Machining is More Than Geometry

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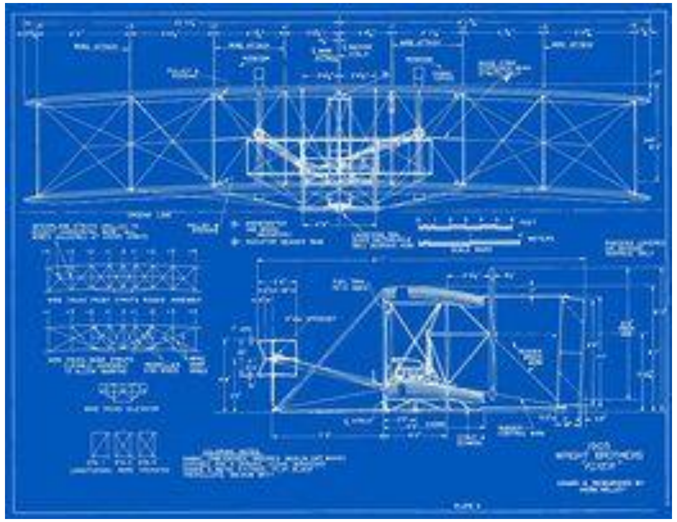
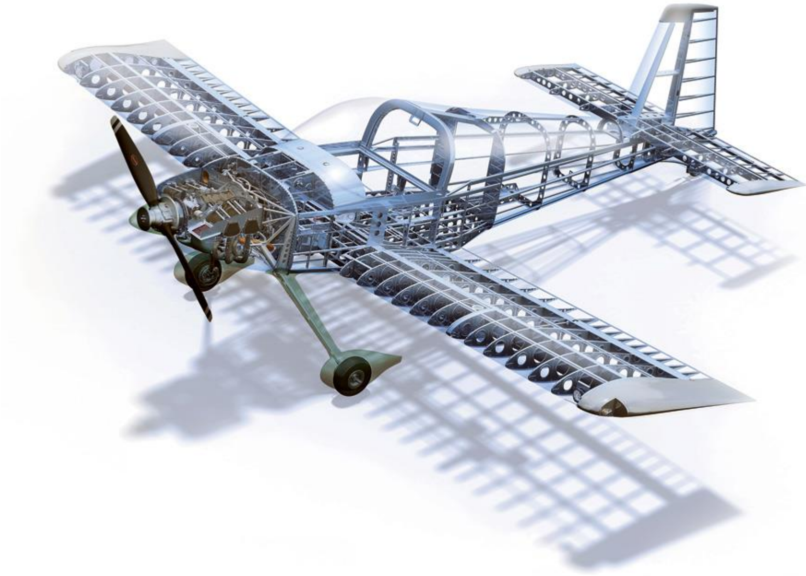
We live in a digital world

What was once blueprints and pencils



is now…

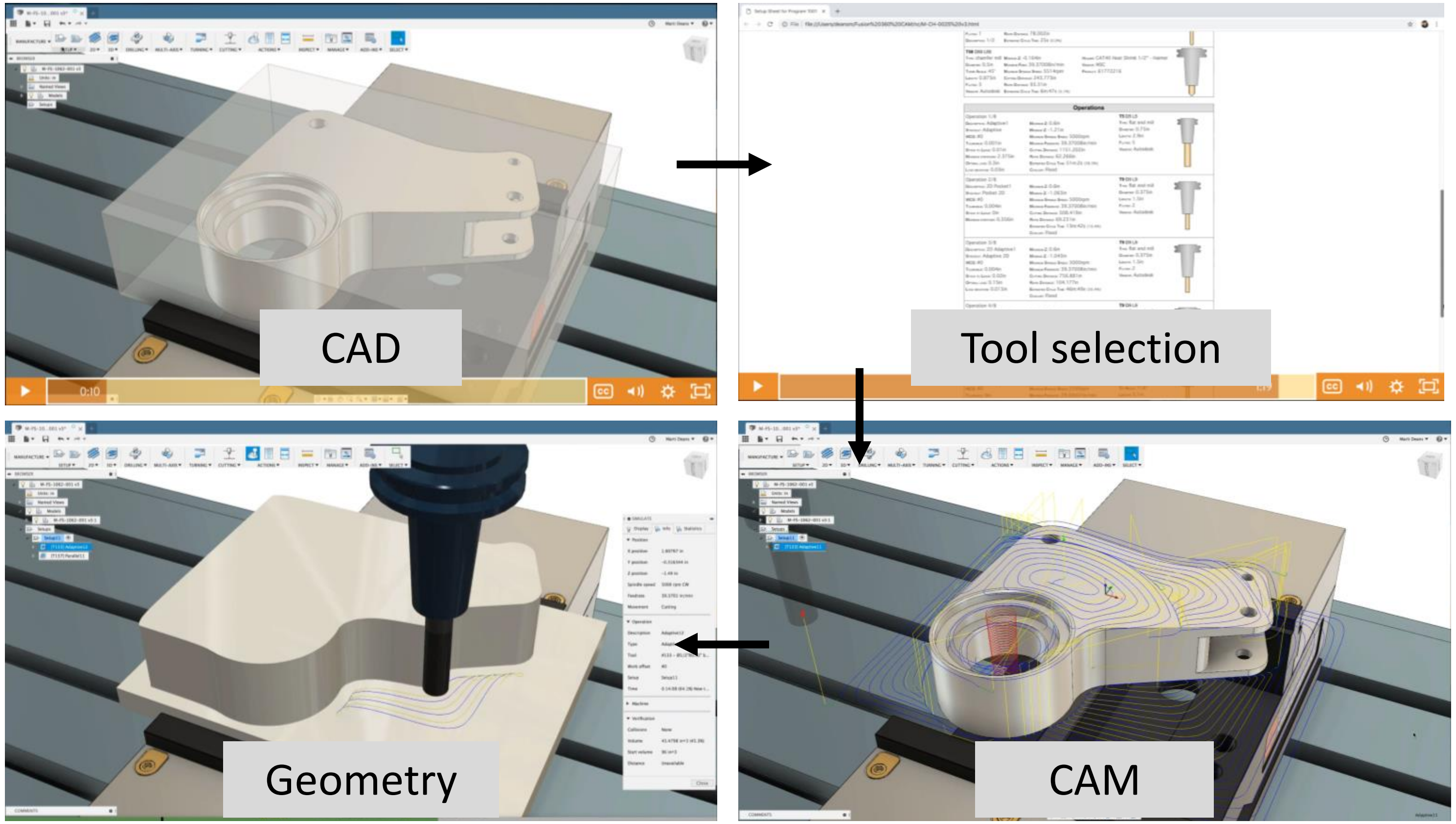
solid models and software applications.



We live in a digital world

For discrete part manufacturing by machining, the digital world steps are:

- Design the part using computer-aided design (CAD) software
- Select the cutting tools that will be used to remove material from the pre-form (bar stock, forging, casting, additively manufactured near-net shape part)
- Generate the tool path using computer-aided manufacturing (CAM) software to produce the final design from the pre-form
- Remove material by following the tool path
- Inspect the part for conformance to design specifications (geometry, surface finish, microstructure, …)

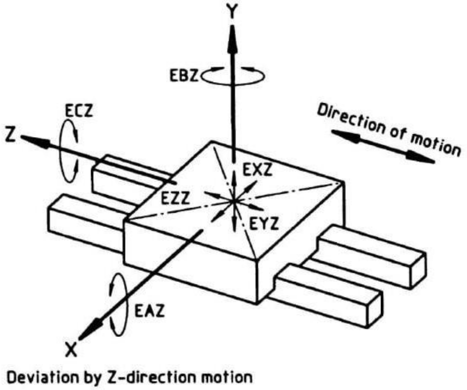


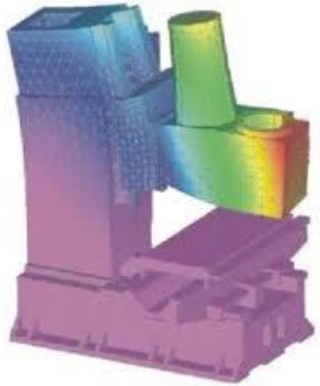
What can go wrong?

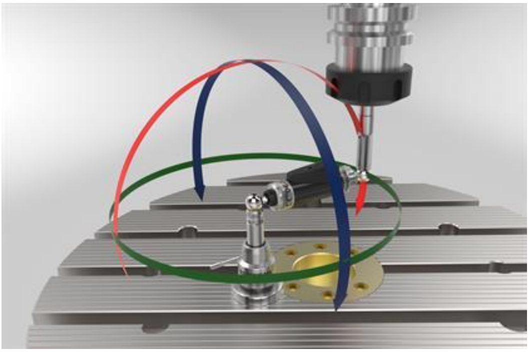
These steps suggest that a digital world treatment is sufficient, but we live in a physical world. What can go wrong?

The tool may not follow the commanded path

- machine tool positioning errors
  - quasi-static – kinematics/thermal state
  - dynamic – high-speed contouring





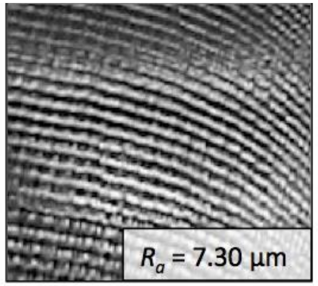


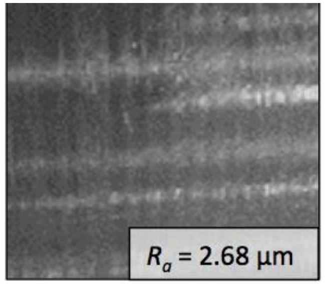
The tool may wear out

- Machining is a competition between the sharp cutting edge and workpiece
- Higher speeds lead to higher temperature and accelerated wear
- Empirical – tool material/geometry, work material, coolant, parameters (sub-optimal)

Vibration may be excessive

- The cutting force causes tool/workpiece displacement
- Can result in chatter, a self-excited vibration
- Behavior depends on setup (sub-optimal)



