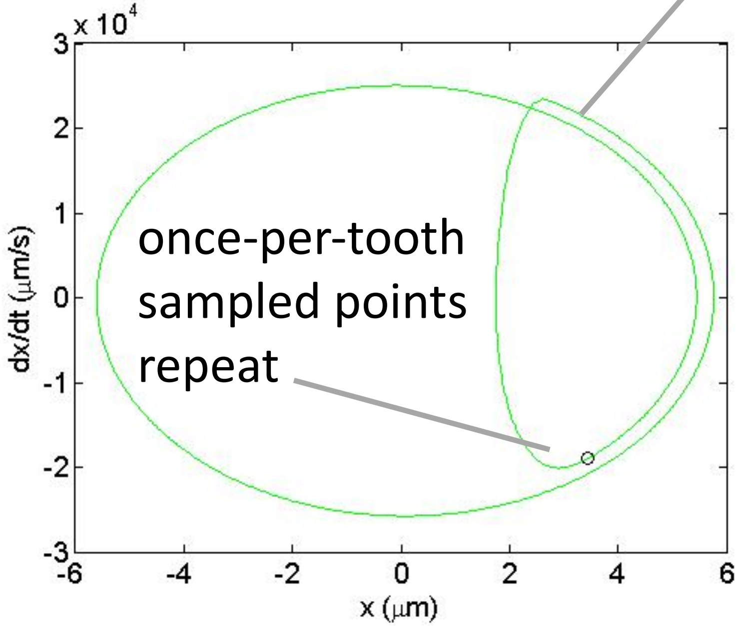
- 5% radial immersion up milling
- 30000 rpm spindle speed
- 721 Hz natural frequency, 0.009 damping ratio, and 4.1×10^5 N/m stiffness
- cutter has one tooth, a 45 deg helix angle, and an 8 mm diameter
- aluminum alloy cutting force coefficients are: k_{tc} = 604×10^6 N/m^2 and k_{nc} = 223×10^6 N/m^2 (zero edge coefficients)

