Modelling and detection of machine tool chatter in high speed milling

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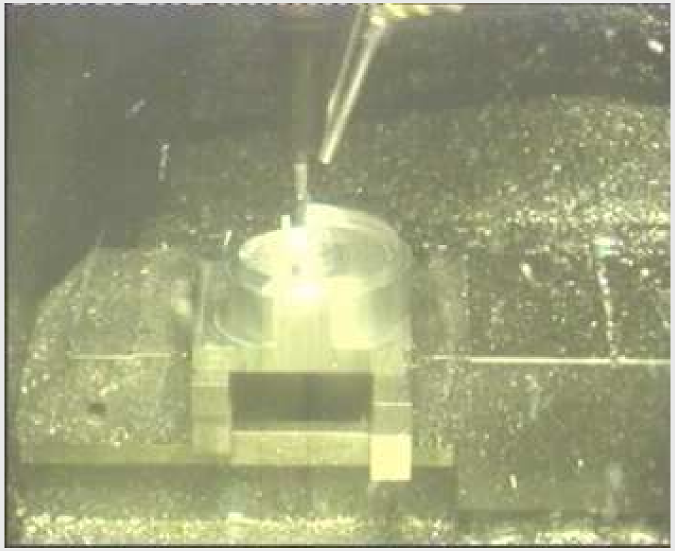
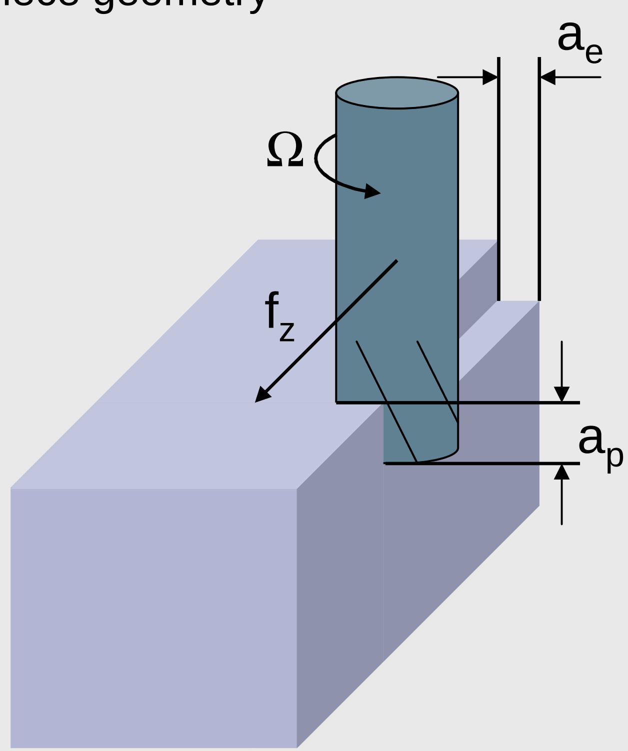
Introduction

- Benefits of high speed versus conventional milling
  - High spindle speeds → high productivity
  - Relatively low forces → complex workpiece geometry
- Relative new technique (1990's)
- Goal: maximize metal removal rate

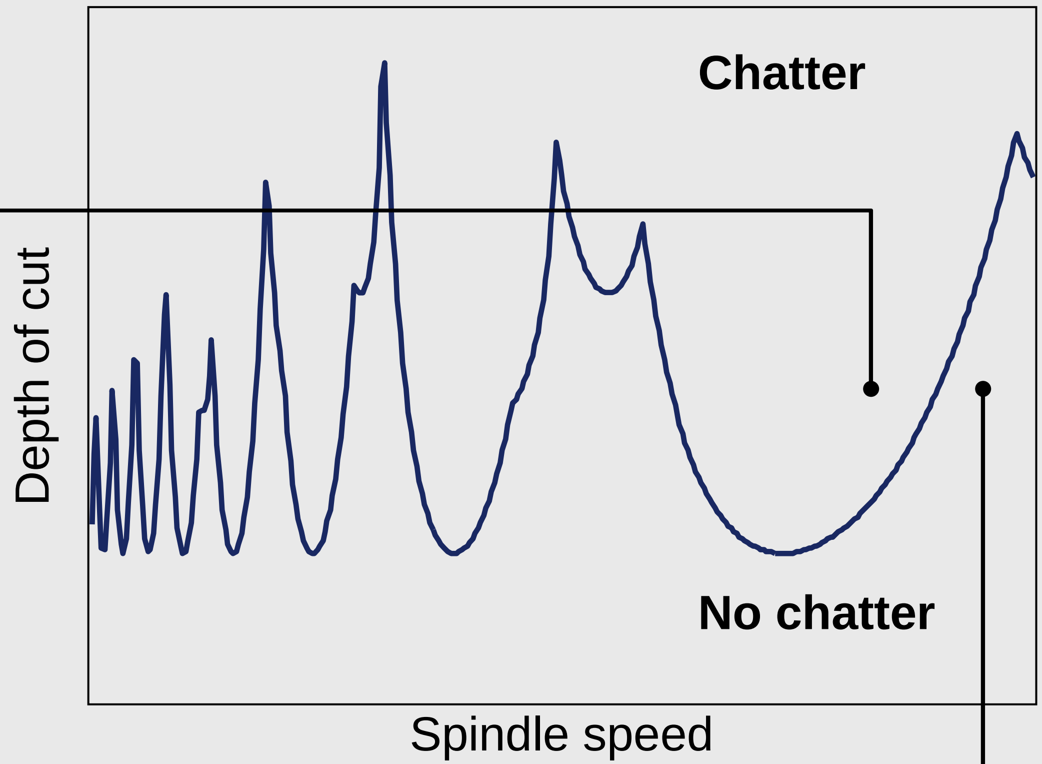




Chatter

- Heavy vibrations of the cutter
- Bad surface quality
- Rapid tool wear
- Noise

Stability Lobes Diagram (SLD)