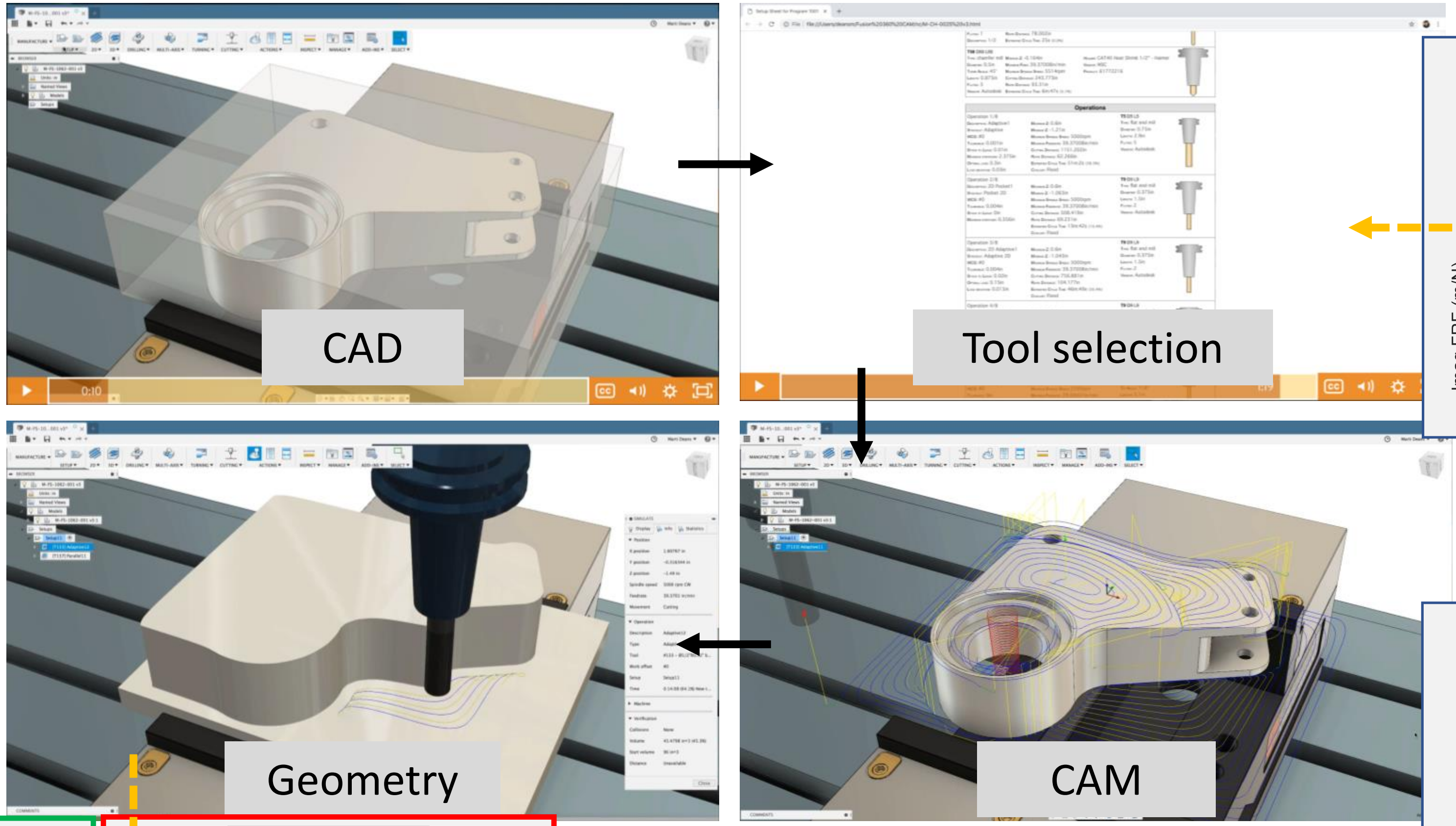


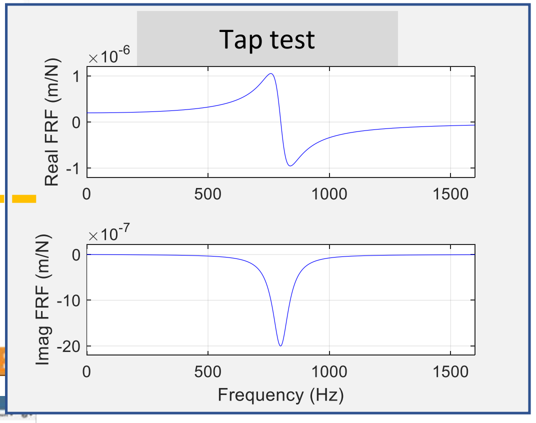
Machine tool may fail

- Preventative maintenance
- Predictive maintenance

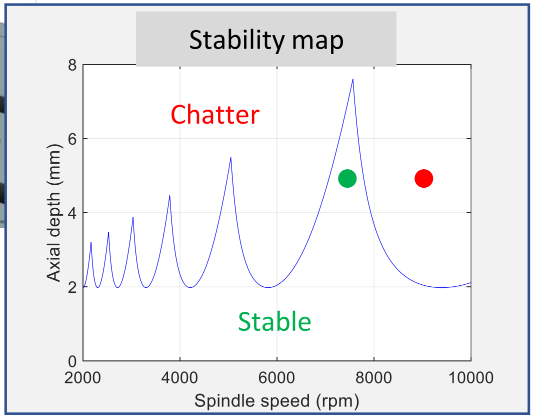
Machining is more than geometry

Let's consider vibration implications

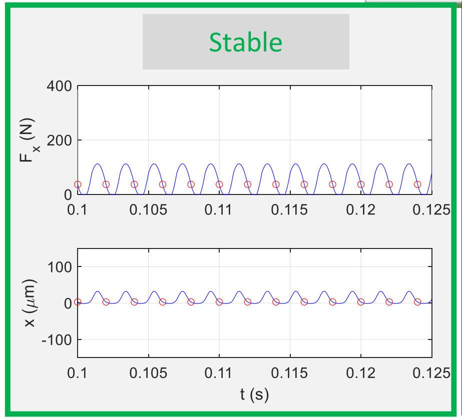


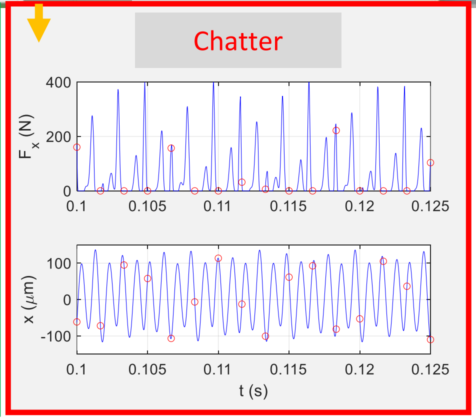


Structural dynamics



Machining parameters

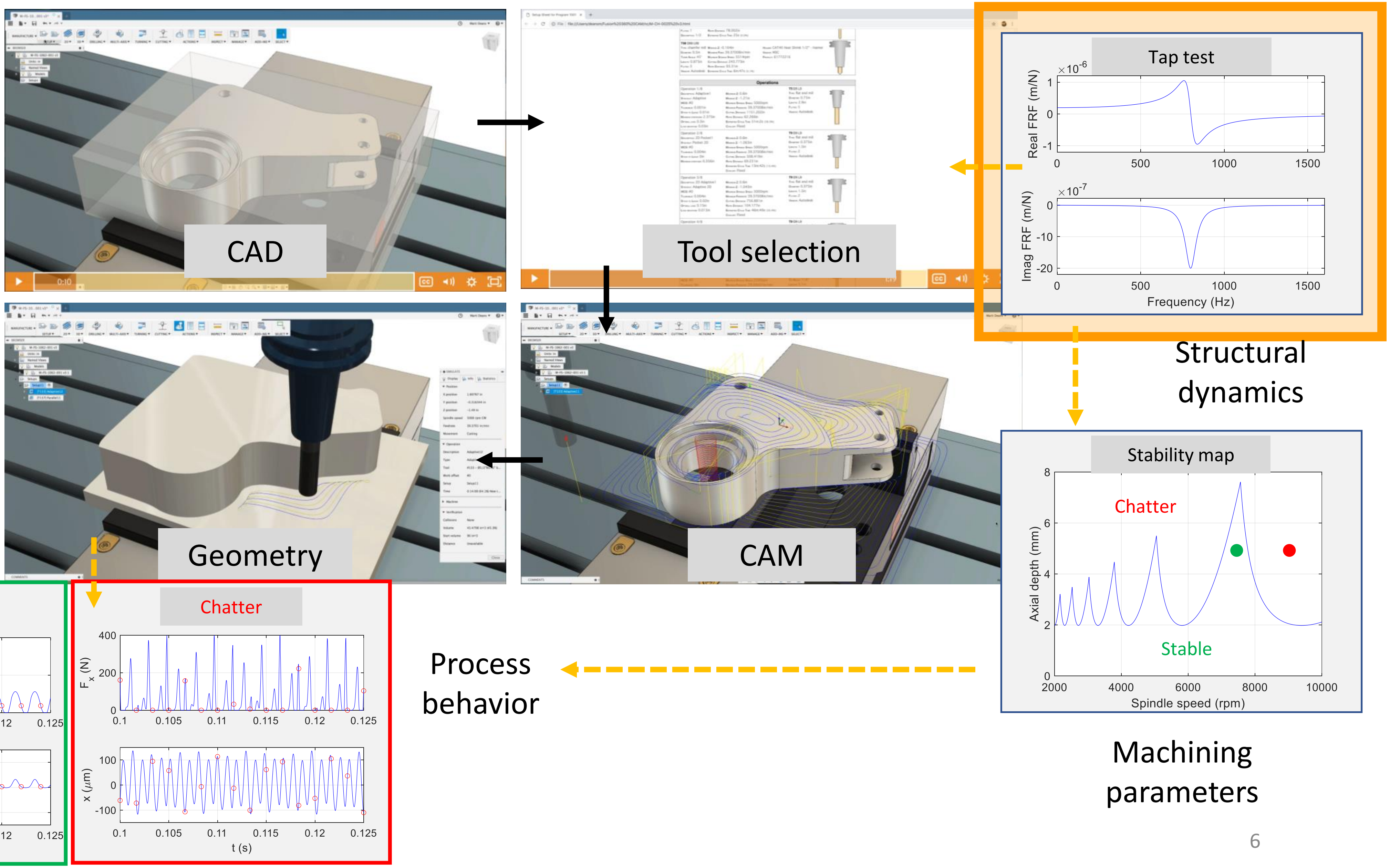


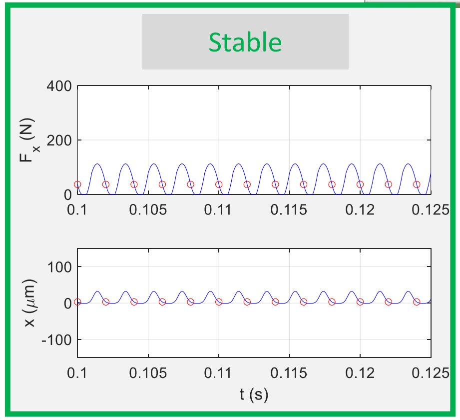


Process behavior

Machining is more than geometry

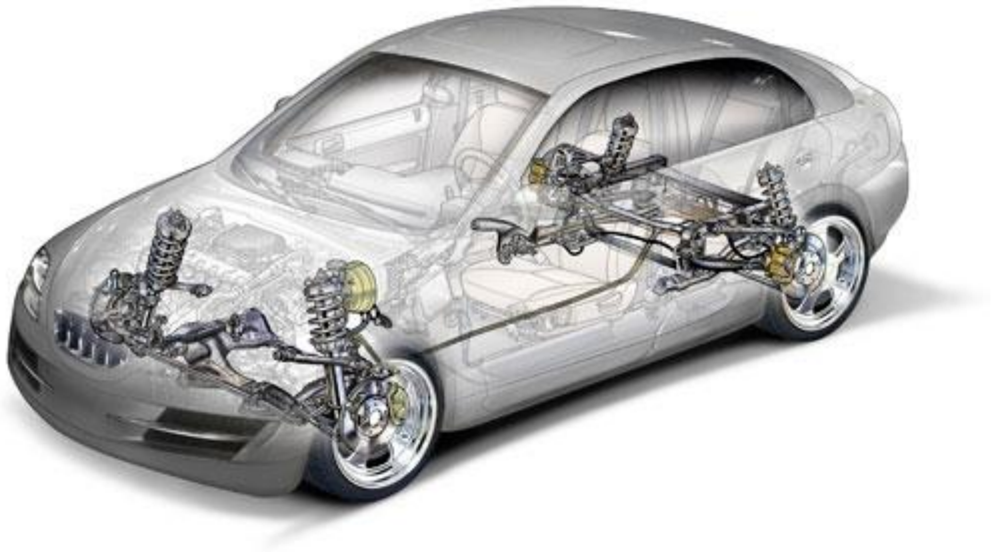
Let's consider vibration implications





Mechanical vibrations

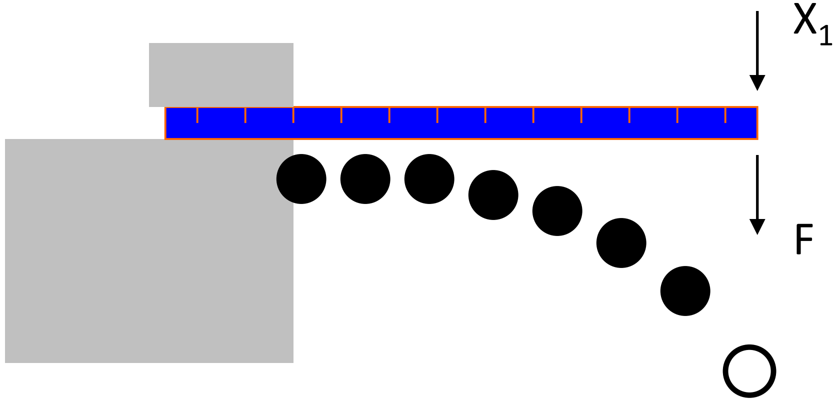
All structures vibrate

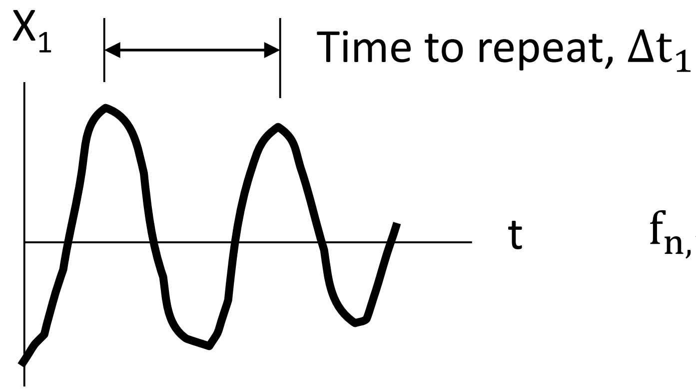


Mechanical vibrations

Natural frequency: vibrating frequency that is inherent to the structure

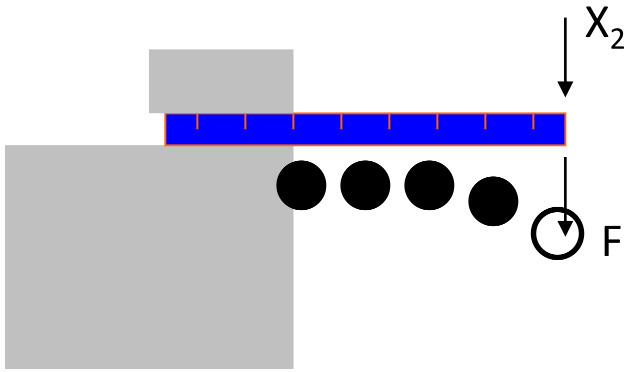
Cantilever beam: ruler clamped to a table

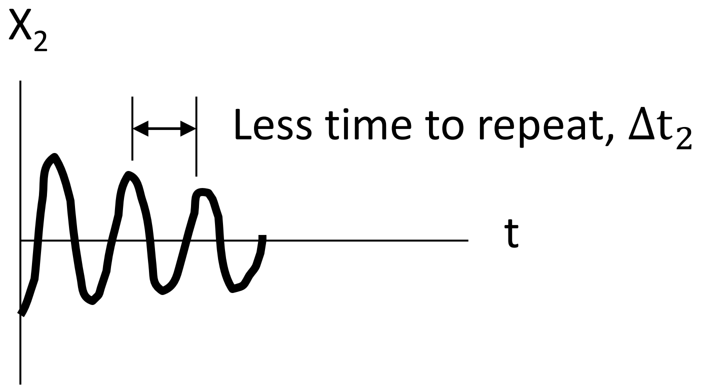




$$f_{n,1} = \frac{1}{\Delta t_1}$$

Motion stops after some time: damping





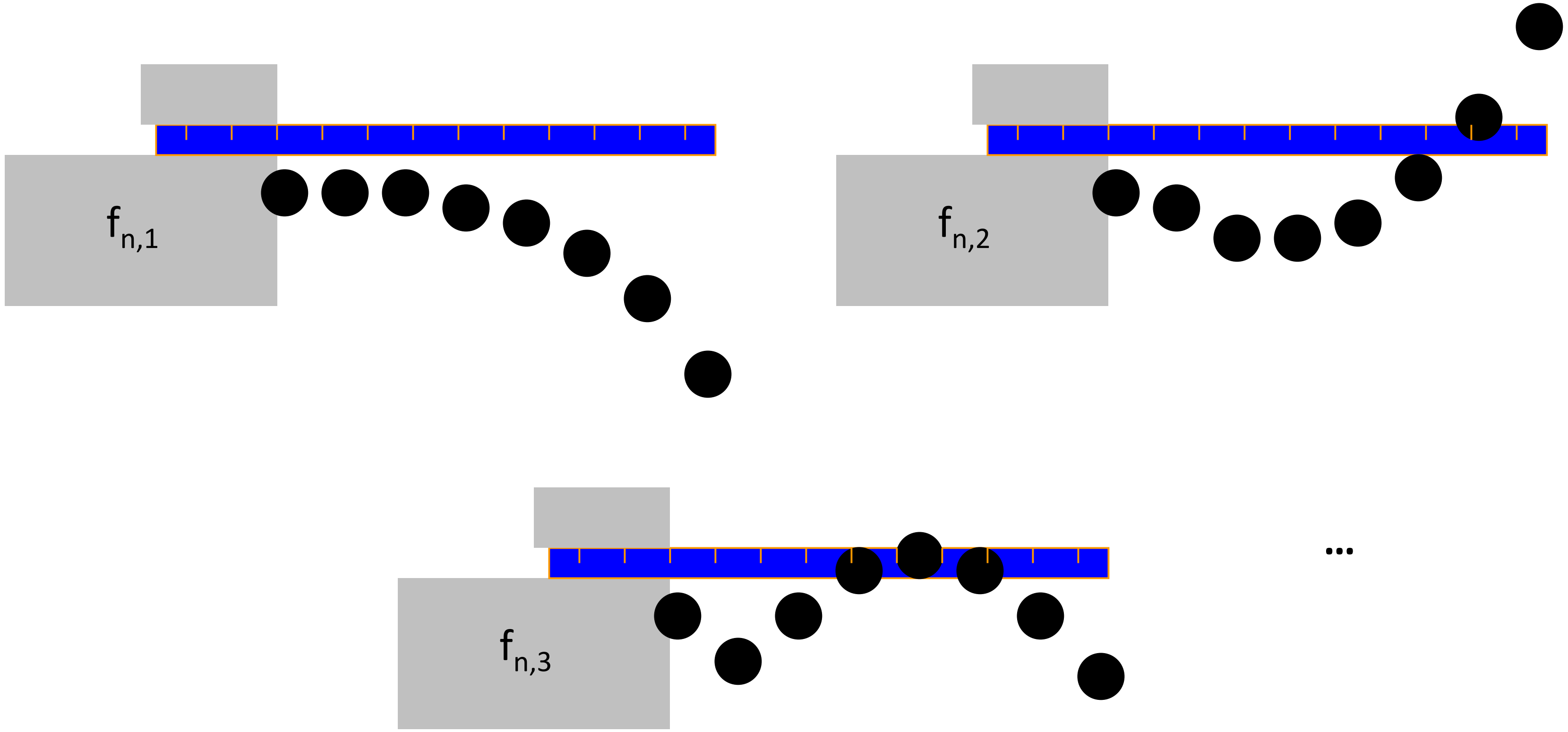
$$f_{n,2} = \frac{1}{\Delta t_2} > f_{n,1}$$

Shorter beam

- higher natural frequency
- smaller amplitude for same excitation; it has higher stiffness

Mechanical vibrations

- **Mode shape**: deformation profile while vibrating at a natural frequency
- Cantilever beam 1st, 2nd, and 3rd mode shapes
- Each mode shape has an associated natural frequency

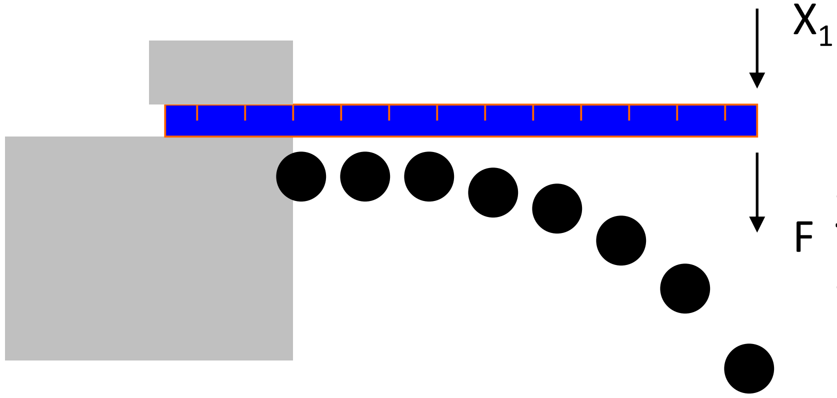


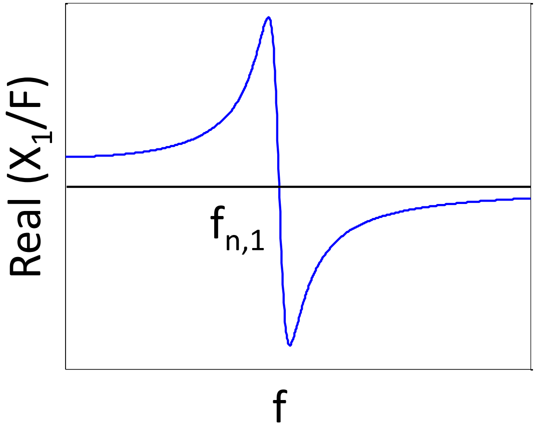
Multiple natural frequencies and associated mode shapes are present in every structure.