Stable cut, b = 0.5 mm



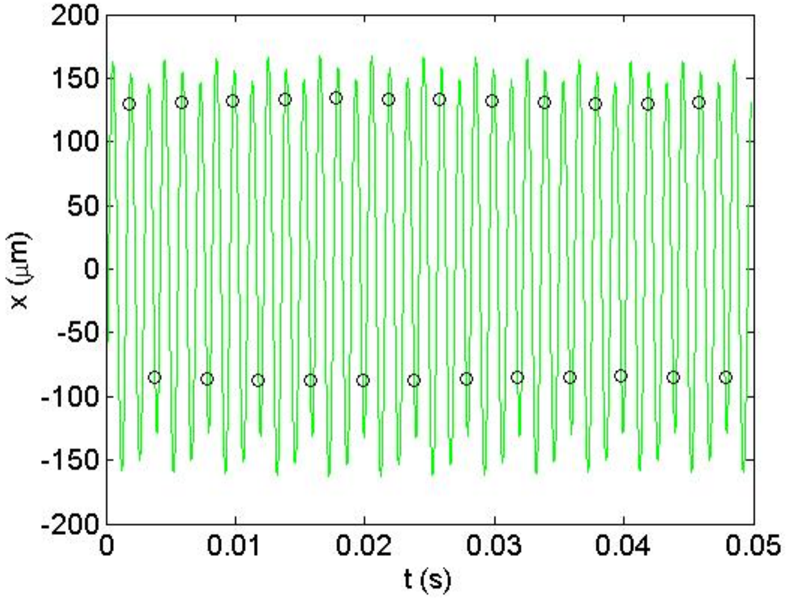
Poincaré map

x vs. $\dot{x}$

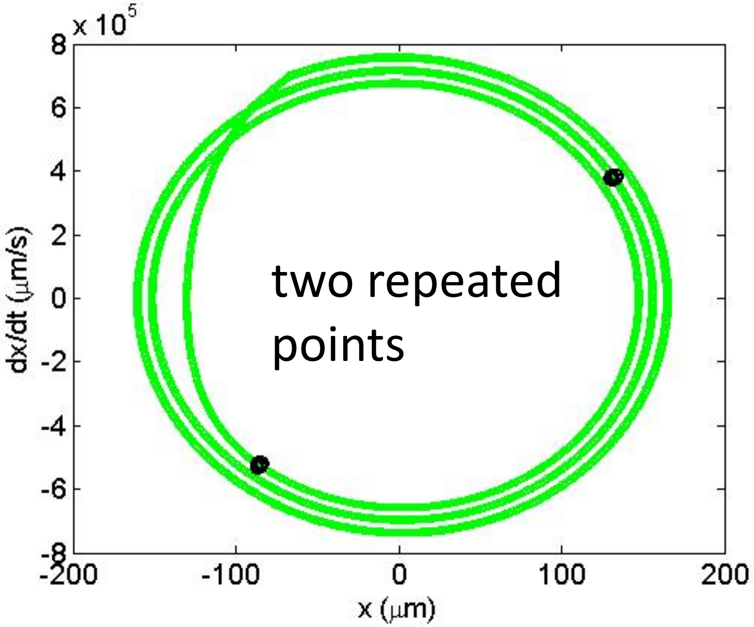


Bifurcation prediction

Unstable cut, b = 2.5 mm



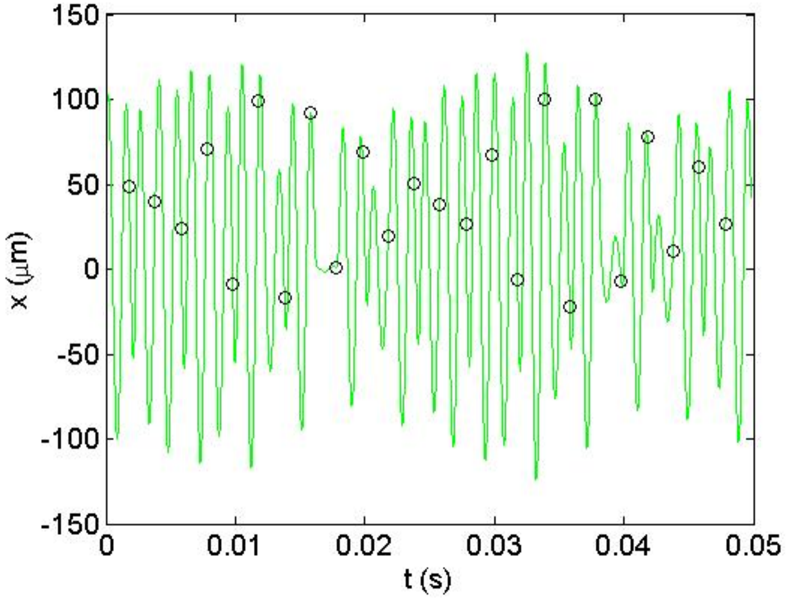
Poincaré map



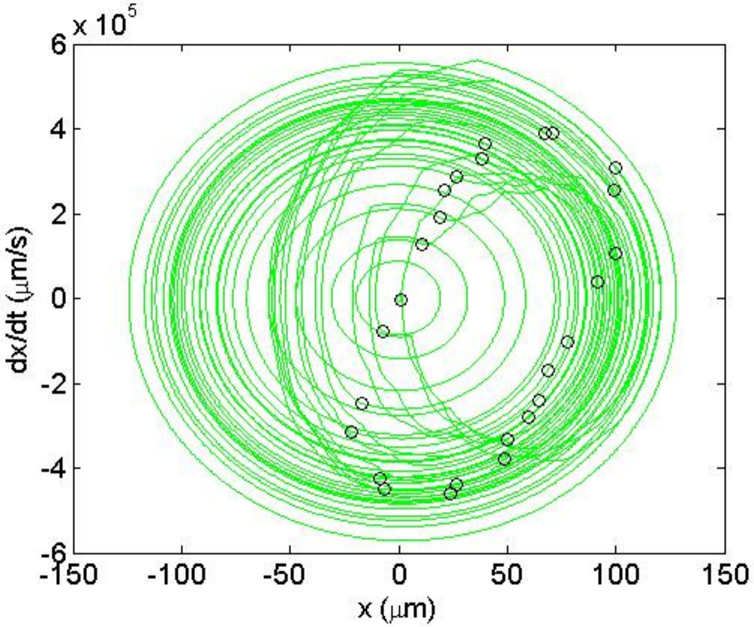
Period-2 bifurcation – once-per-tooth sampled points repeat at two distinct locations (special type of instability or chatter).