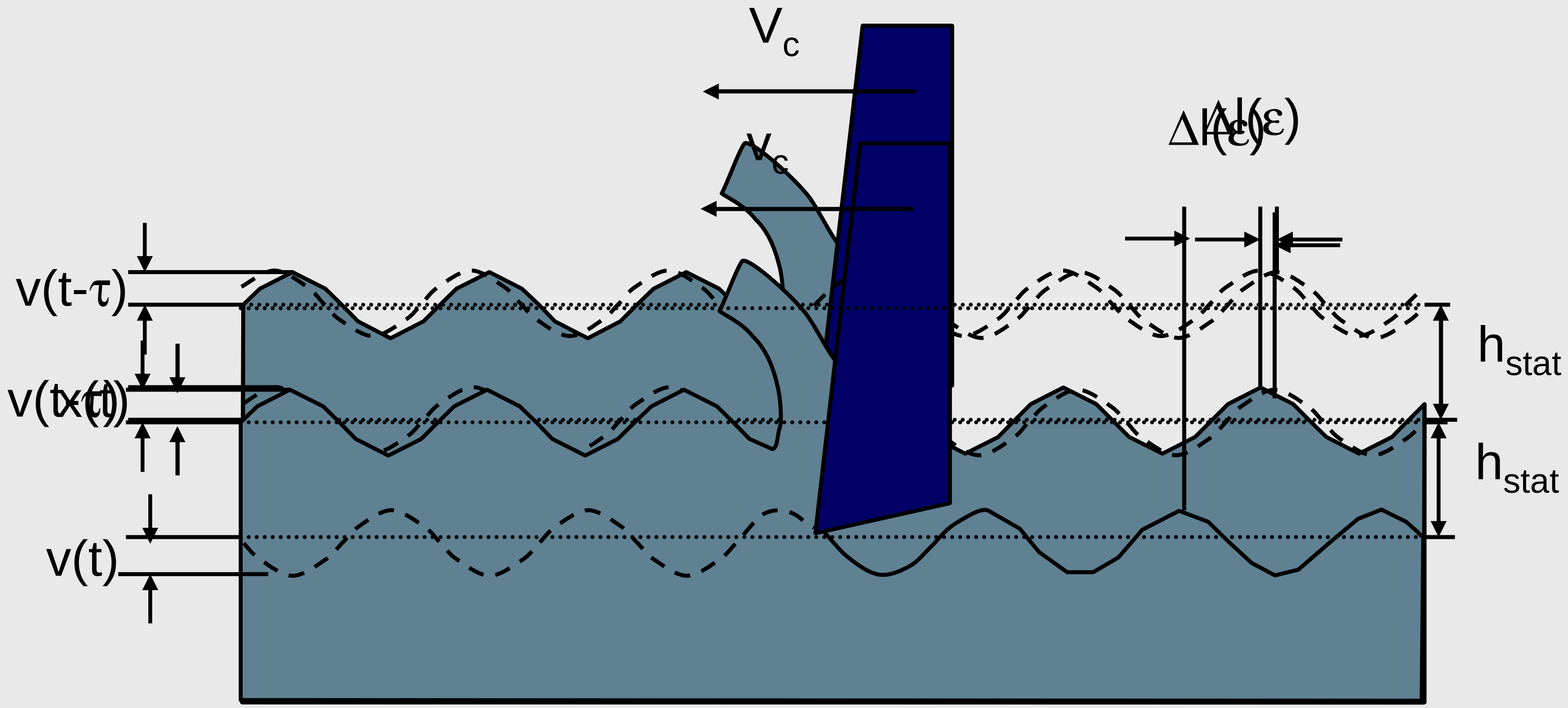


Research goals

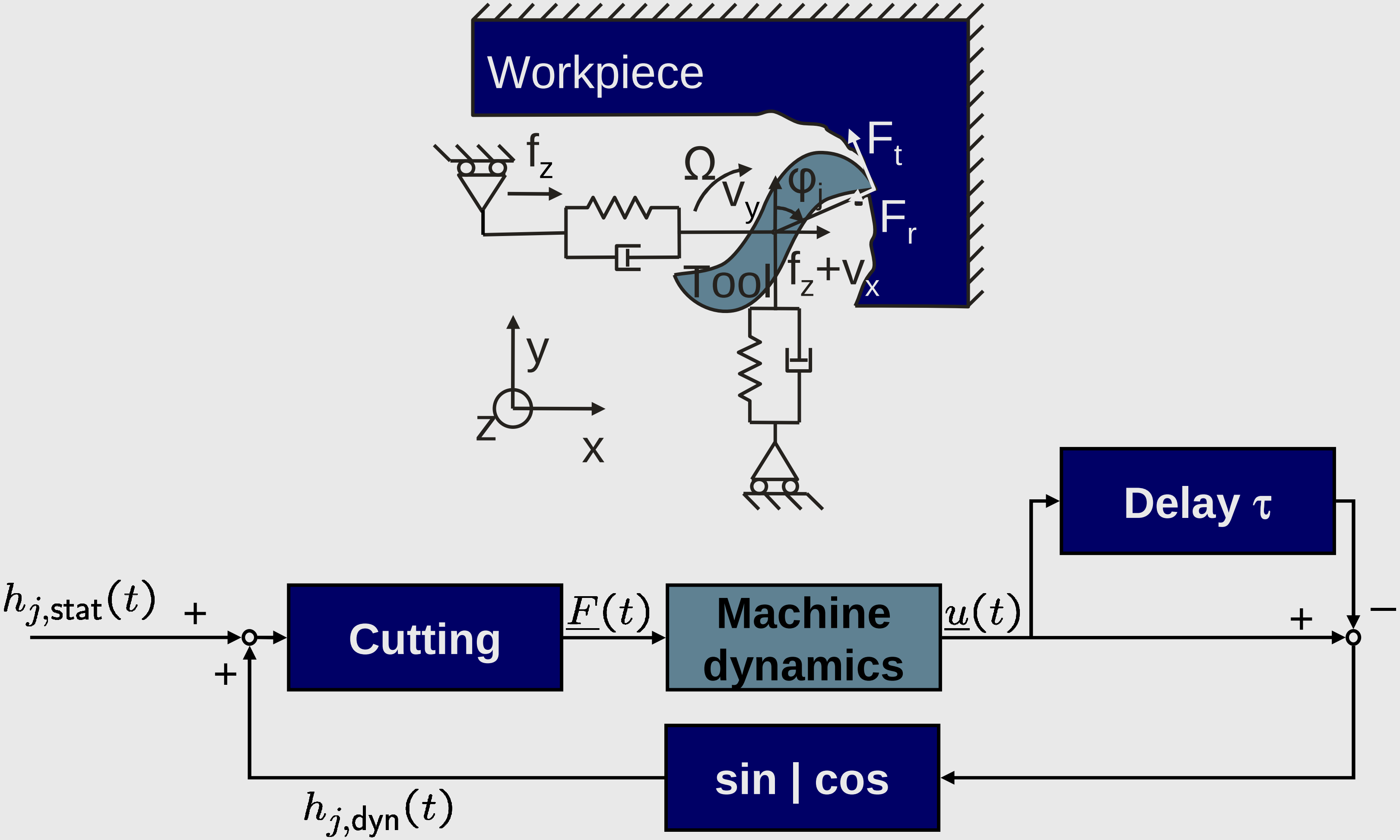
Chatter control

- Predict the stability lobes in a fast and reliable way
- Make a device that ensures a stable cut at high metal removal rate, even if the shape of the lobe changes
- Gain insight into the qualitative behaviour at the stability limit → what is chatter?