Mechanical vibrations

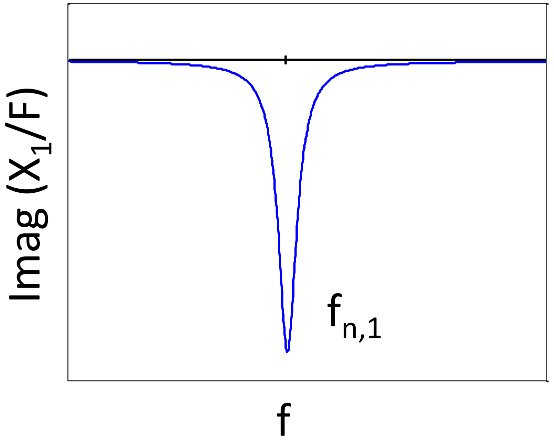
Frequency response function (FRF)

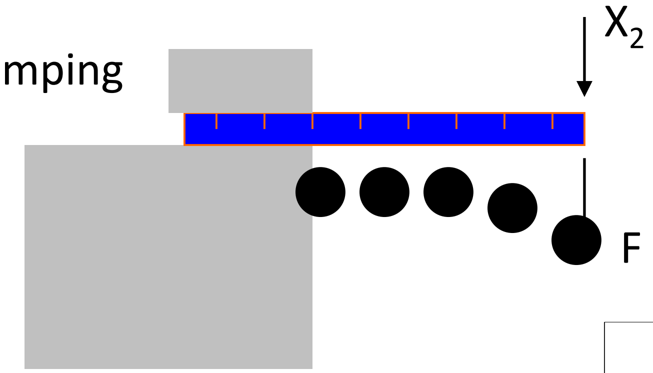
- contains information about natural frequency, stiffness, and damping
- specific to the structure and location: dynamic fingerprint

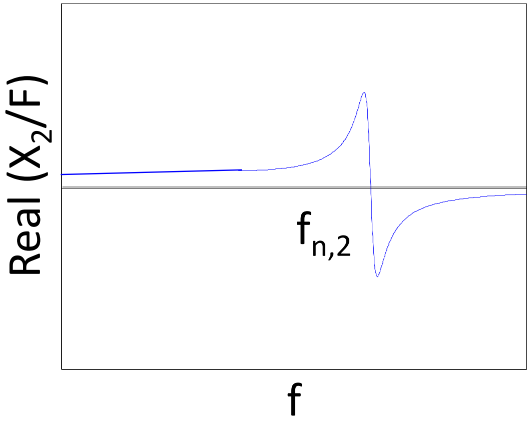




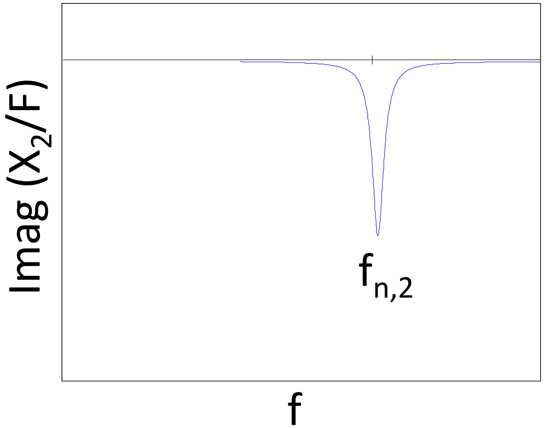
Lower natural frequency, larger amplitude



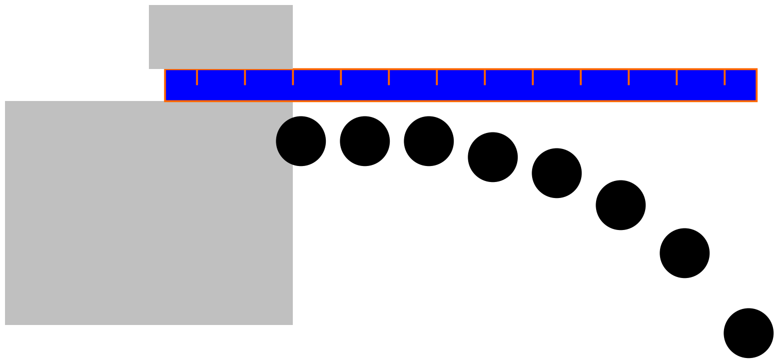




Higher natural frequency, smaller amplitude



Frequency response function (FRF)
- can be expressed mathematically
- complex-valued function (real and imaginary parts)



$$\mathrm{Re}\left[\frac{X}{F}(f)\right] = \frac{1}{k}\left(\frac{1-\left(\frac{f}{f_n}\right)^2}{\left(1-\left(\frac{f}{f_n}\right)^2\right)^2+\left(2\zeta\left(\frac{f}{f_n}\right)\right)^2}\right)$$

Excitation frequency

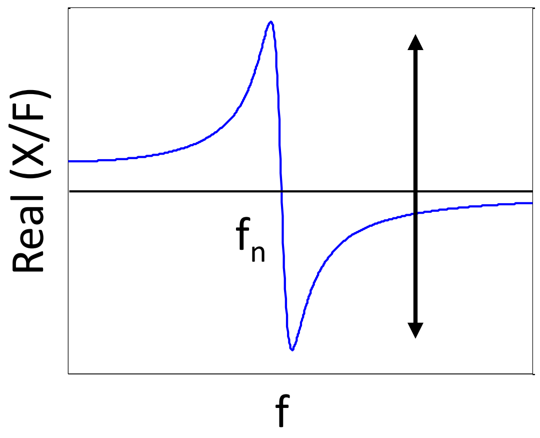
Stiffness

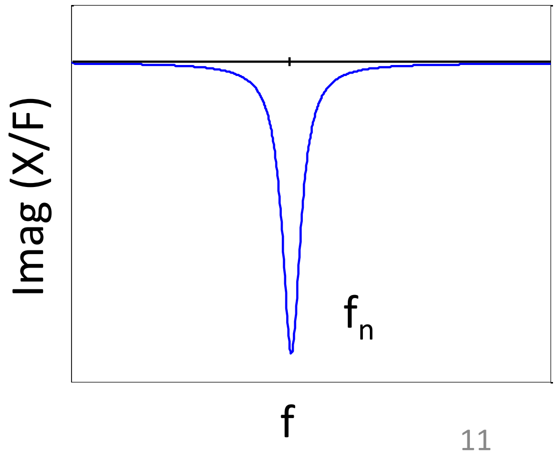
Natural frequency

Damping ratio

$$\mathrm{Im}\left[\frac{X}{F}(f)\right] = \frac{1}{k}\left(\frac{-2\zeta\frac{f}{f_n}}{\left(1-\left(\frac{f}{f_n}\right)^2\right)^2+\left(2\zeta\left(\frac{f}{f_n}\right)\right)^2}\right)$$

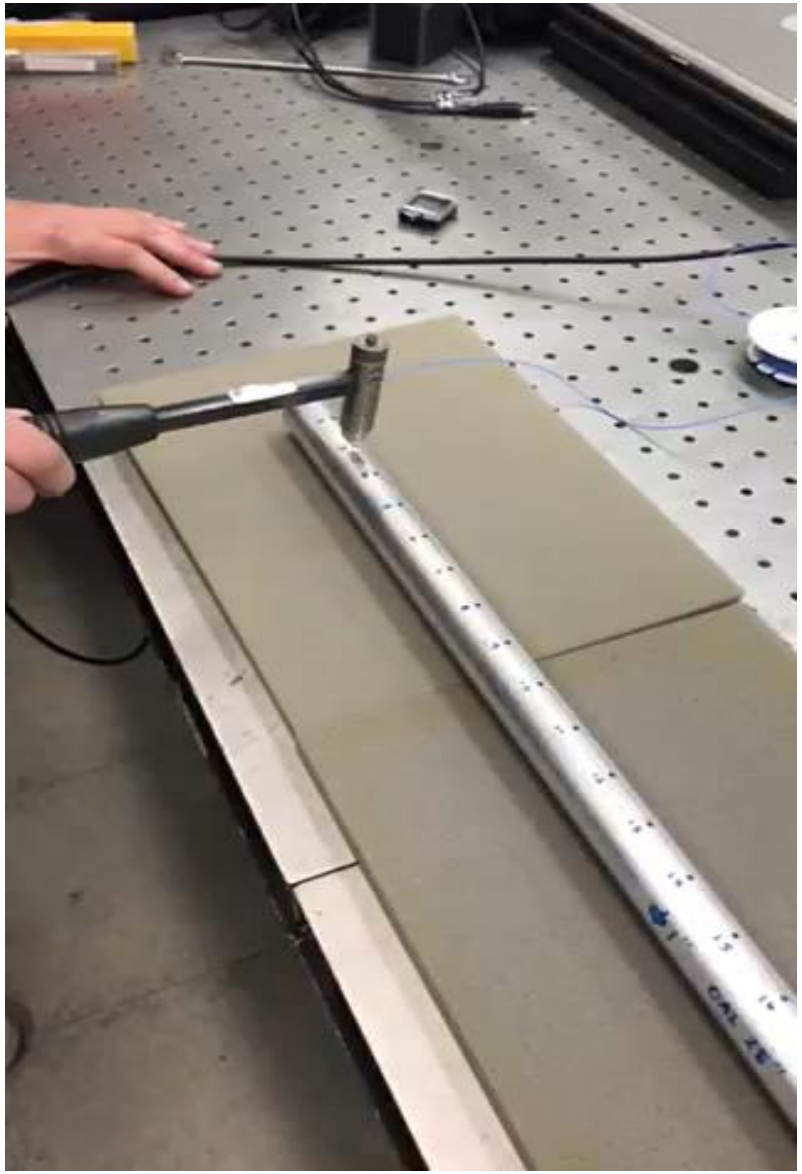
Larger amplitude with smaller stiffness and damping

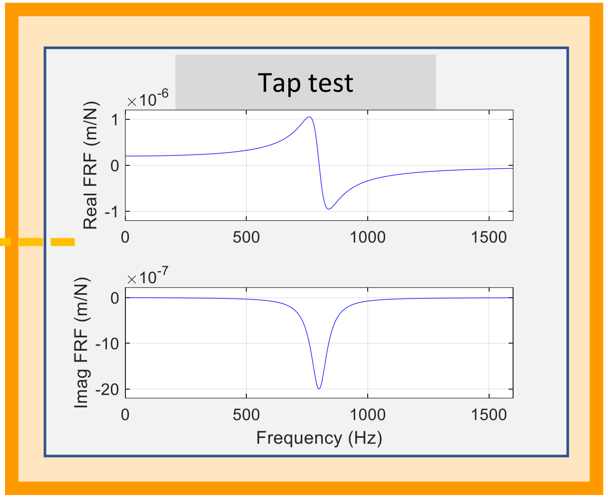




Tap test

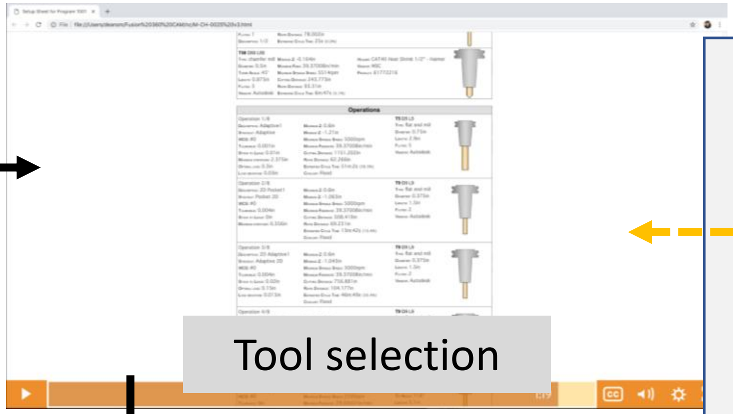
- Instrumented hammer excites the structure
- Accelerometer measures the response
- Ratio is the FRF
- Provides the information required to predict machining performance