Bifurcation prediction

Unstable cut, b = 5 mm



Poincaré map



Secondary Hopf bifurcation – once-per-tooth sampled points do not repeat.

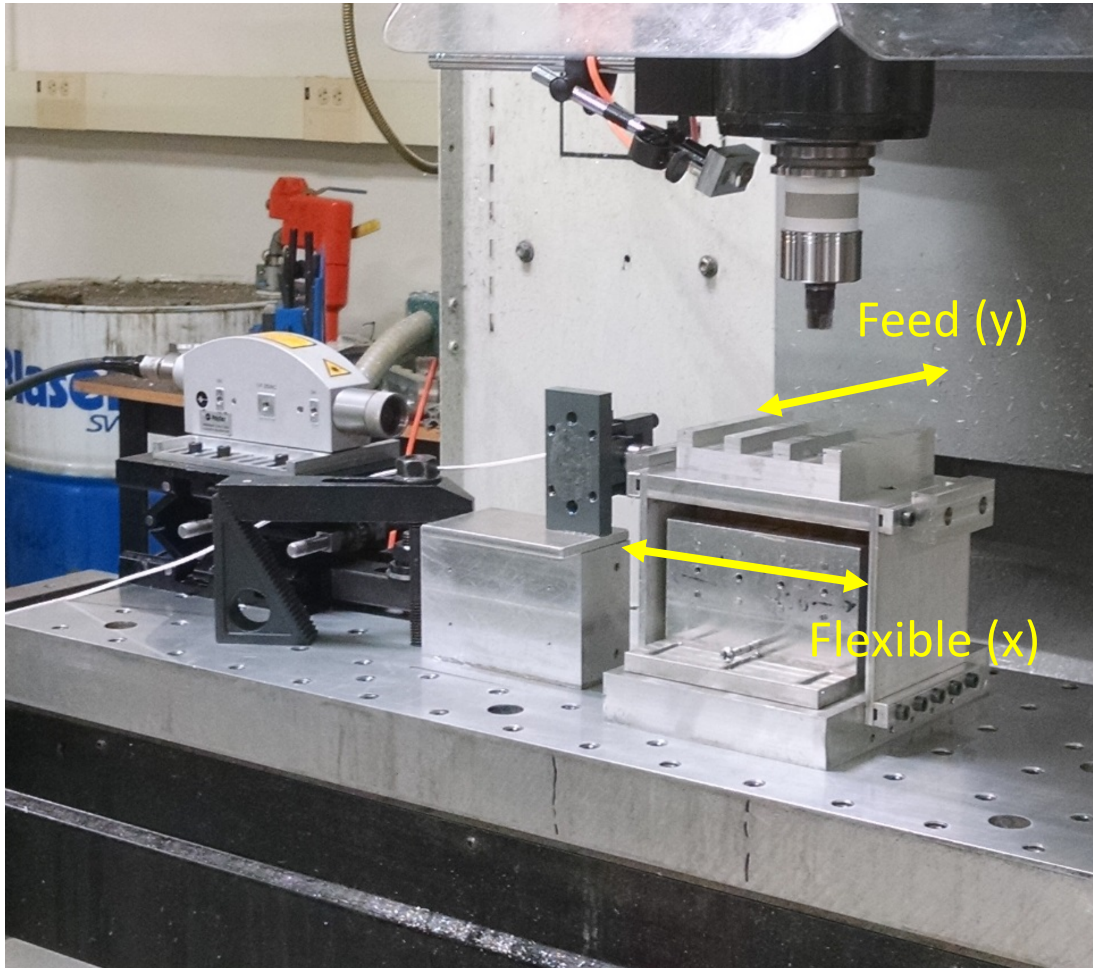
Chatter frequency is near the system natural frequency. This incommensurate frequency yields an **elliptical distribution** of points in the Poincaré map.