Regenerative chatter

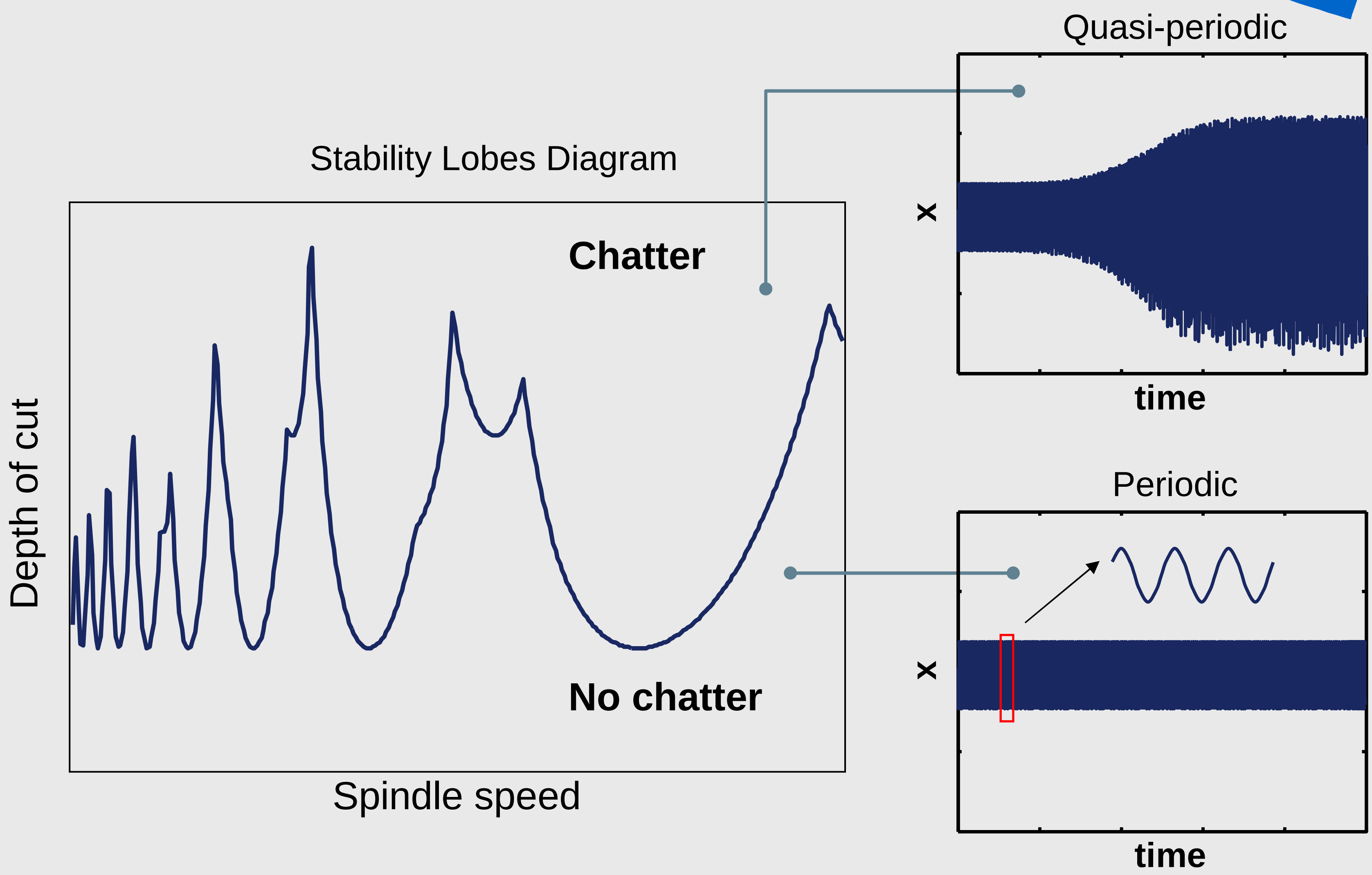


The model



Workpiece
F_t
f_z
Ω
v_y
φ_j
F_r
Tool
f_z+v_x
y
z
x
Delay τ
$h_{j,\text{stat}}(t)$
+
Cutting
$\underline{F}(t)$
Machine dynamics
$\underline{u}(t)$
+
−
+
sin | cos
$h_{j,\text{dyn}}(t)$

The stability limit

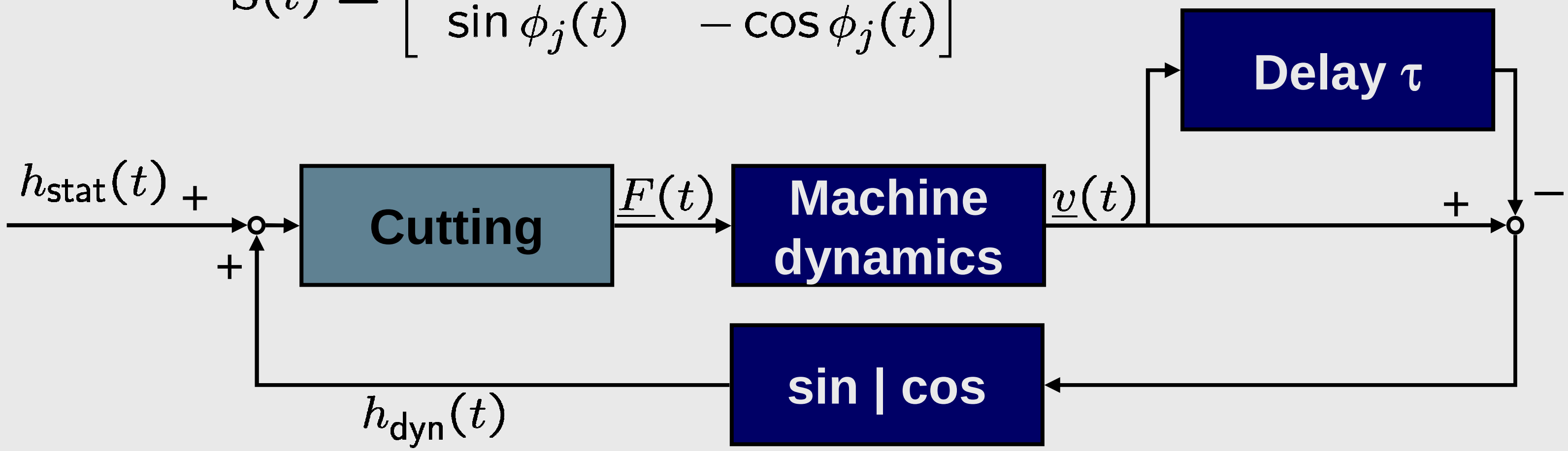


Cutting force

$$F_{t_j} = g_j\, a_p\, K_{tc}\, h_j(t)^{x_F}$$
$$F_{r_j} = g_j\, a_p\, K_{rc}\, h_j(t)^{x_F}$$

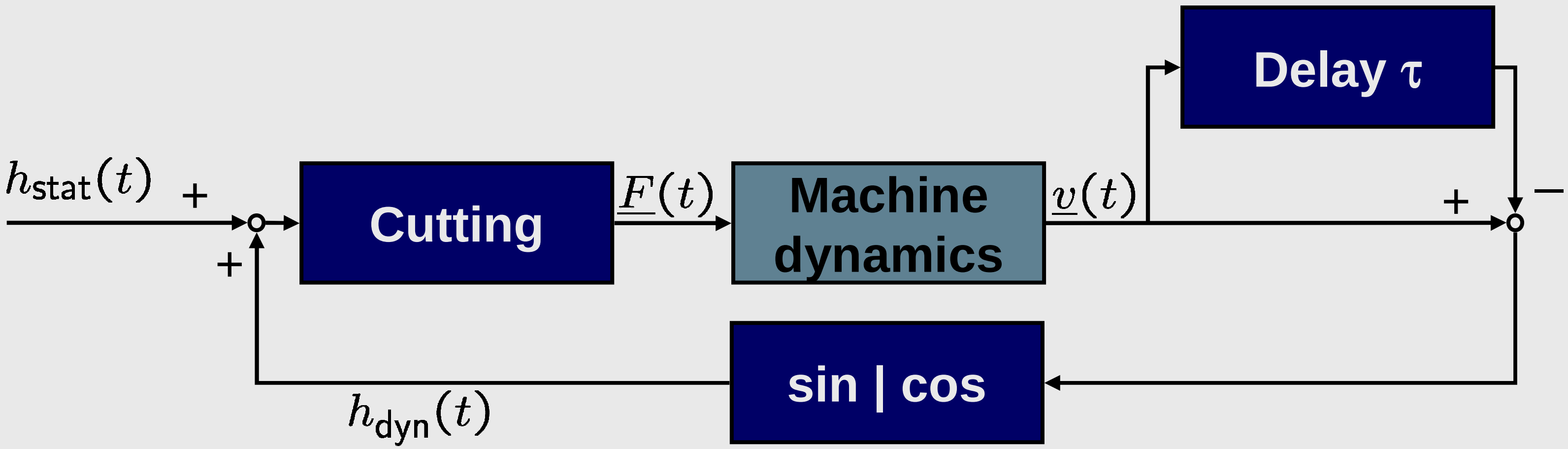
$$\underline{F}(t) = \begin{bmatrix} F_x(t) \\ F_y(t) \end{bmatrix} = a_p \sum_{j=0}^{z-1} g_j\, h_j(t)^{x_F}\, \mathbf{S}(t) \begin{bmatrix} K_{tc} \\ K_{rc} \end{bmatrix}$$

$$\mathbf{S}(t) = \begin{bmatrix} -\cos\phi_j(t) & -\sin\phi_j(t) \\ \sin\phi_j(t) & -\cos\phi_j(t) \end{bmatrix}$$