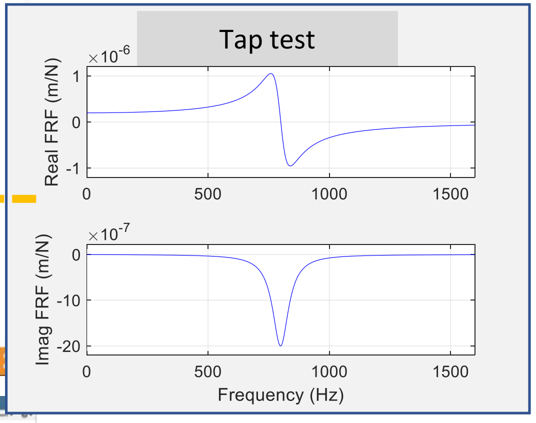




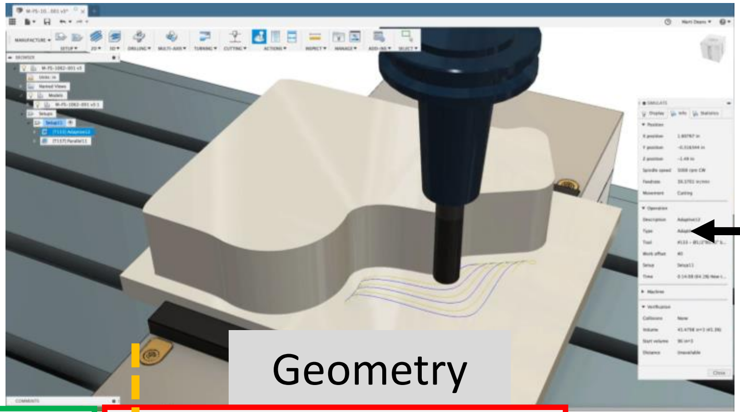
Machining dynamics

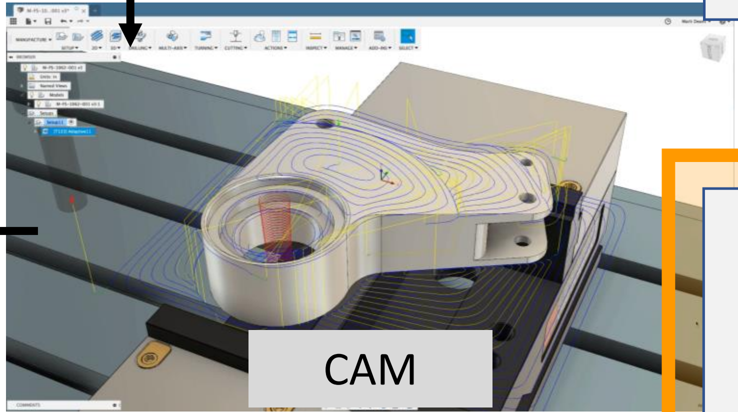
Let's consider vibration implications

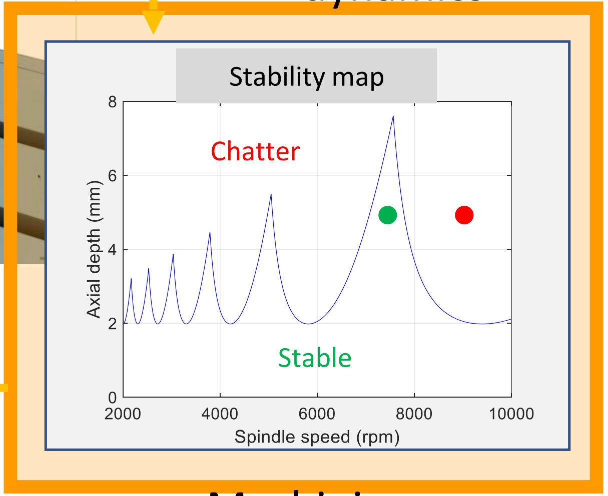


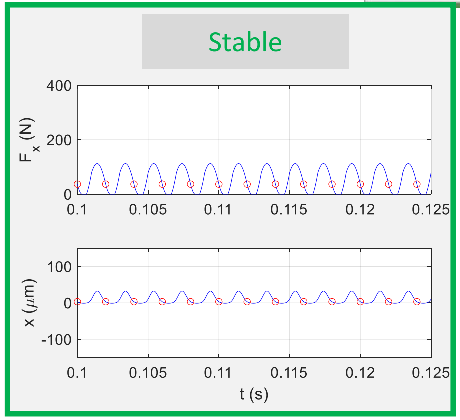


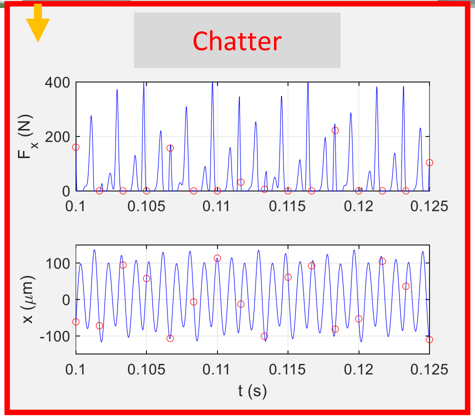
Structural dynamics











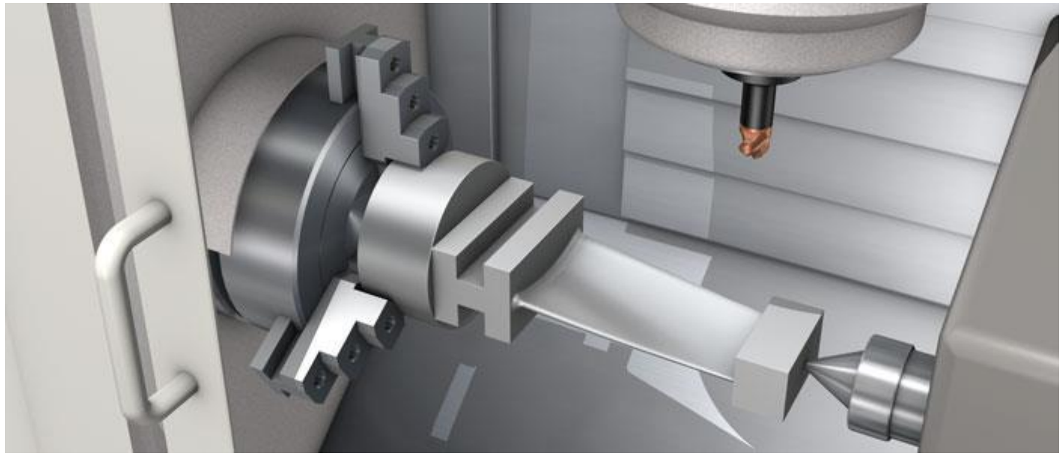
Process behavior

Machining parameters

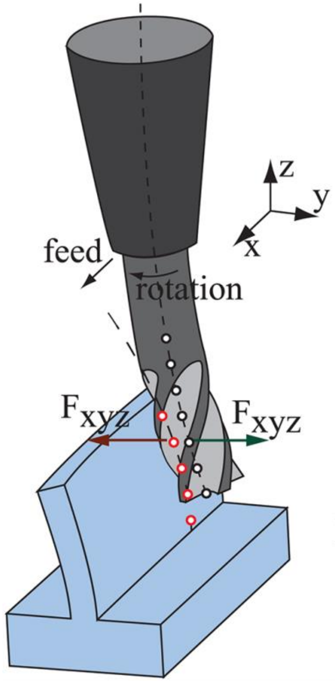
Tool flexibility
Cutting tools are designed to be stiff. The materials are selected to be hard and resist deformation.

However, when the cutting force is applied to the tool it still deflects. You can think of a tool as a stiff spring.

Workpiece flexibility
Sometimes the workpiece is also flexible. In this case, the workpiece can deflect as much or more than the tool when the cutting force is applied. It can also be thought of as a spring.

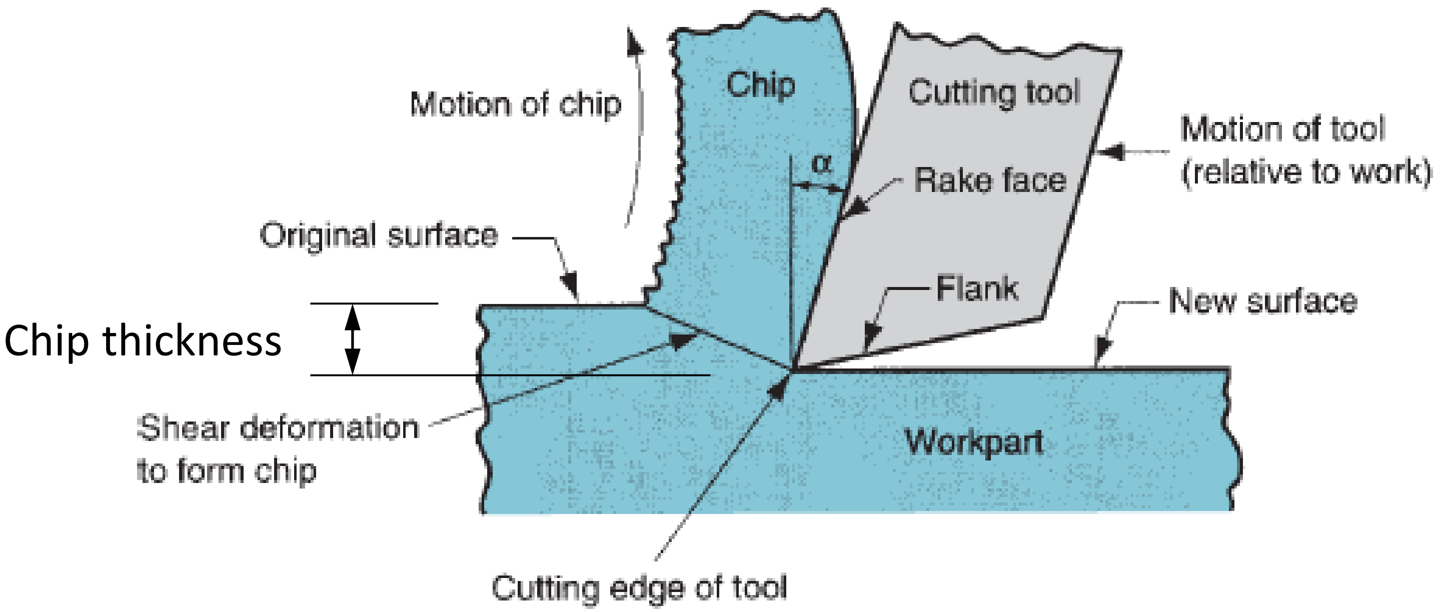


Damping is also important!



Cutting force

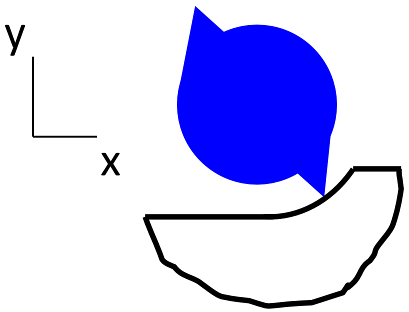
The cutting force is generated as the tool shears away material in the form of a chip.

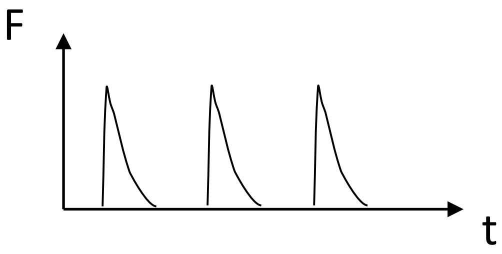


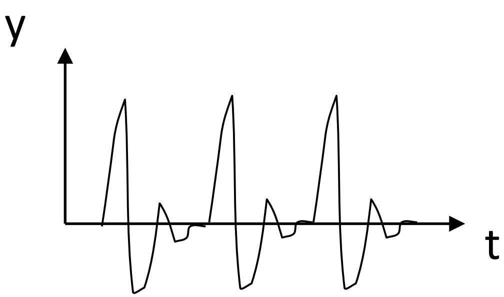
- The cutting force depends on the chip thickness, chip width (into page), material properties, and tool geometry.
- Larger chip width/thickness and gives higher force.

Why does vibration occur in milling?

- teeth constantly enter and exit the cut
- the cutting force varies with these entries and exits
- the variable cutting force acts on the flexible tool and/or workpiece and causes displacement
- this variable displacement is vibration
- the amplitude of vibration depends on the tool/workpiece stiffness and spindle rotating frequency





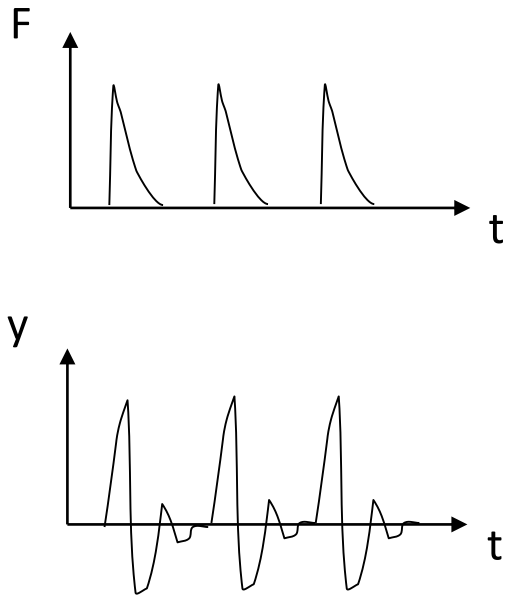


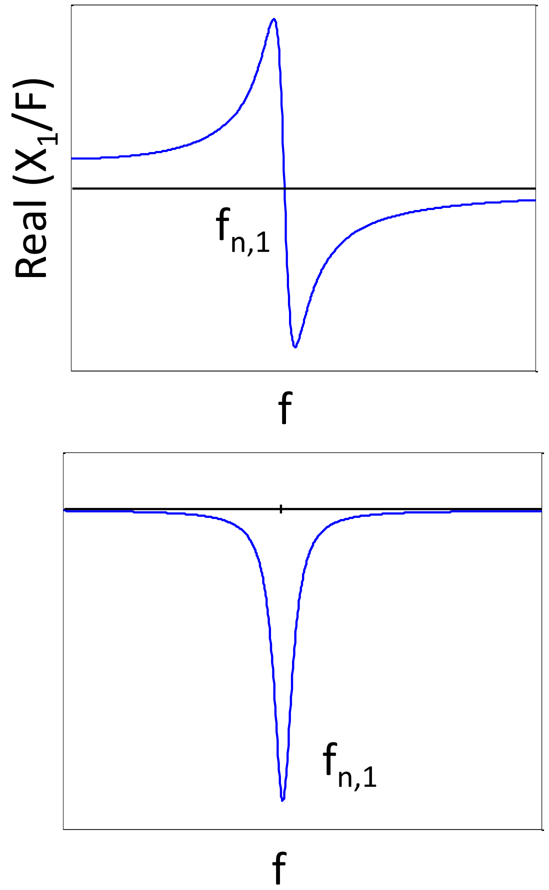
There are two main types of vibration in milling.

1) Forced vibration

The variable force causes the tool or workpiece to vibrate at the same frequency. For a spindle speed of 12000 rpm and a cutter with two teeth, the tooth passing frequency is 12000/60*2 = 400 Hz.

The corresponding amplitude of vibration depends on the relationship between the tooth passing frequency and the tool/workpiece dynamics. We describe the dynamics using the **frequency response function**, or FRF.



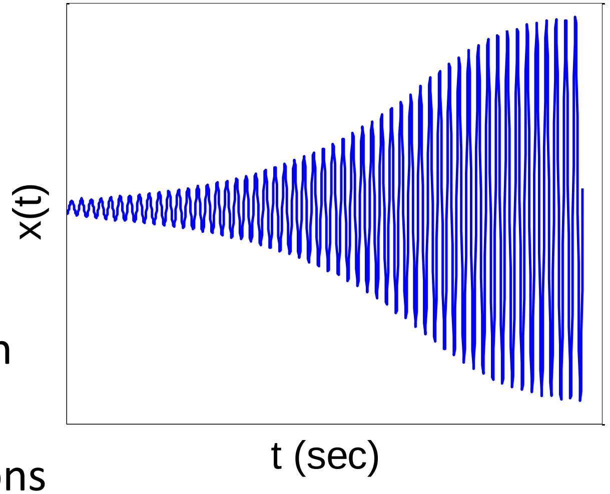


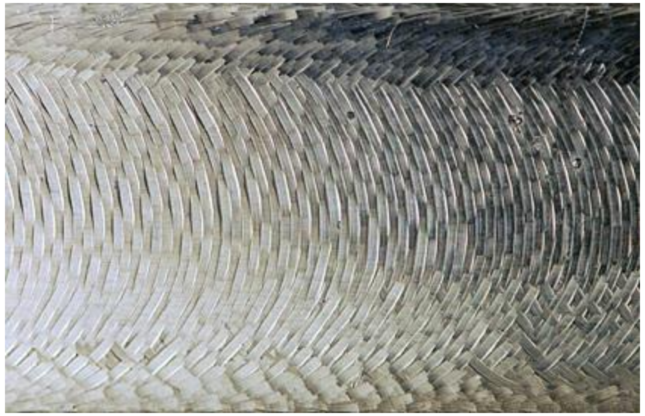
2) Self-excited vibration

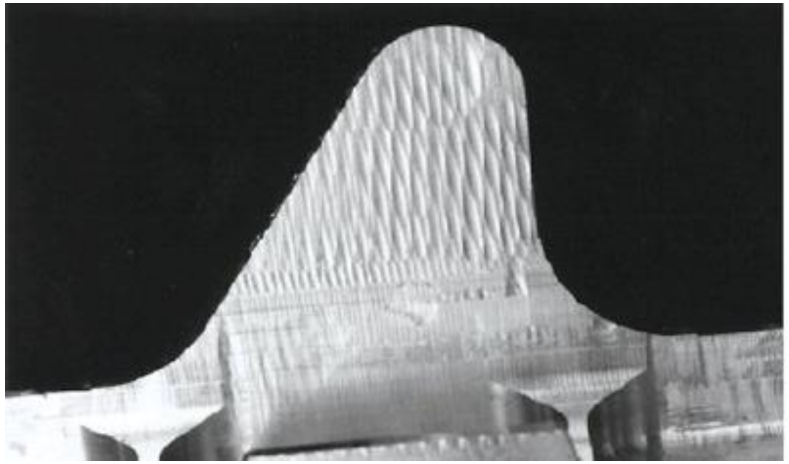
Steady input force is modulated into vibration at the system **natural frequency**.