Results

Experimental setup for stability and SLE

Flexure dynamics
- Stiffness: 1.75×10^6 N/m
- Damping ratio: 1.36%
- Natural frequency: 125.8 Hz

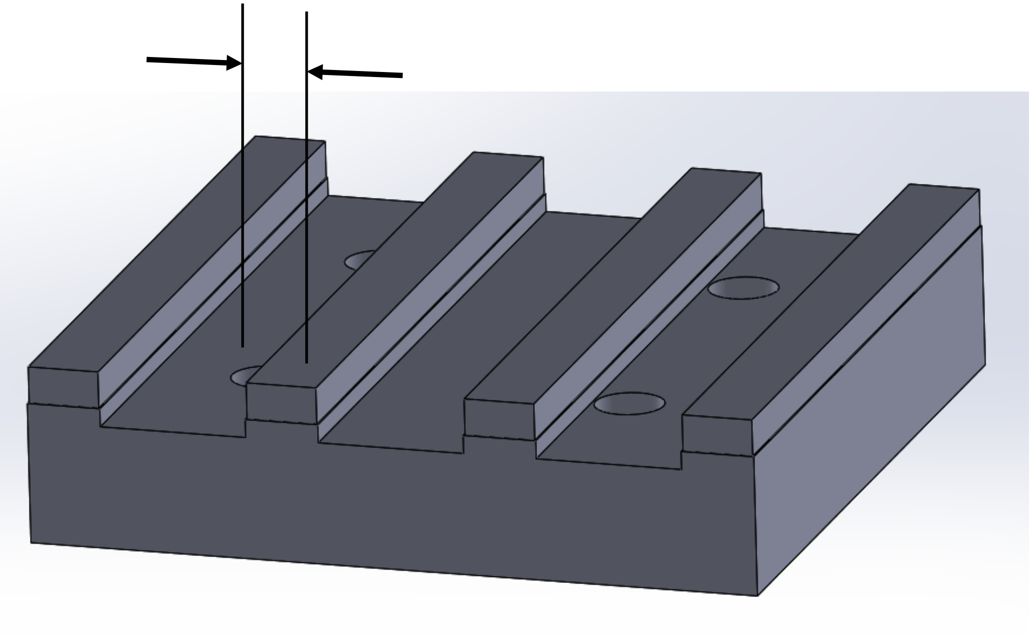
Tool dynamics
- Stiffness: 4.24×10^7 N/m
- Damping ratio: 9.5%
- Natural frequency: 1188 Hz



Results

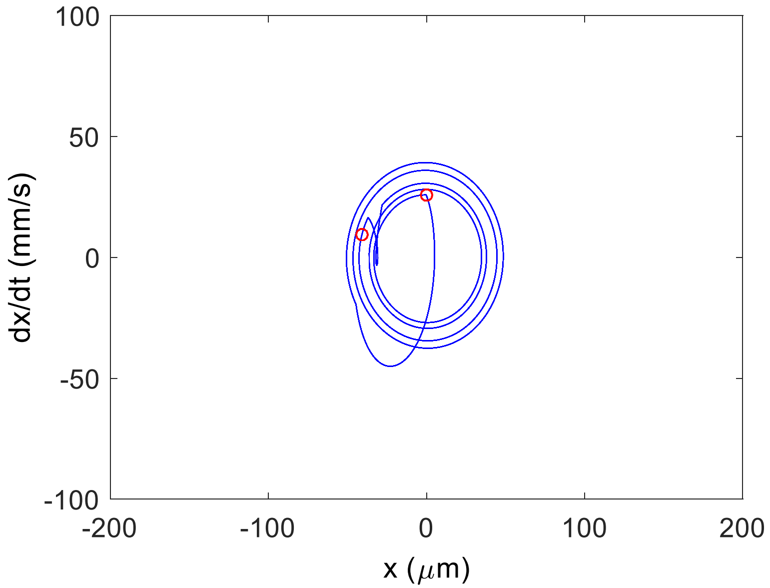
- Initial ribs machined on flexure (9.82 mm wide).
- Final pass completed with 2 mm radial depth of cut, 5 mm axial depth of cut.
- Spindle speed was varied.
- 0.35 mm/tooth
- Up milling
- Single carbide insert cutter
- 6061-T6 aluminum workpiece
- Surface location error (SLE) was measured.