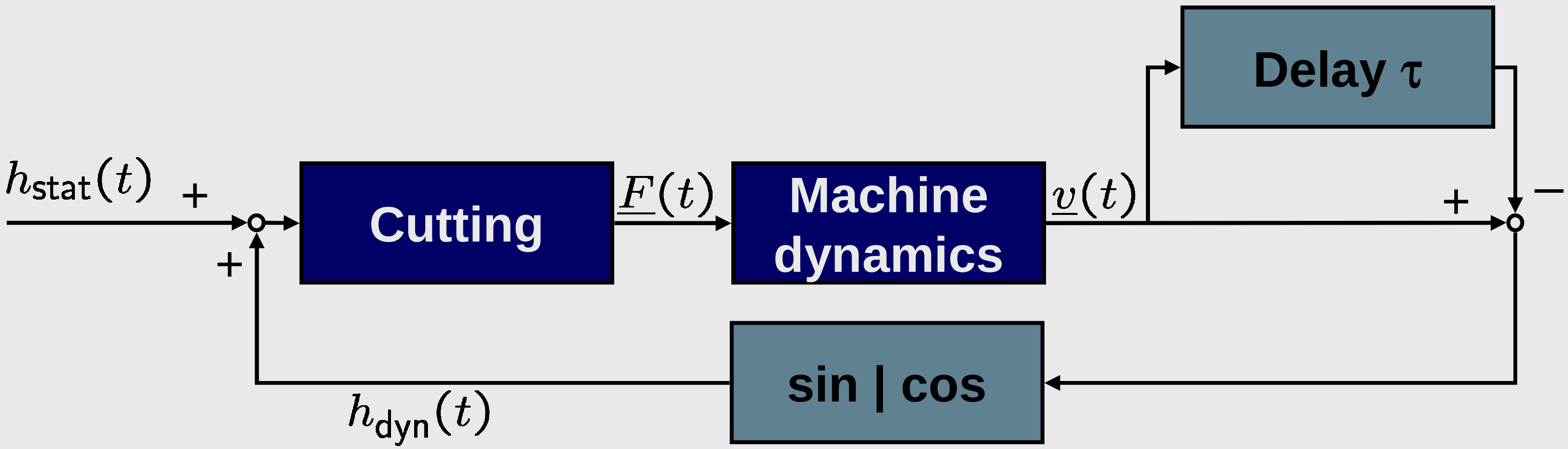
Machine dynamics

$$\underline{\dot{x}}(t) = \mathbf{A}\underline{x}(t) + \mathbf{B}\underline{F}(t)$$
$$\underline{v}(t) = \mathbf{C}\underline{x}(t)$$



Chip thickness

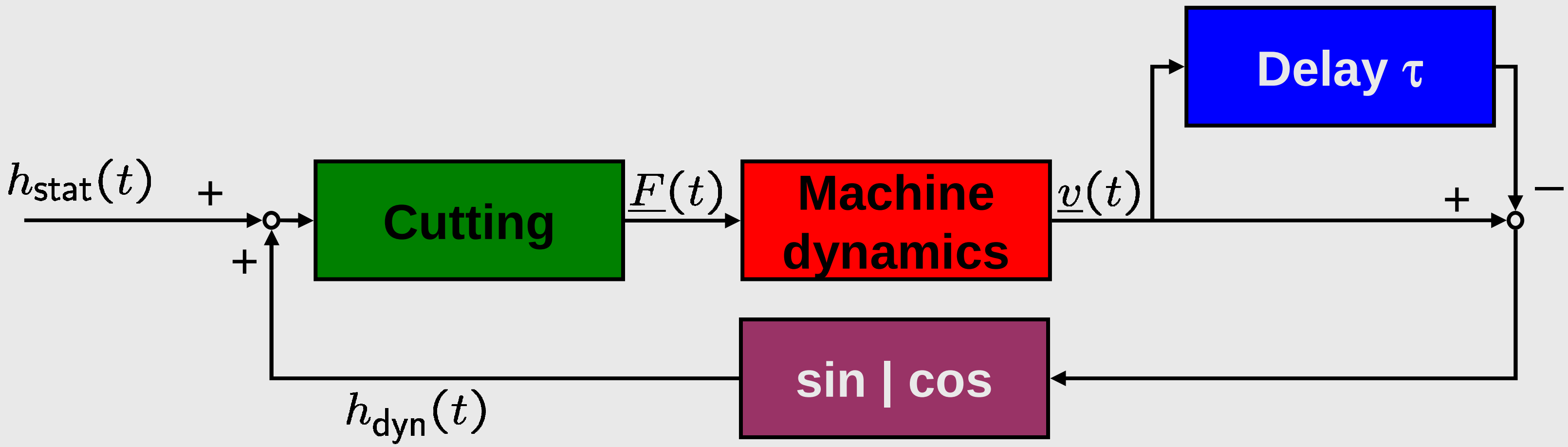
$$h_j(t) = h_{j,\text{stat}}(t) + \left[\sin\phi_j(t) \quad \cos\phi_j(t)\right]\left(\underline{v}(t) - \underline{v}(t-\tau)\right)$$