Examples include:

- whistle - steady air flow produces acoustic vibration
- violin - bow across string produces vibration at frequency that depends on the string length
- airplane wing flutter
- **chatter** in machining - steady excitation of teeth impacting work leads to large tool vibrations at system natural frequency

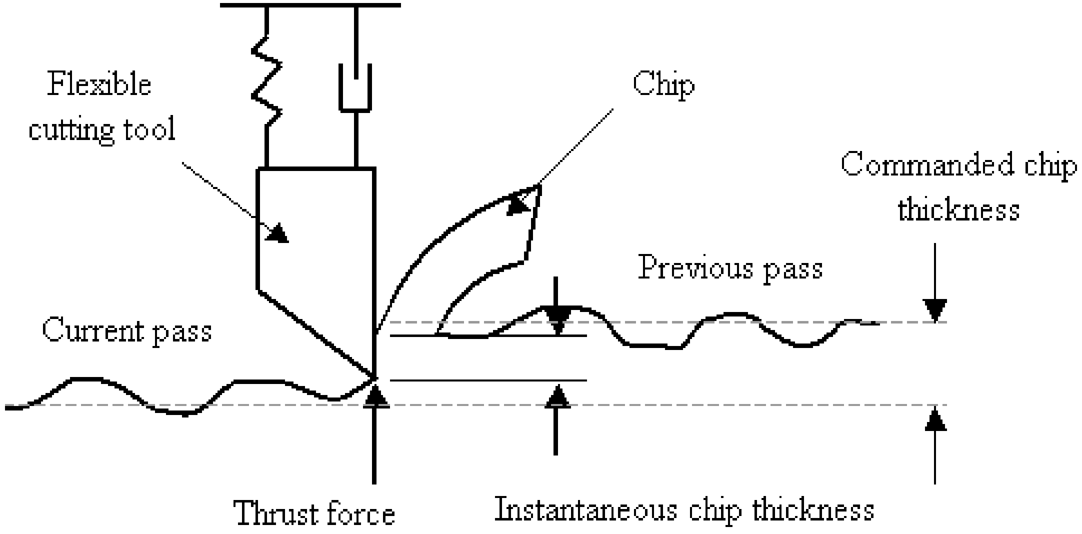


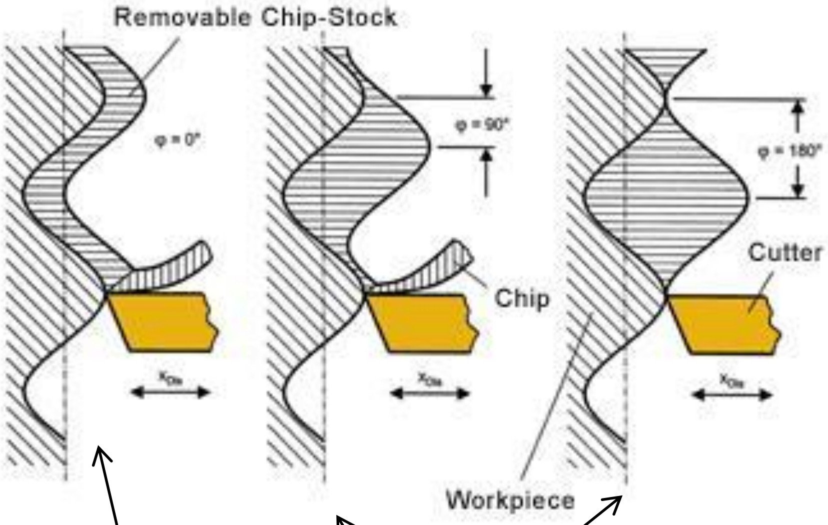




Tacoma Narrows Bridge opened in July 1940, but collapsed due to aero-elastic flutter four months later.

Why does chatter (self-excited vibration) occur in machining?





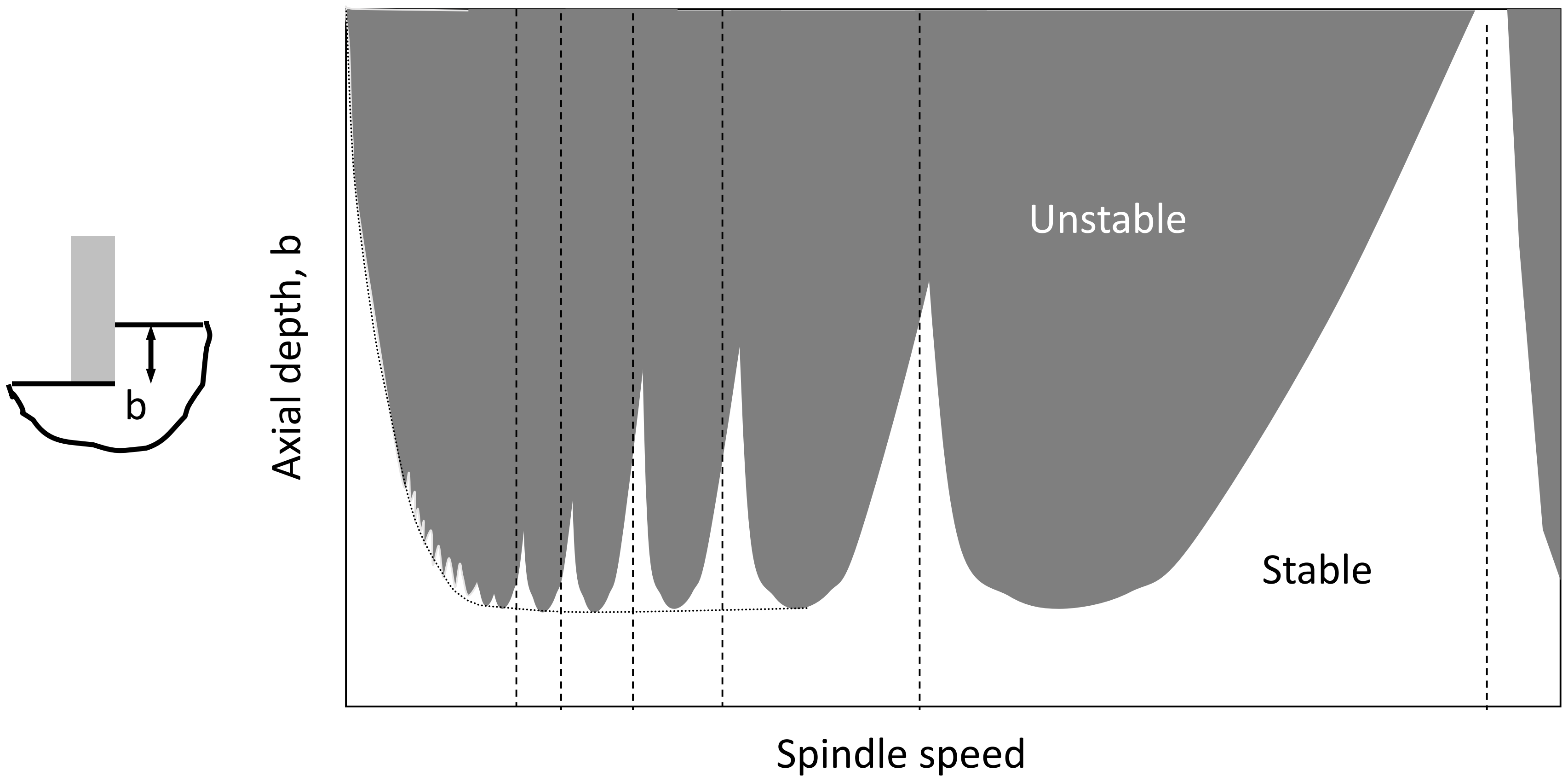
Regeneration is a primary mechanism for chatter

feedback

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

Chip thickness varies so force varies → unstable

Chip thickness is nearly constant – small force variation → stable

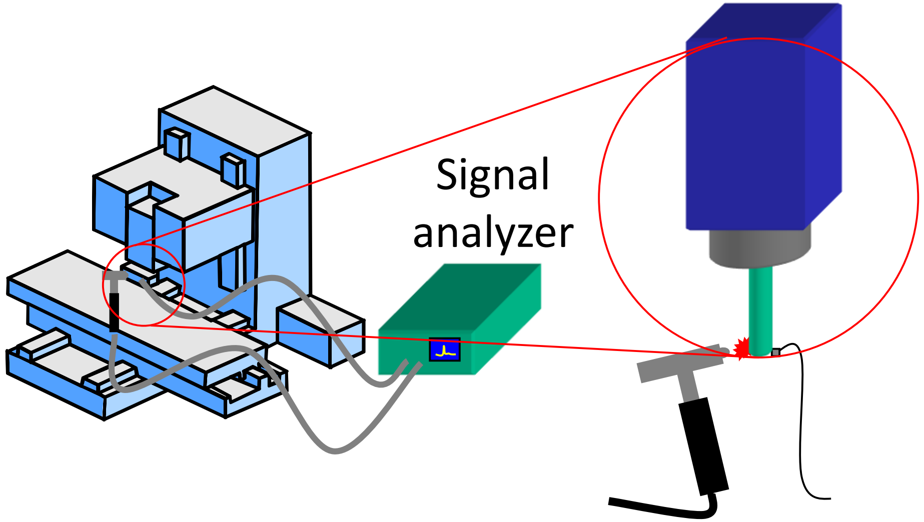


Stability map for milling

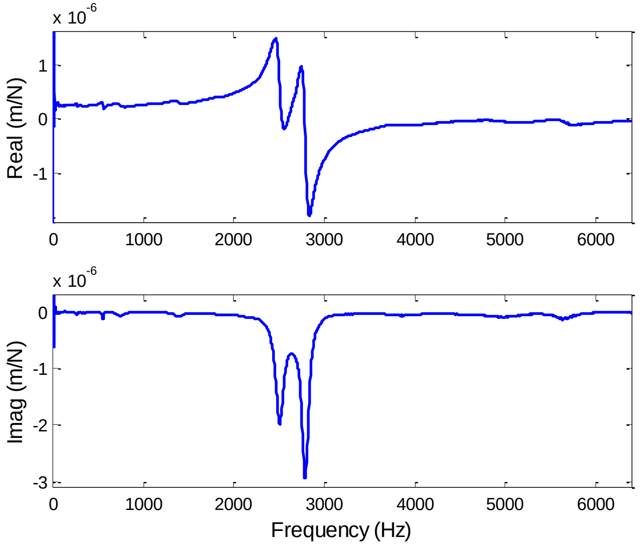
- separates unstable (chatter) from stable (forced vibration) zones
- select spindle speed and axial depth combination to obtain stable cutting conditions without trial cuts
- best spindle speeds depend on dynamics and probably do not correspond to handbook values.

Machining dynamics

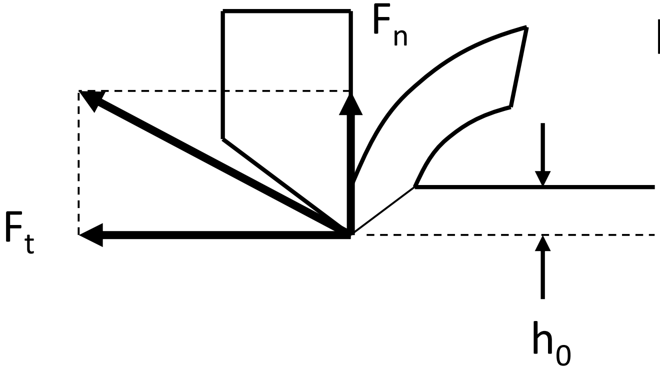
How can we construct a stability map for milling?



Frequency Response Function (FRF)