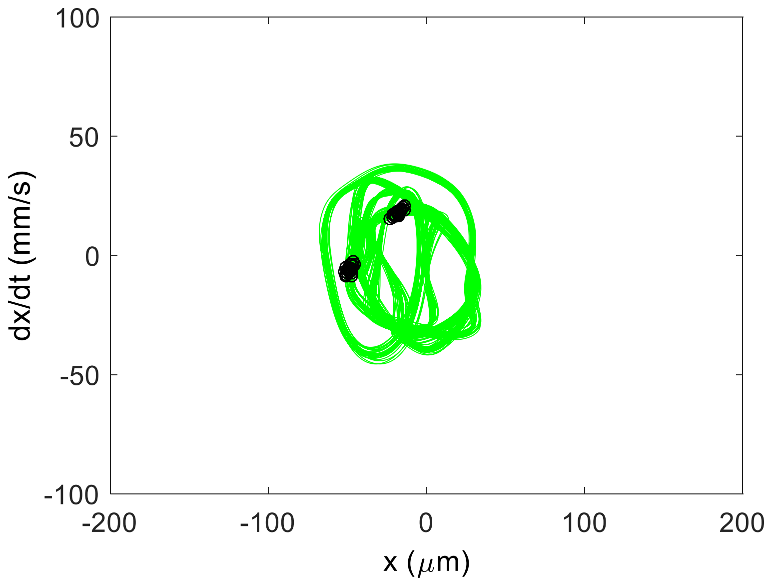
SLE = commanded width – actual width



Results

Spindle speed (rpm)	Behavior
3180	**Period-2**
3190	Period-2
3200	Period-2
3210	Period-2
3270	Stable
3300	Stable
3330	Stable
3360	Stable
3400	Stable
3500	Stable
3600	Stable





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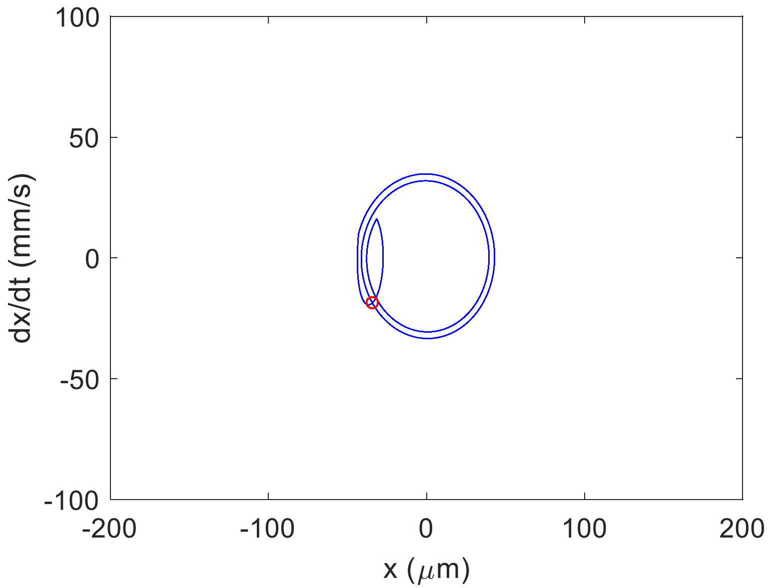