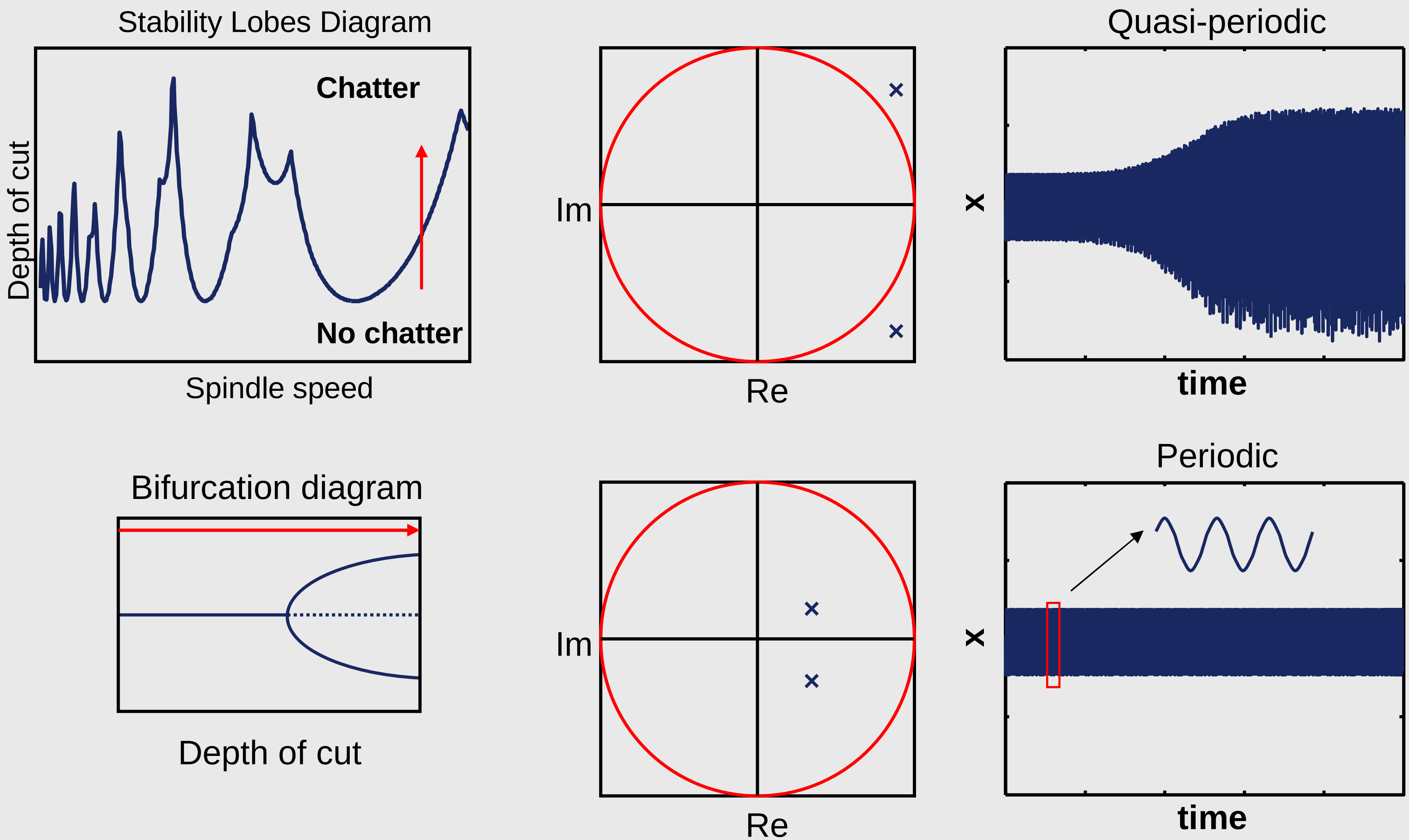
The model

$$\underline{\dot{x}}(t) = \mathbf{A}\underline{x}(t) + \mathbf{B}a_p \sum_{j=0}^{z-1} g_j \Bigg(\bigg(h_{j,\mathrm{stat}}(t) + \begin{bmatrix} \sin\phi_j(t) & \cos\phi_j(t) \end{bmatrix} \Big(\mathbf{C}\underline{x}(t) - \mathbf{C}\underline{x}(t-\tau) \Big) \bigg)^{x_F} \mathbf{S}(t) \begin{bmatrix} K_{tc} \\ K_{rc} \end{bmatrix} \Bigg)$$

$$\underline{v}(t) = \mathbf{C}\underline{x}(t)$$



Bifurcation



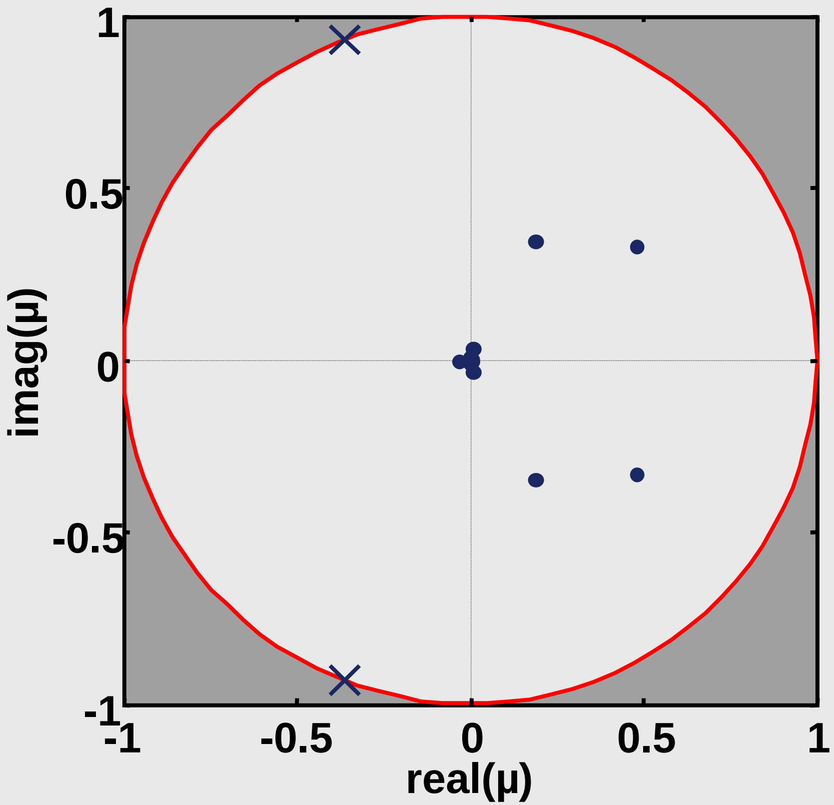
The model

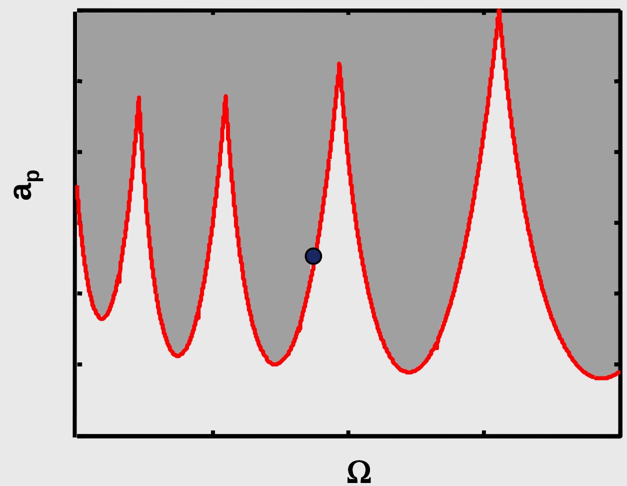
- Set of non-autonomous non-linear delay differential equations
- Find stability limit using semi-discretisation method*
- Chatter is born through a bifurcation: stable periodic solution loses stability
- Bifurcation point: Floquet multipliers cross unit circle

* T. Insperger and G. Stépán, Int. J. Num. Meth. Eng., (2004)

Stability

- Secondary Hopf or Period Doubling bifurcation
- Extra frequency f_c → quasi periodic behaviour