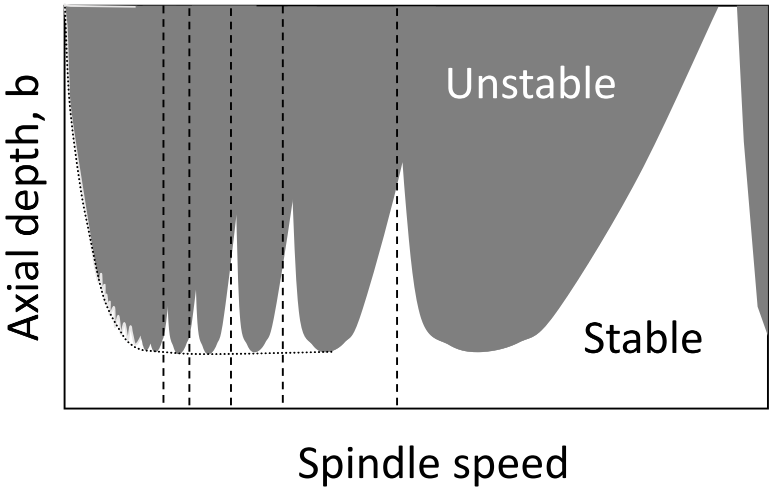


Cutting force coefficients

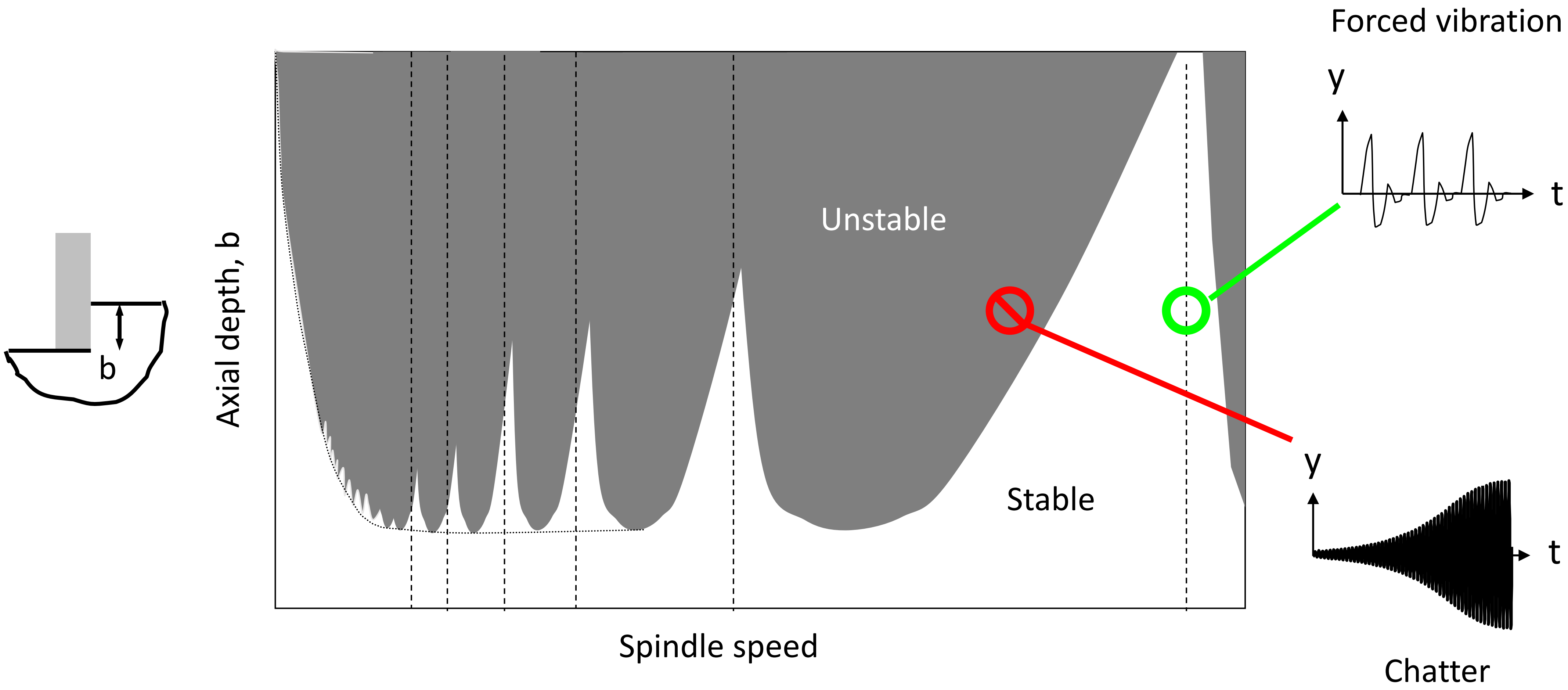


$$F_t = k_t h_0 b$$

$$F_n = k_n h_0 b$$

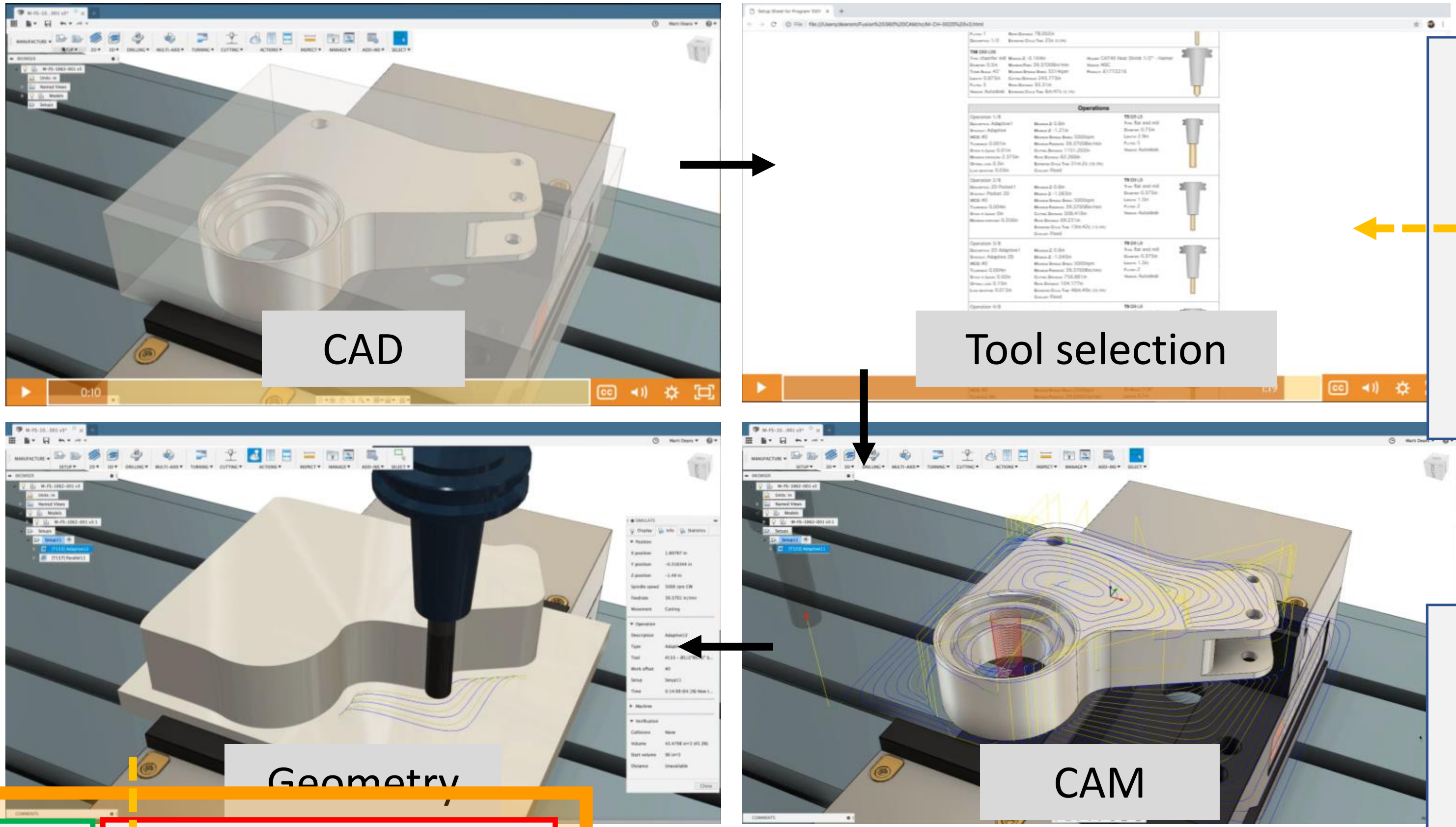


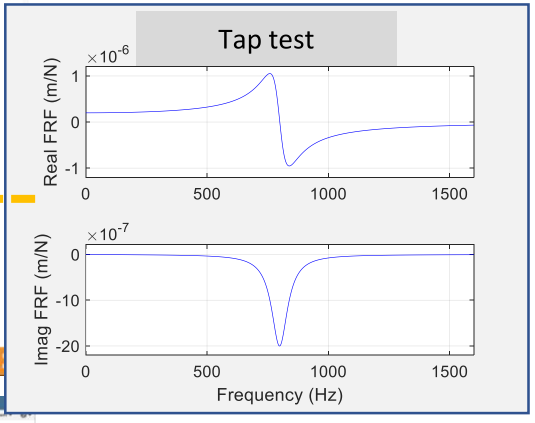
How do the two vibration types relate to the stability lobe diagram?



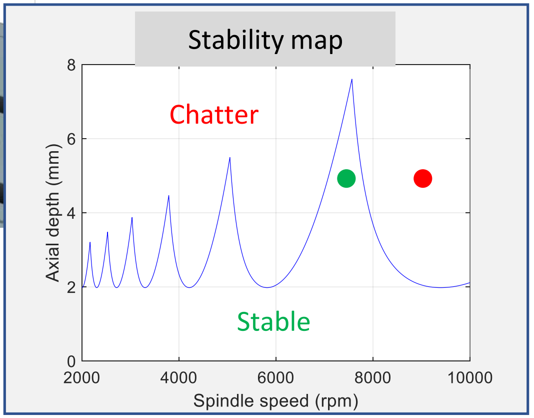
Machining dynamics

Let's consider vibration implications



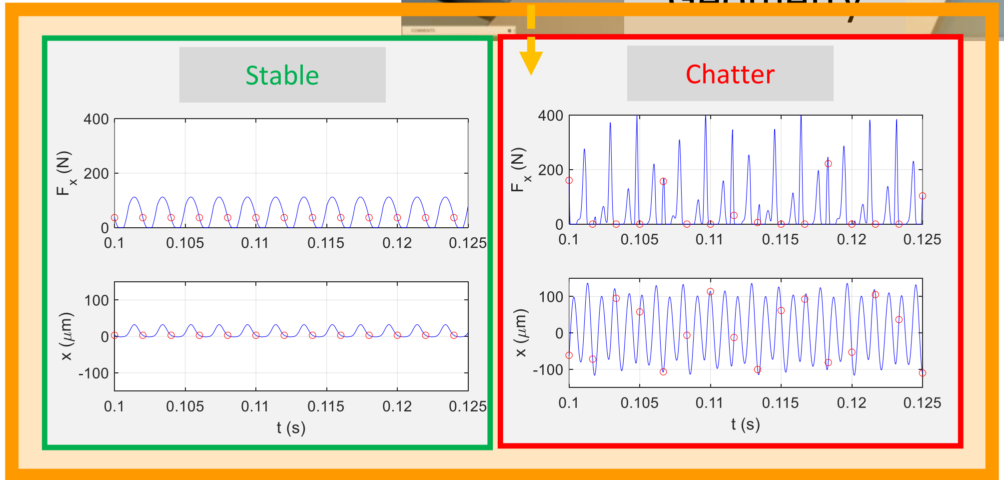


Structural dynamics



Machining parameters

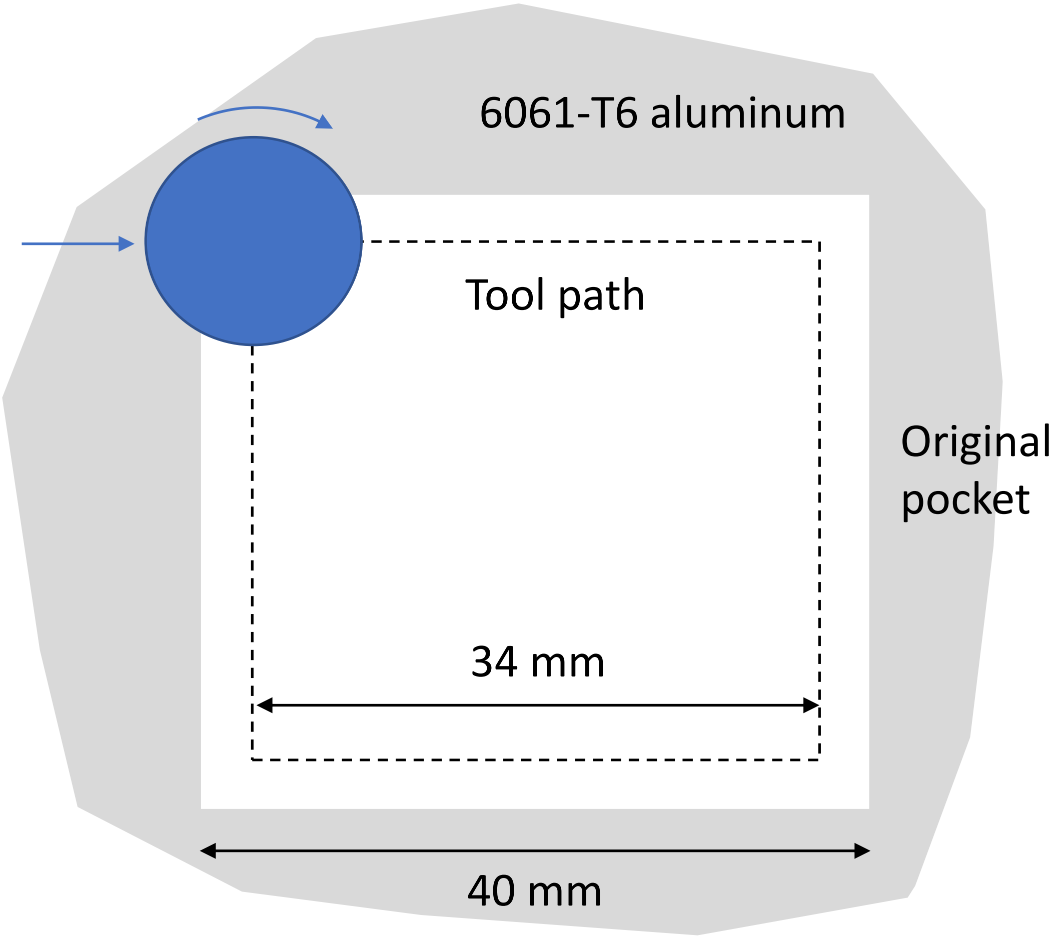
Process behavior



Machining is more than geometry

Test case description

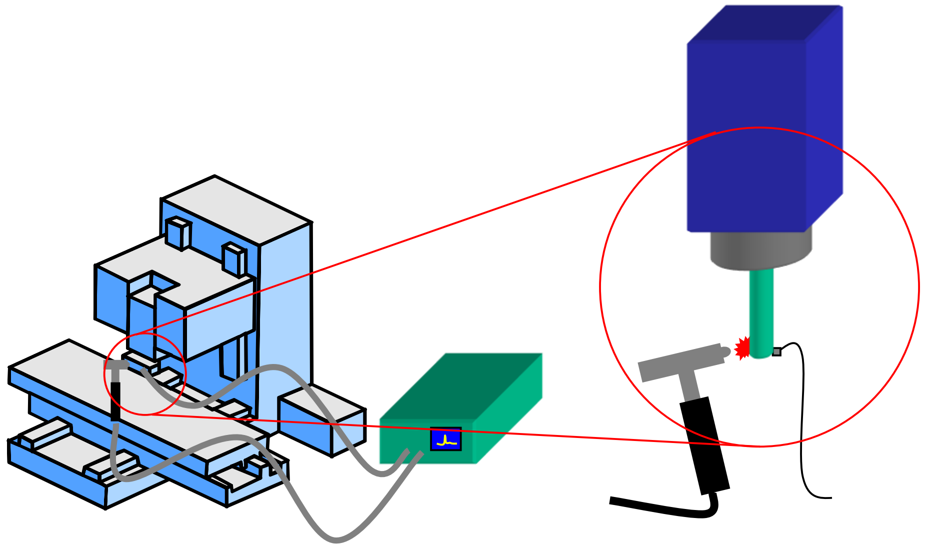
- 25% radial immersion up milling (3 mm radial depth)
- 12 mm diameter endmill, 4 teeth, 30 deg helix
- 4 mm axial depth
- 0.25 mm feed per tooth
- {5500, 6400, 7400} rpm spindle speed

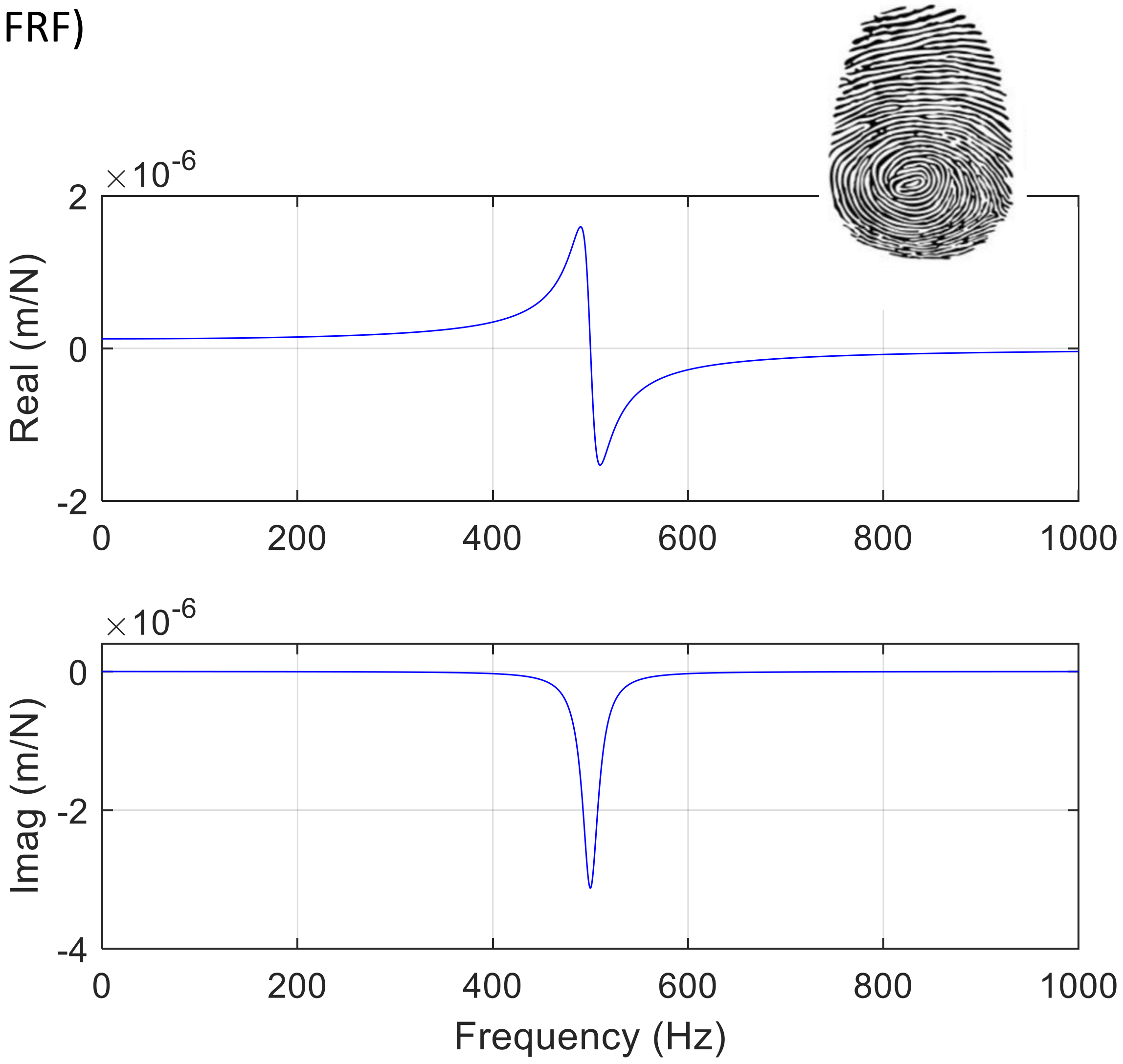


Machining is more than geometry

Tool point dynamic response (frequency response function, FRF)