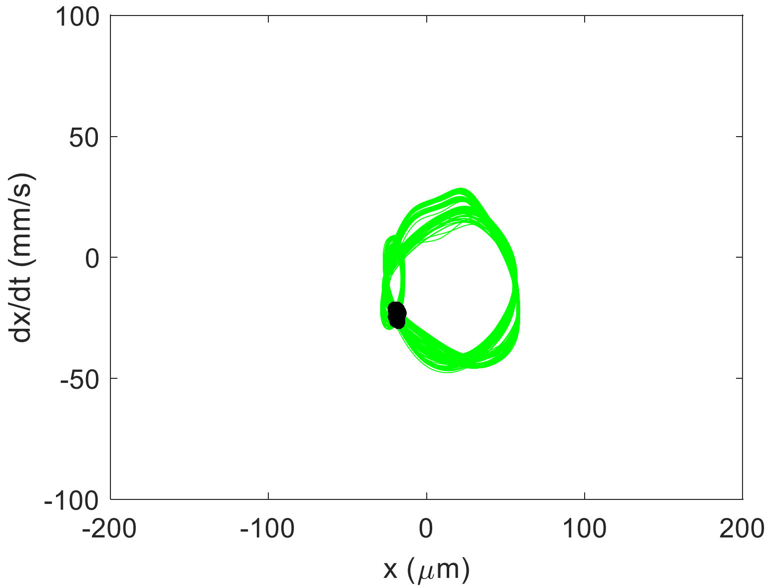

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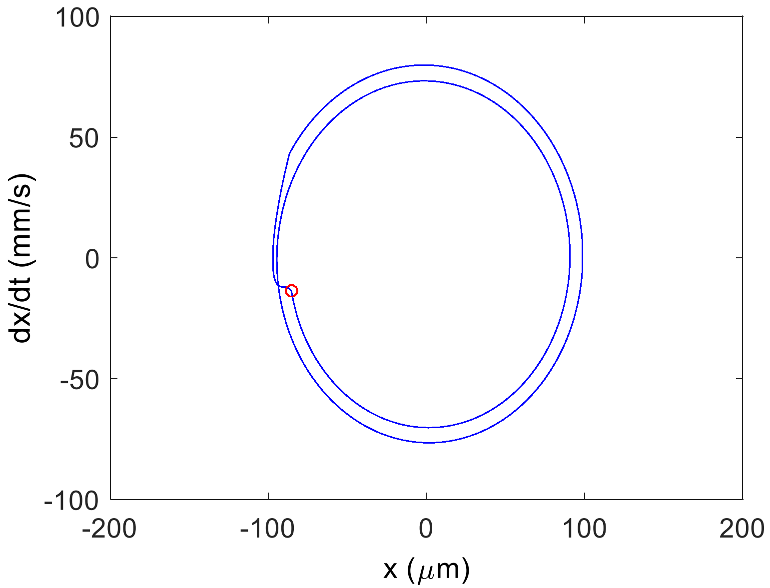