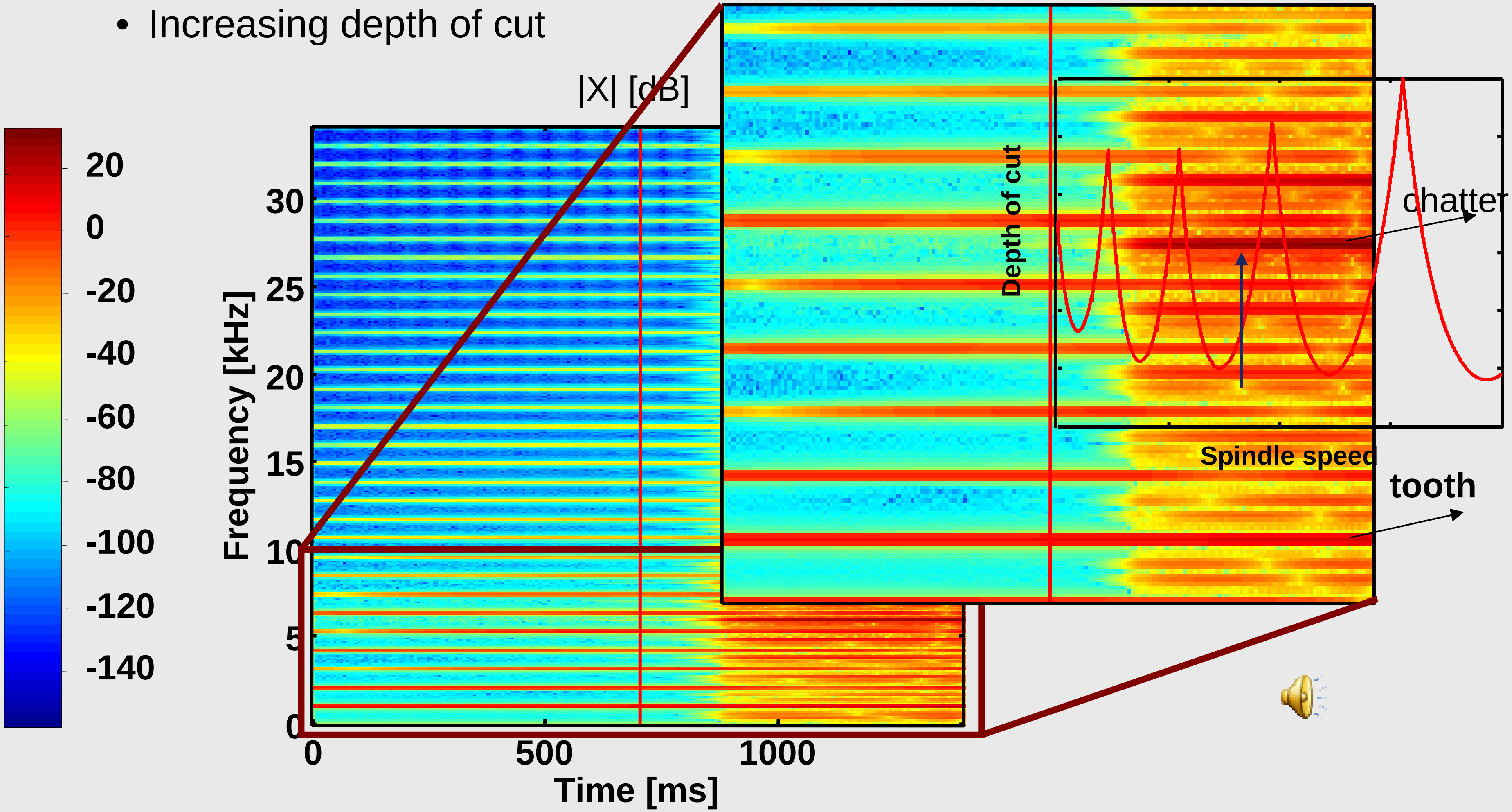


Chatter frequencies

- Stability criterion gives one chatter frequency f_c
- Interaction chatter frequency and spindle speed with non linear system → large number of chatter frequencies
- One dominant chatter frequency close to the natural frequency of the system