- 500 Hz, 8×10^6 m/N stiffness, 2% damping
- x (feed) and y directions assumed symmetric
- workpiece assumed rigid relative to tool

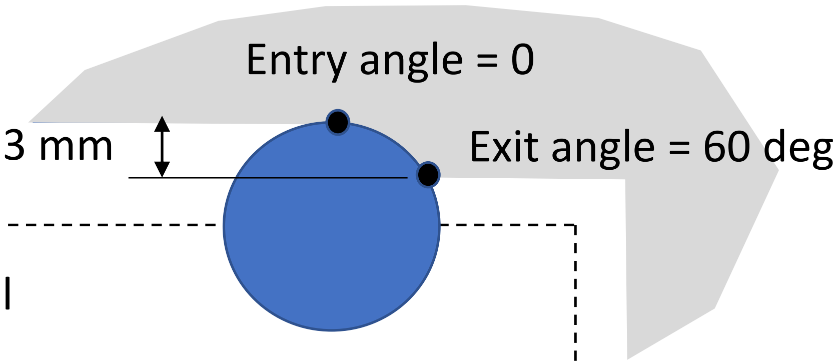




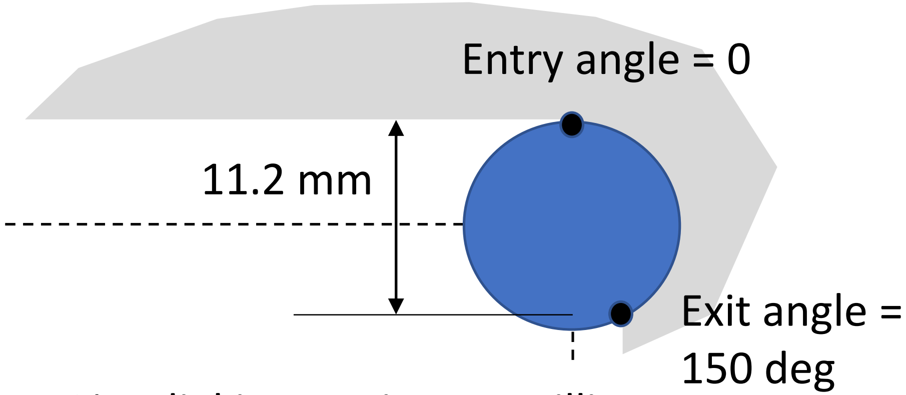
Cutting force model: 6061-T6 aluminum

Machining is more than geometry

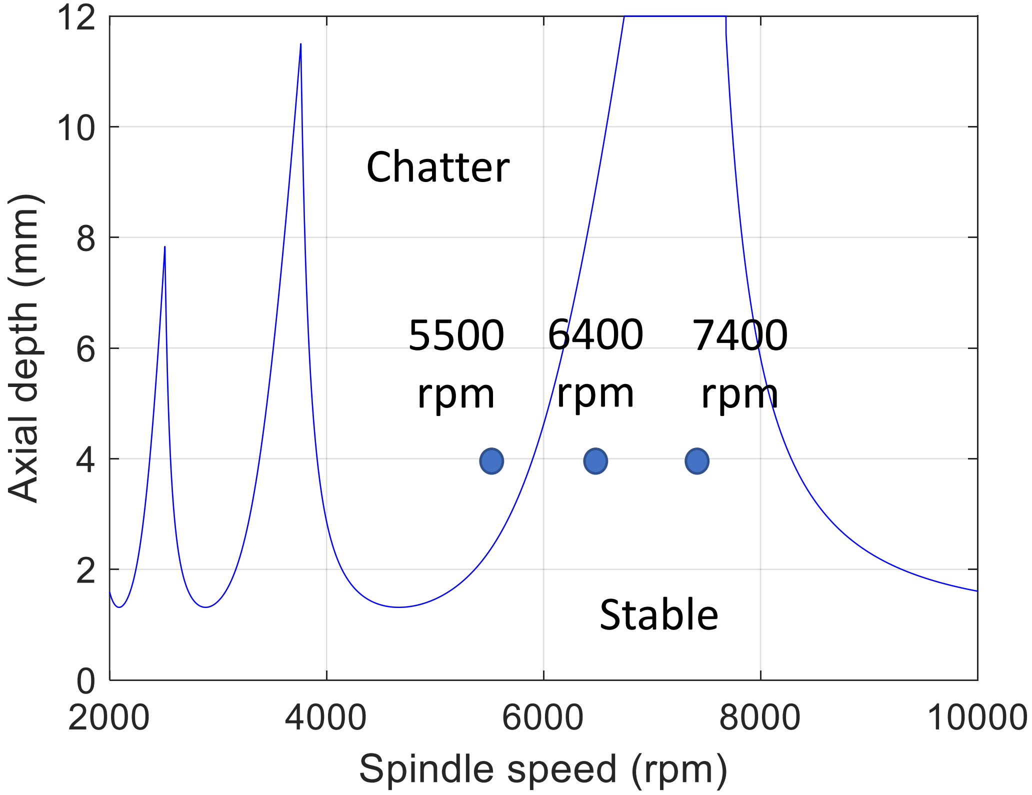
- FRF
- Force model

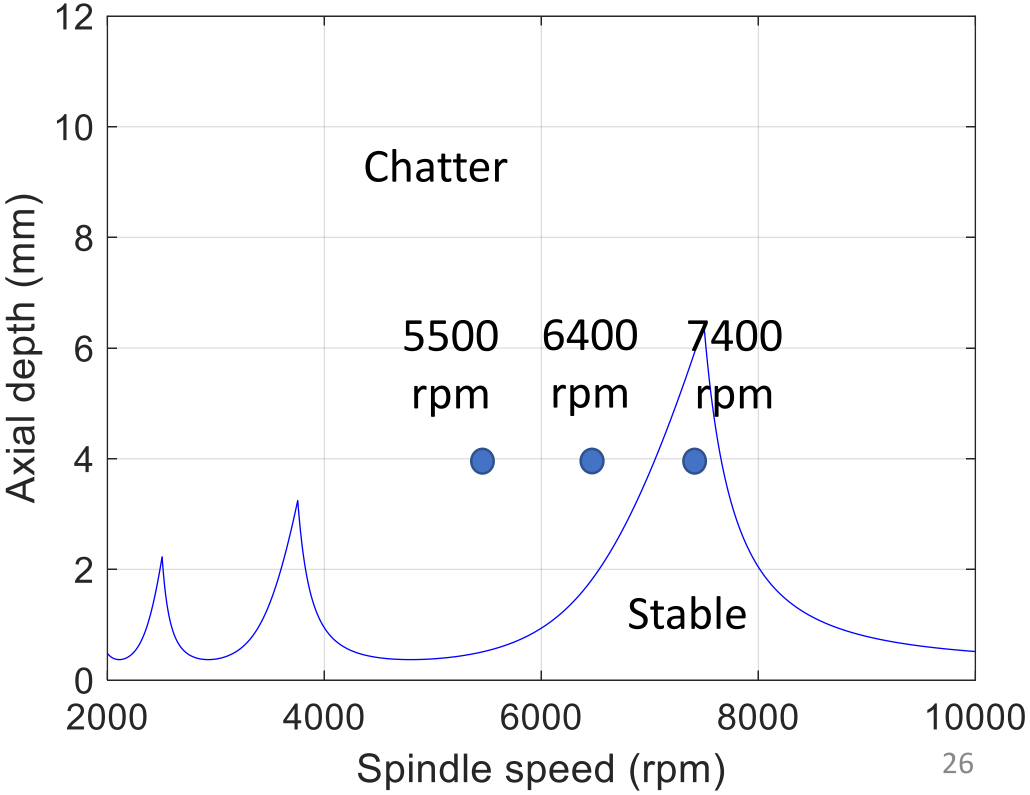


25% radial immersion up milling

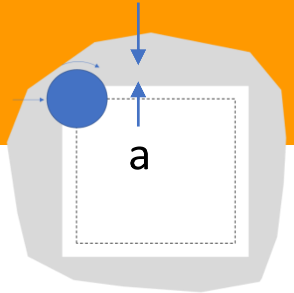


75% radial immersion up milling



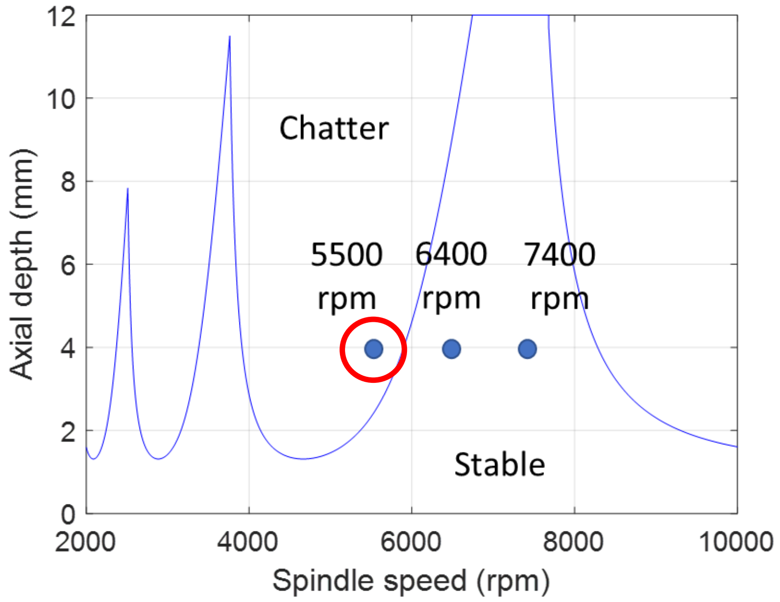


Machining is more than geometry

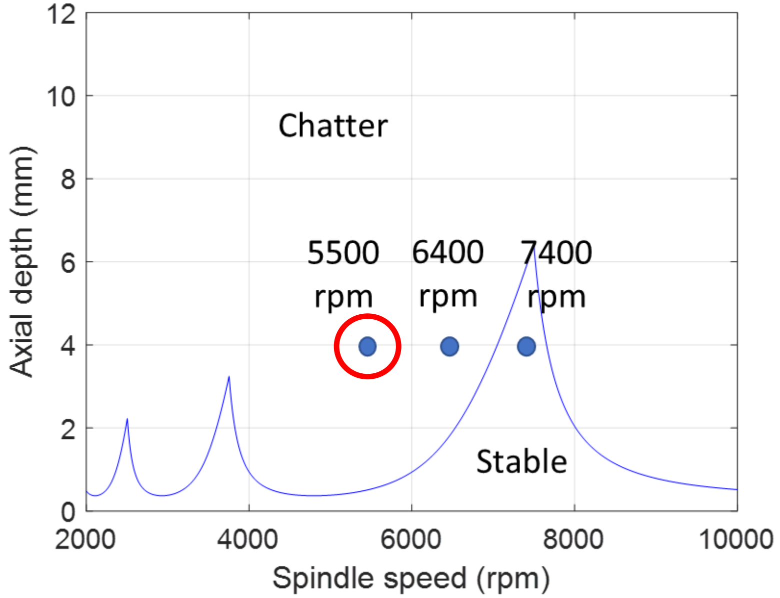


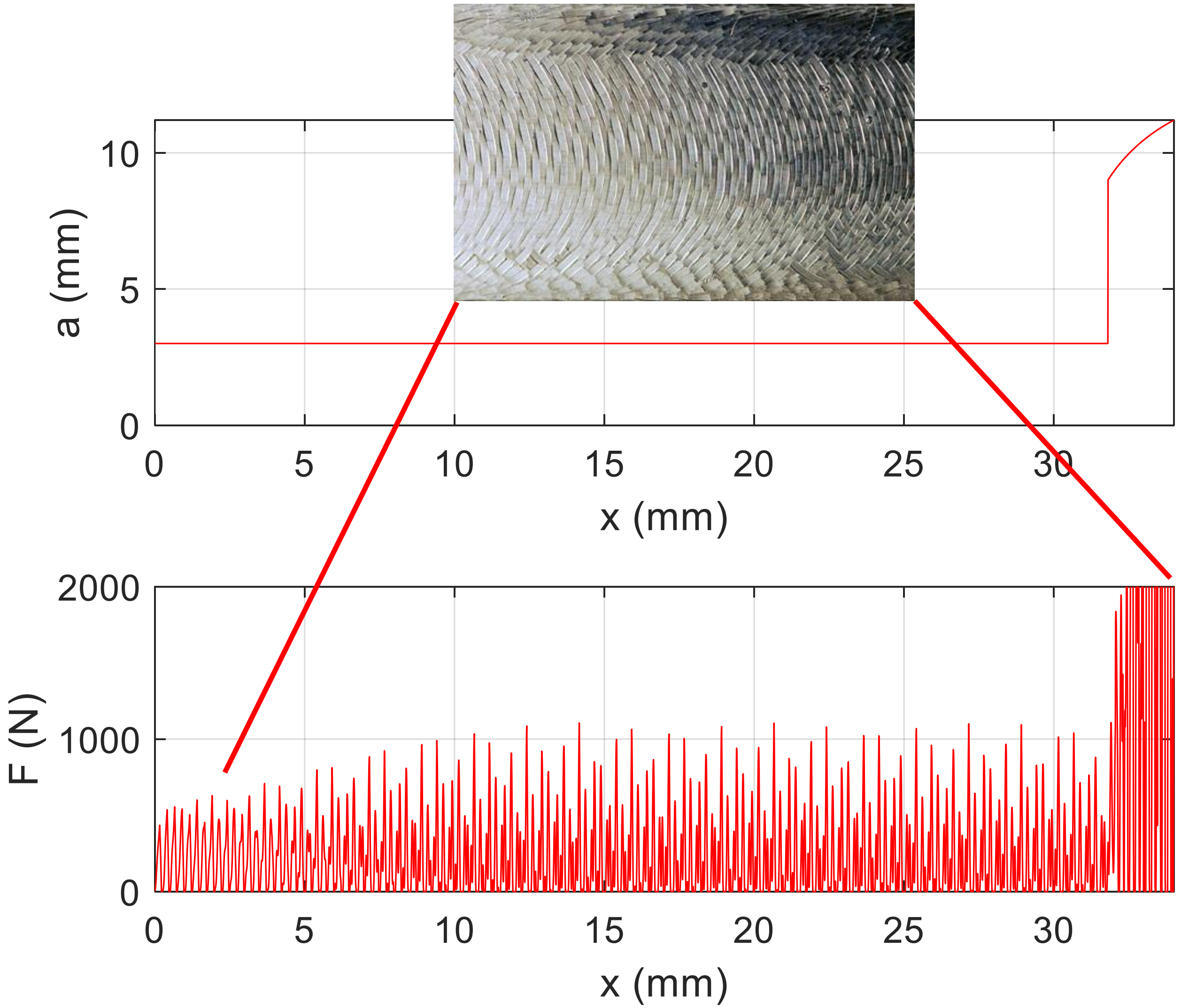
5500 rpm: Unstable for 25% radial immersion, unstable for 75% radial immersion