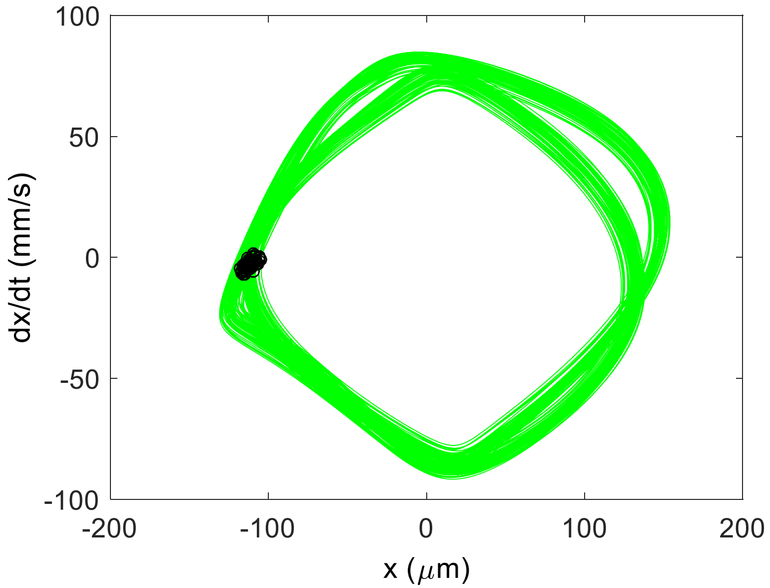
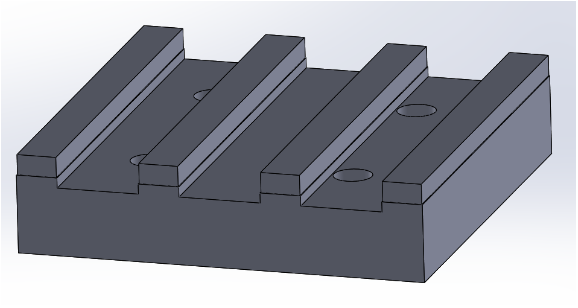
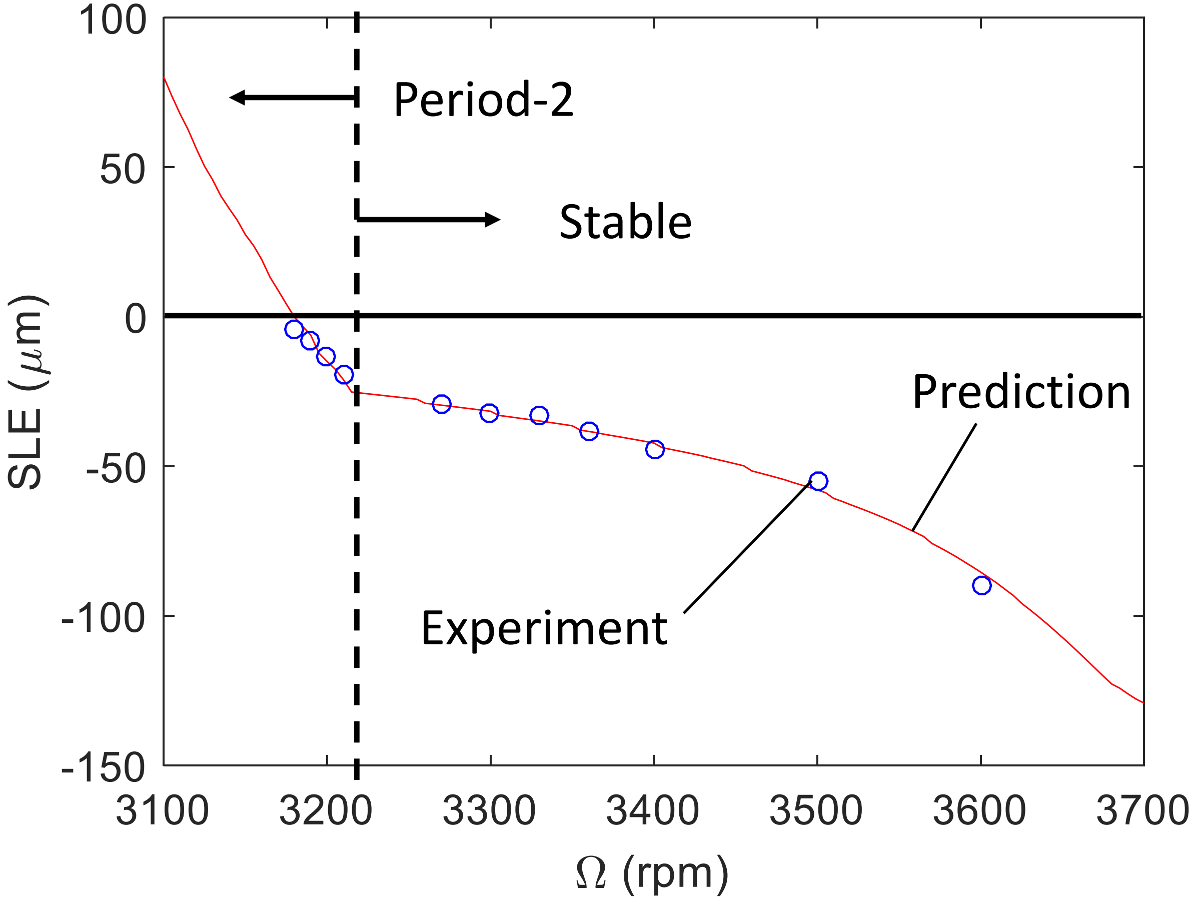