Simulation of the model

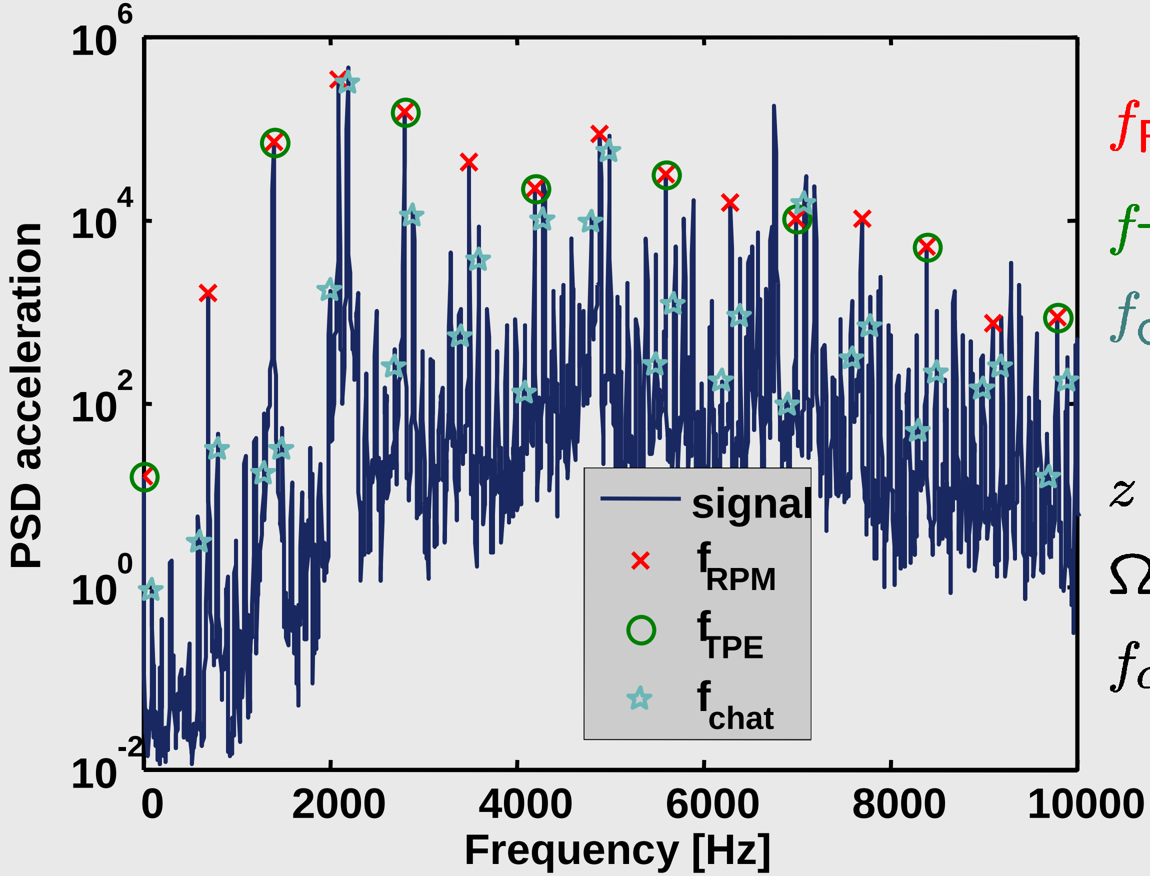
- Increasing depth of cut



Frequencies in chatter

- Peaks due to spindle speed components: ○ ×
- Peaks due to chatter: ☆

Experimental result



$$f_{\text{RPM}} = k\frac{\Omega}{60},\ k = 0, 1, 2, \ldots$$

$$f_{\text{TPE}} = z f_{\text{RPM}}$$

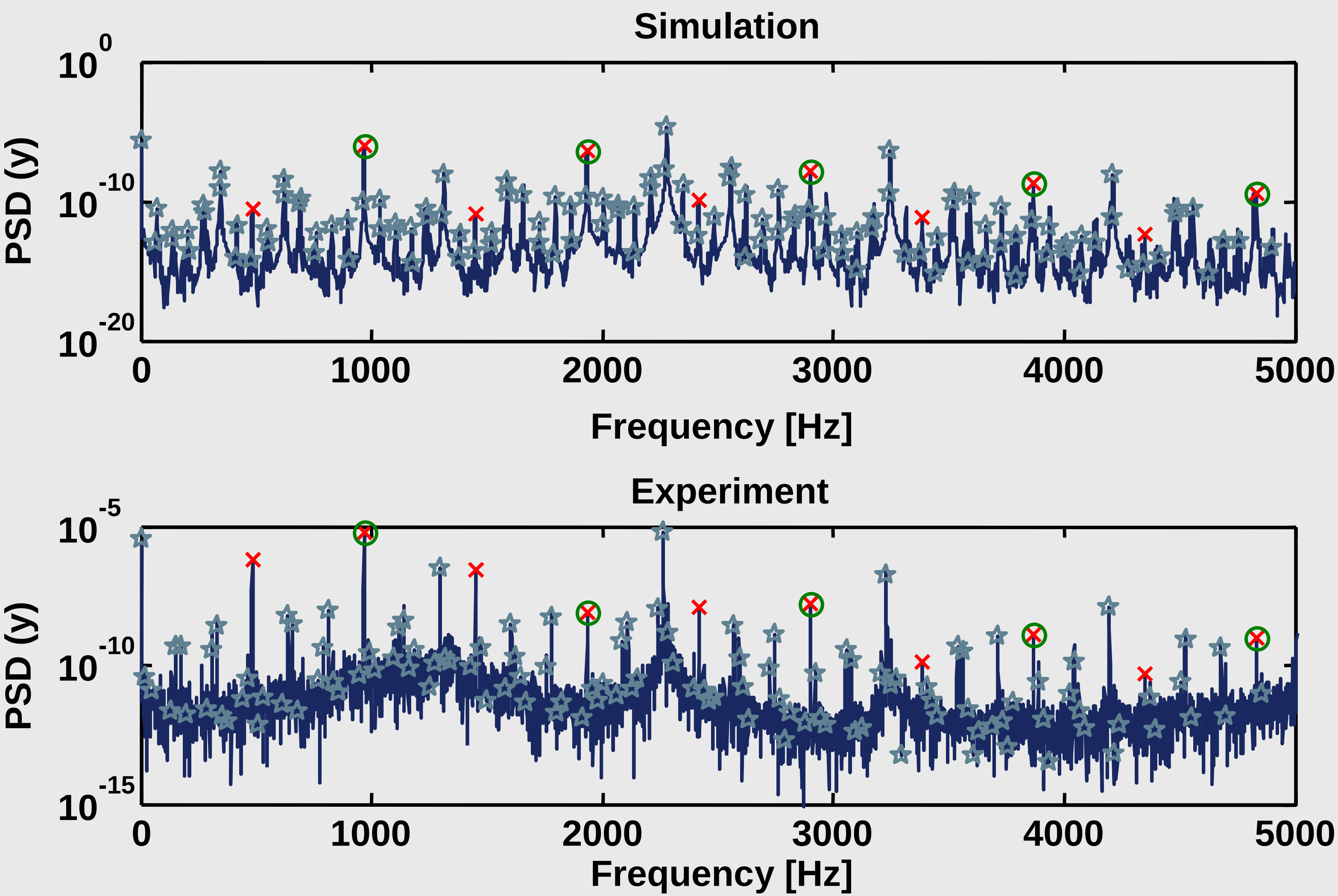
$$f_{\text{chat}} = f_{\text{RPM}} \pm f_c$$

$z = 2$

$\Omega = 42000$ rpm

$f_c = 96$ Hz

Results



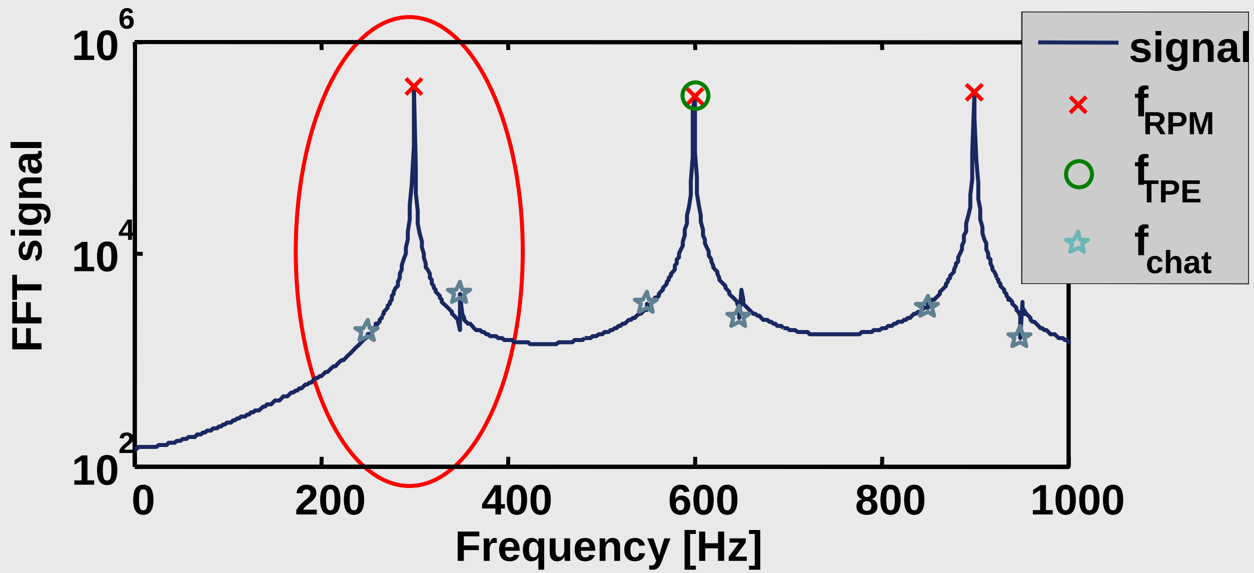
Simulation
PSD (y)
10^0
10^-10
10^-20
0
1000
2000
3000
4000
5000
Frequency [Hz]
Experiment
PSD (y)
10^-5
10^-10
10^-15
0
1000
2000
3000
4000
5000
Frequency [Hz]

Detection

Signal contains frequencies $f_{\text{RPM}} = k\frac{\Omega}{60},\ k = 0, 1, 2, \ldots$

$$f_{\text{chat}} = f_{\text{RPM}} \pm f_c$$

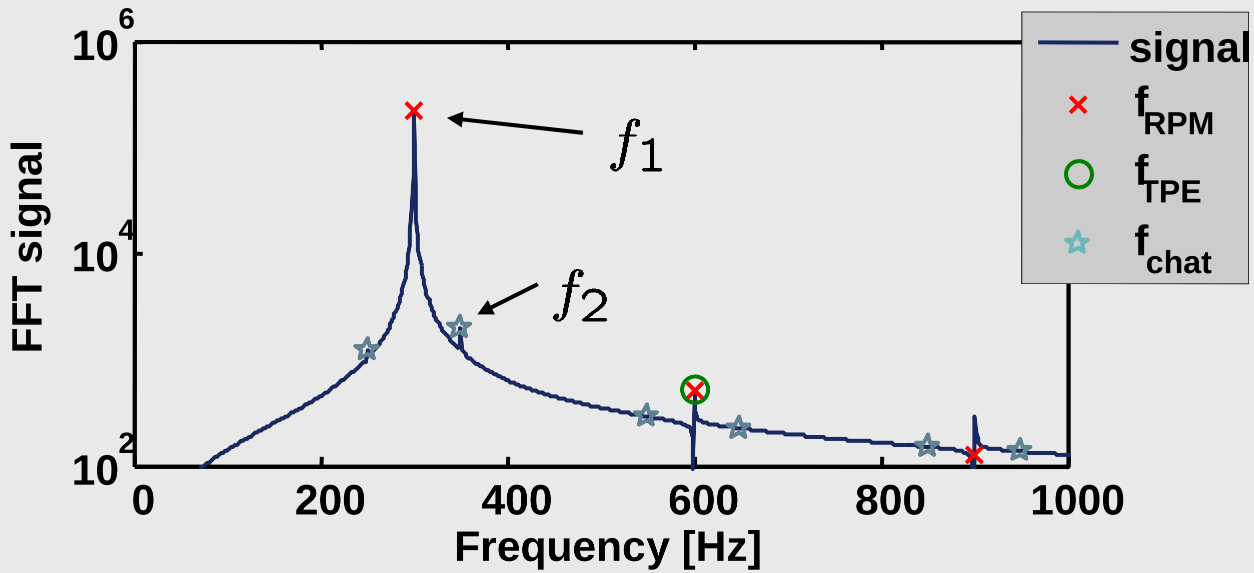
1. Choose frequency band around the n-th harmonic