25% radial immersion up milling

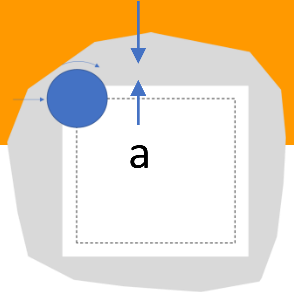


75% radial immersion up milling



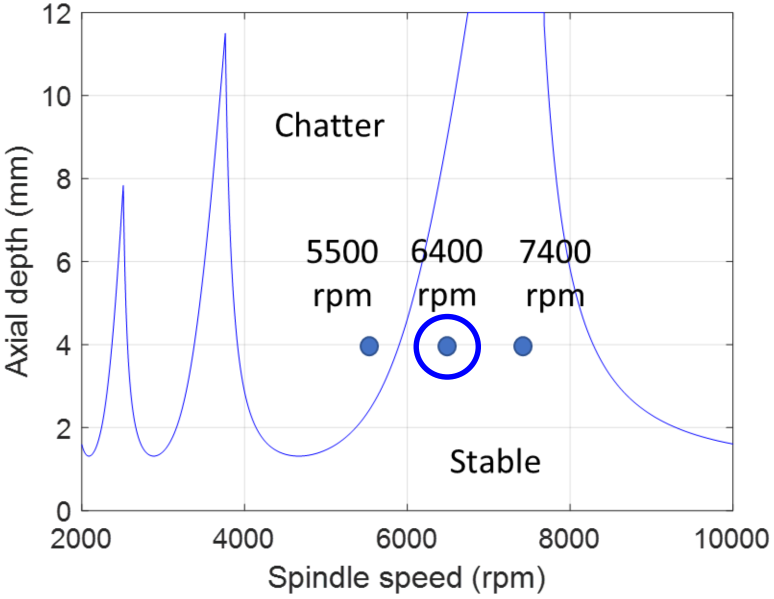


Machining is more than geometry

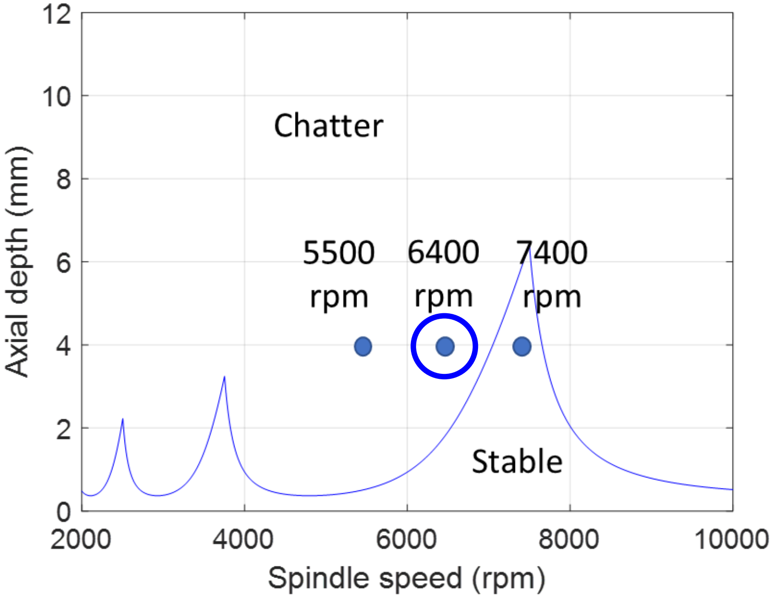


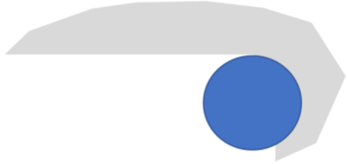
6400 rpm: Stable for 25% radial immersion, unstable for 75% radial immersion

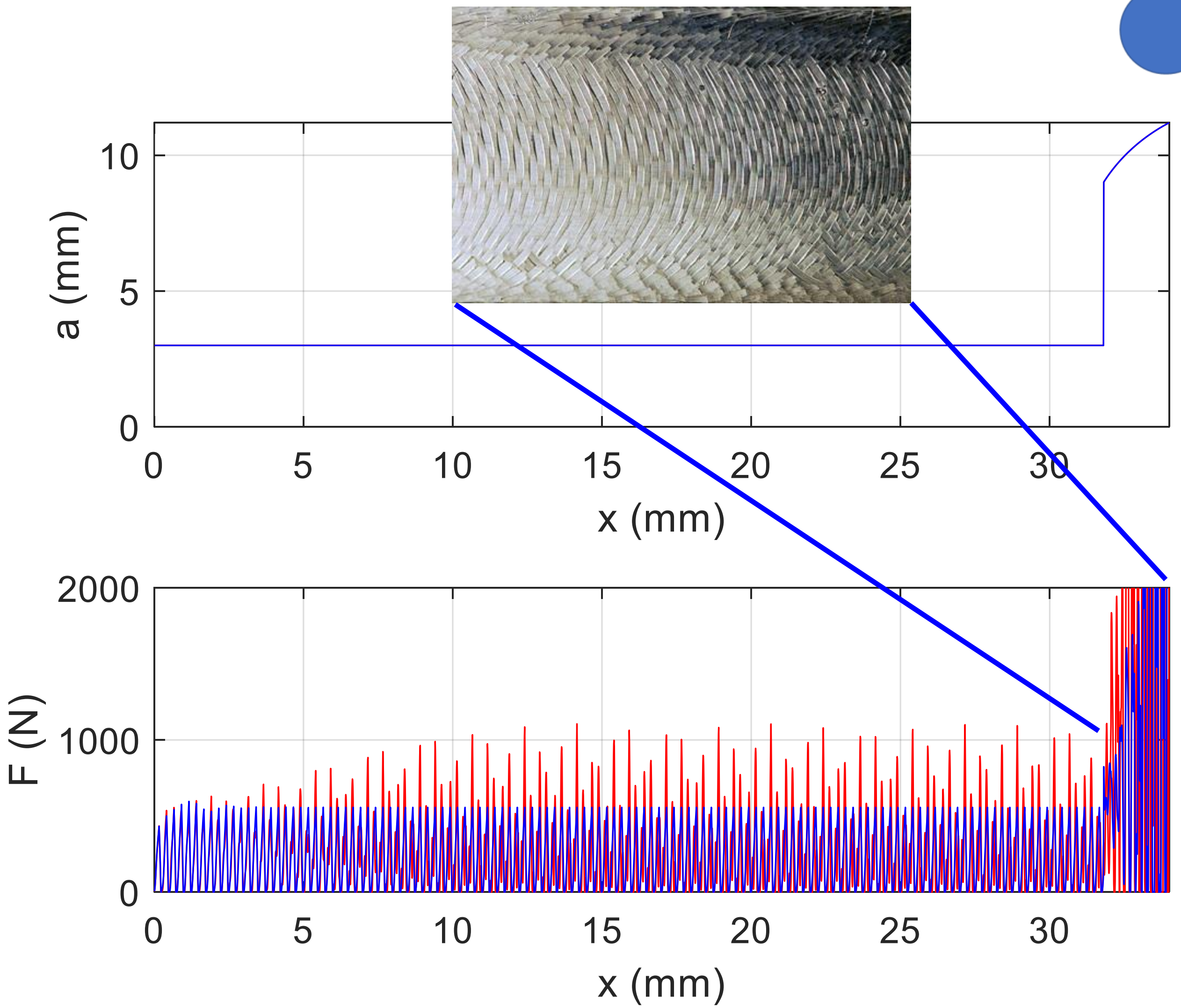
25% radial immersion up milling



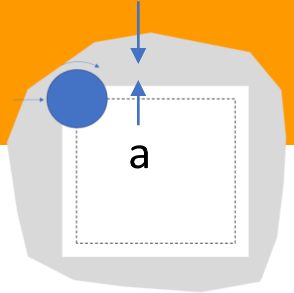
75% radial immersion up milling





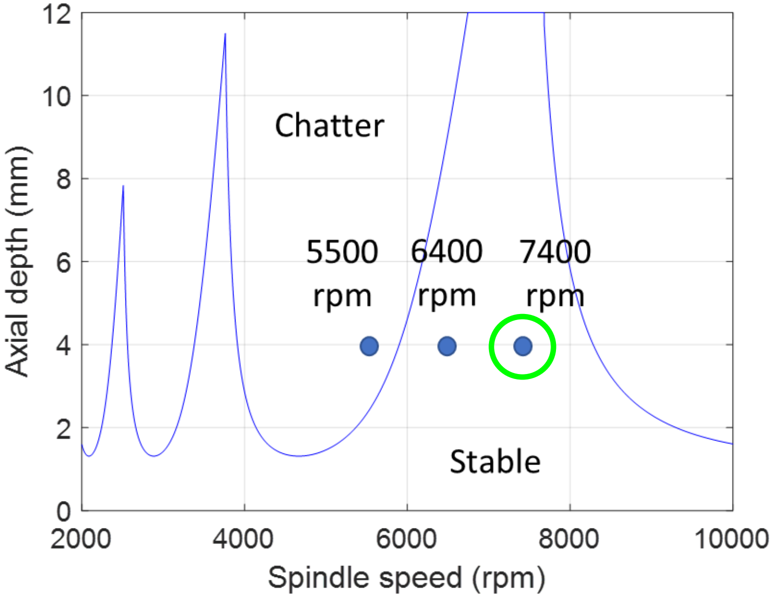


Machining is more than geometry

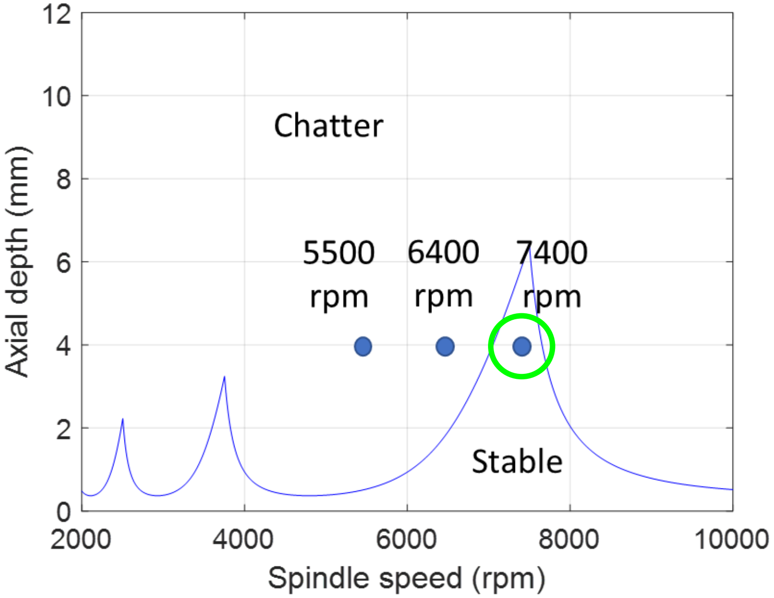


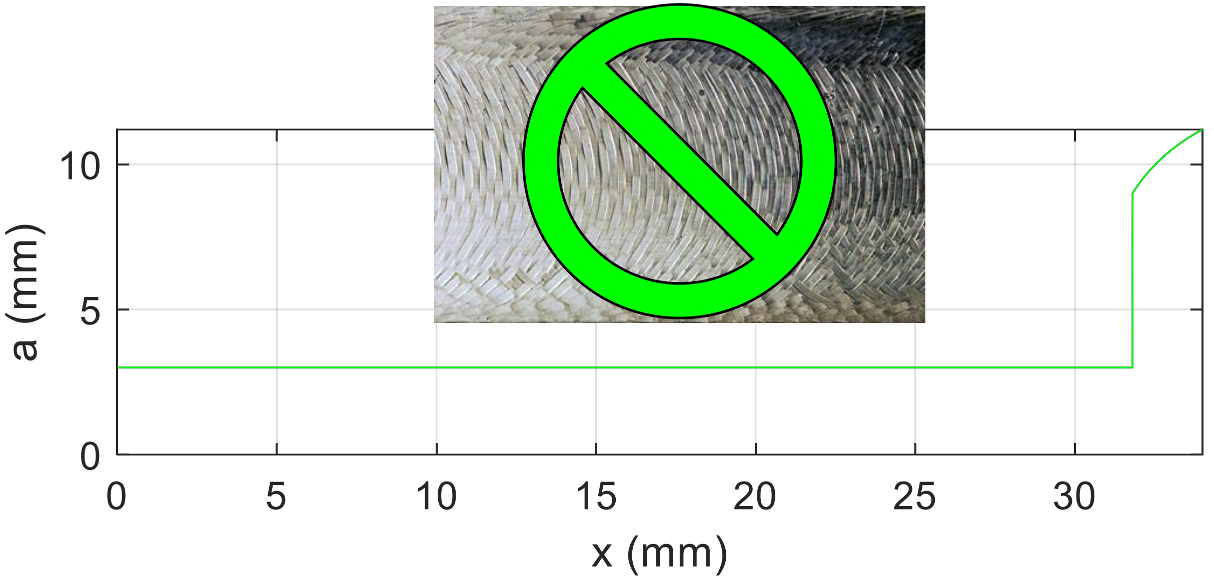
7400 rpm: Stable for 25% radial immersion, stable for 75% radial immersion

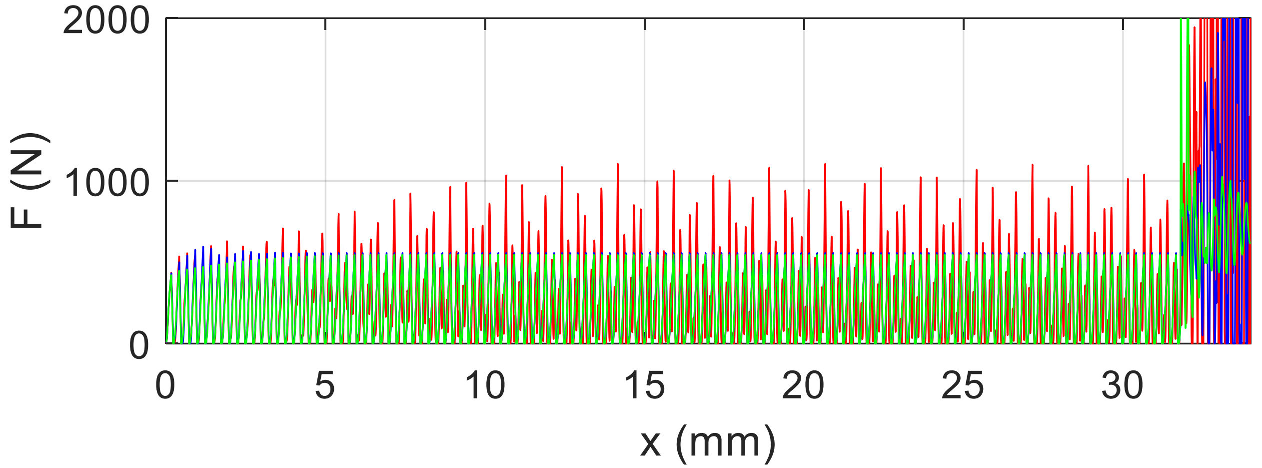
25% radial immersion up milling



75% radial immersion up milling







Machining is more than geometry

Questions?

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