Results

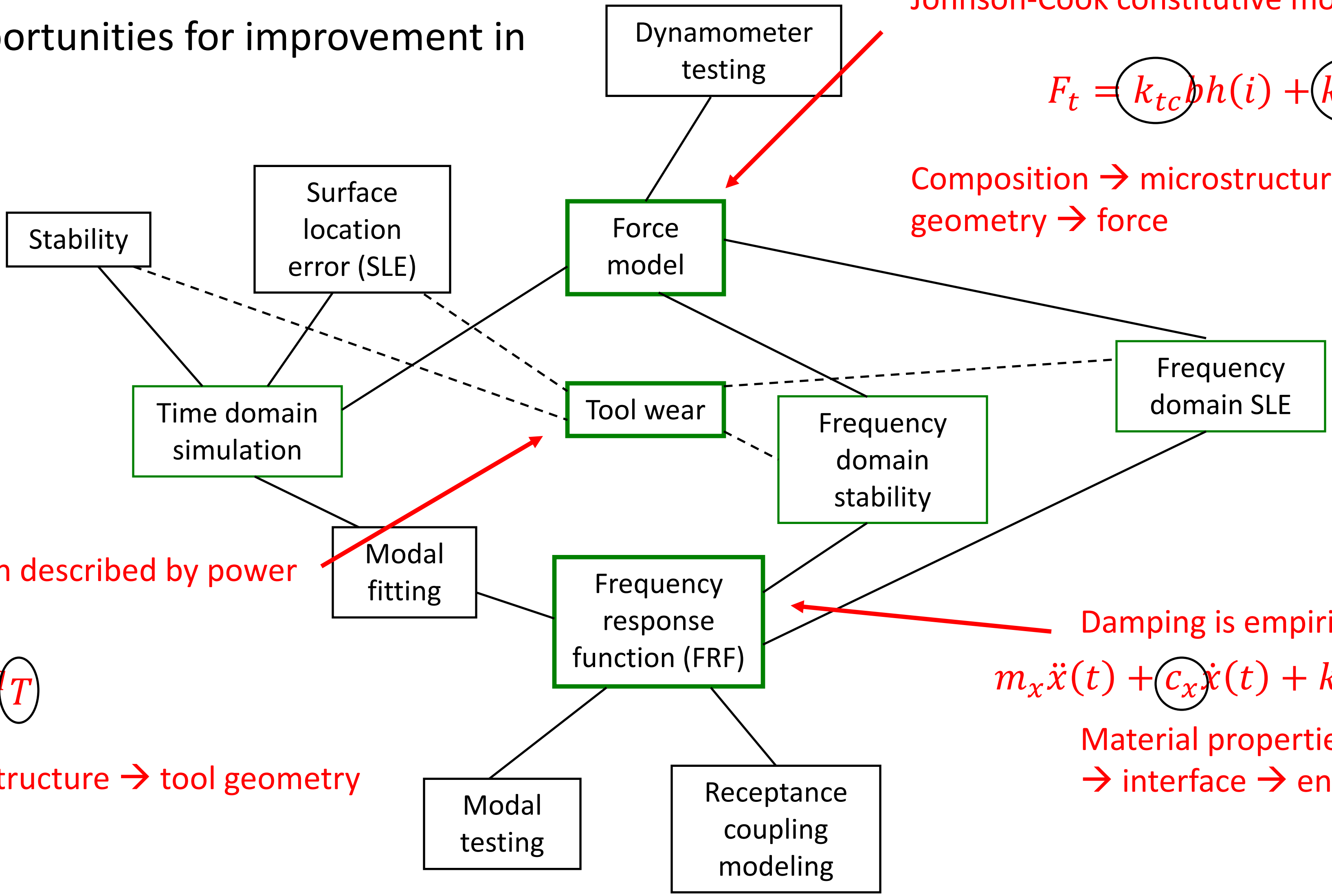


- Parts were measured on CMM and SLE was calculated.
- Experimental results compared to prediction.



Opportunities

- Predictions and experiments differ due to uncertainties.
- What are the opportunities for improvement in machining?



Typically empirical. Can be described using Johnson-Cook constitutive model (or similar).

$$F_t = k_{tc} b h(i) + k_{te} b$$

Composition → microstructure → tool geometry → force

Empirical. Tool life often described by power law (Taylor 1906).

$$C = v^p f_t^q T$$

Composition → microstructure → tool geometry → wear rate

Damping is empirical.

$$m_x \ddot{x}(t) + c_x \dot{x}(t) + k_x x(t) = F_x(t)$$

Material properties → geometry → interface → energy dissipation

Opportunities

Similar opportunities available for other manufacturing operations.

Requirements:

- Process knowledge to define first-principles models (or AI?)
- Materials modeling to relate alloy composition to process behavior
- Experimental capabilities to validate models
- Propagation of input uncertainty to output uncertainty (numerical or analytical)
- Parameter selection under uncertainty (optimization)

Thank you.

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