Detection

2. Apply bandpass filter around n-th harmonic

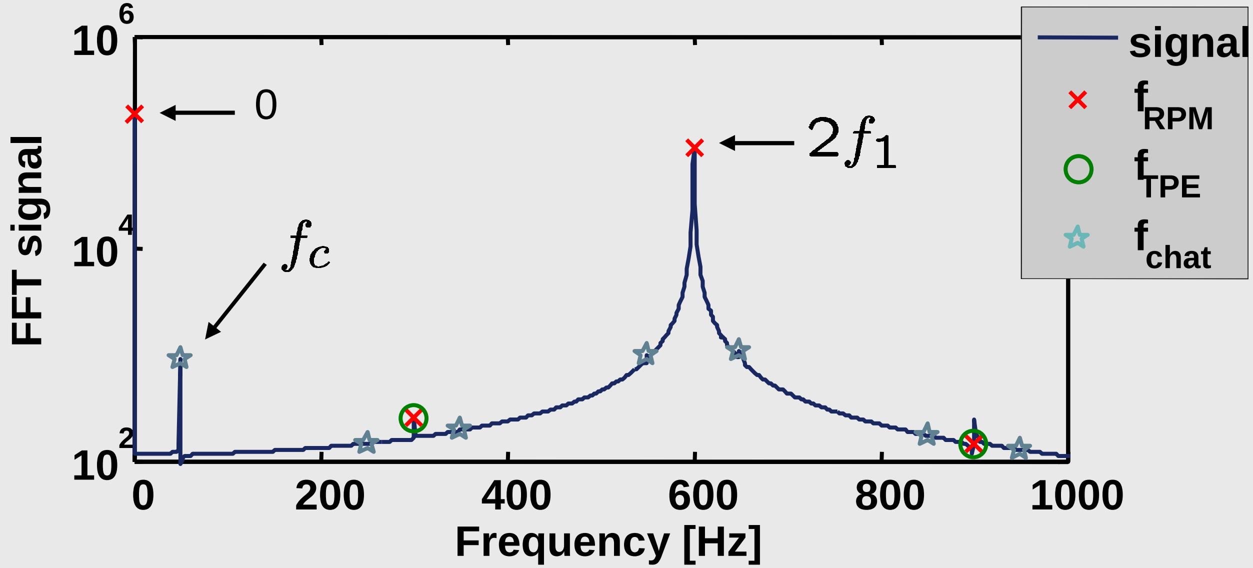
Signal contains frequencies $f_1 = n\frac{\Omega}{60}$ and $f_2 = f_1 \pm f_c$



Detection

3. Apply demodulation: Frequencies shifted with f_1 and $-f_1$

Signal contains frequencies 0, $2f_1$, $2f_1 \pm f_c$ and f_c



Demodulation

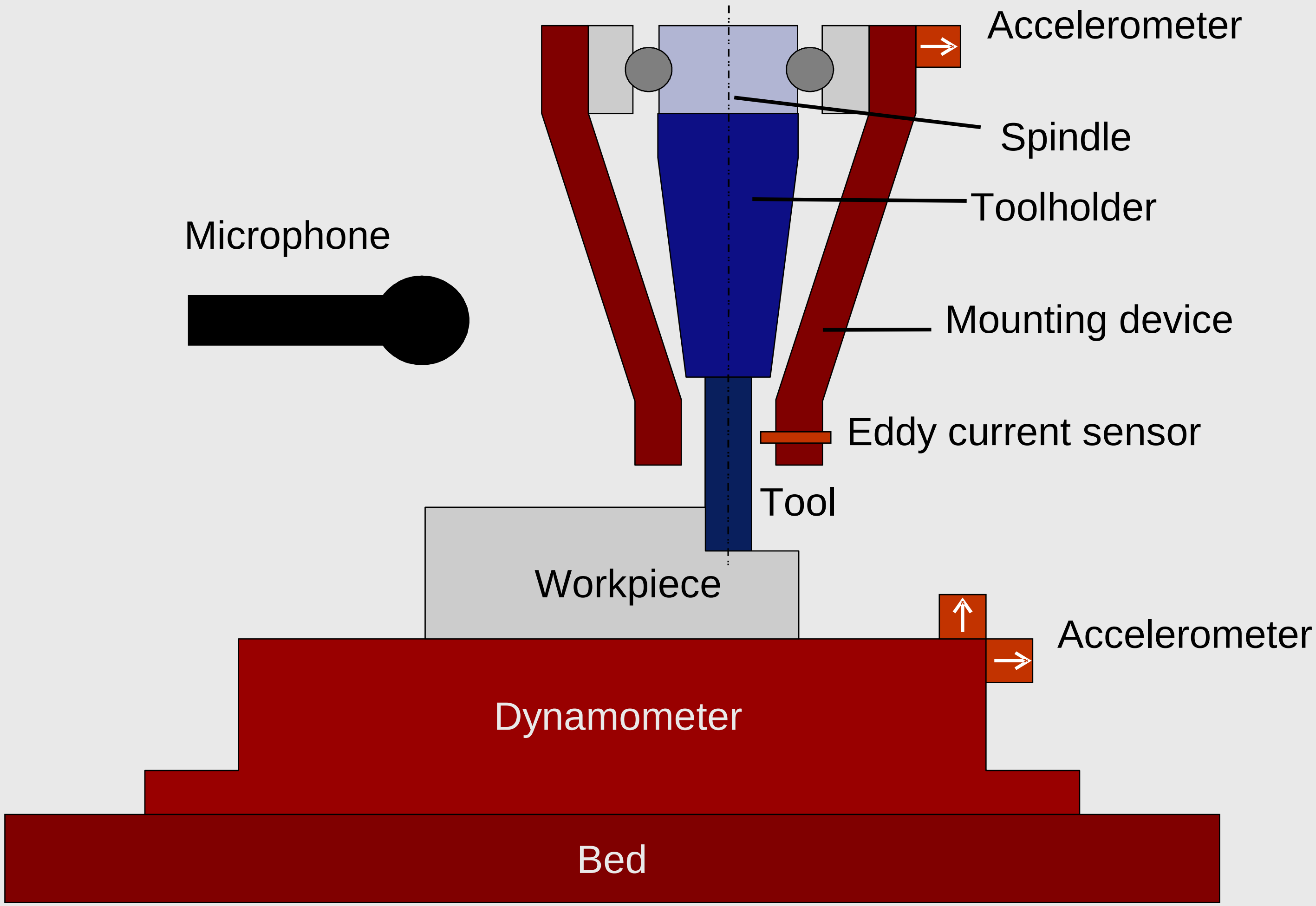
- Example: two sinusoids:

$$\xi(t) = 2c_1 \cos(2\pi f_1 t + \phi_1) + 2c_2 \cos(2\pi f_2 t + \phi_2)$$

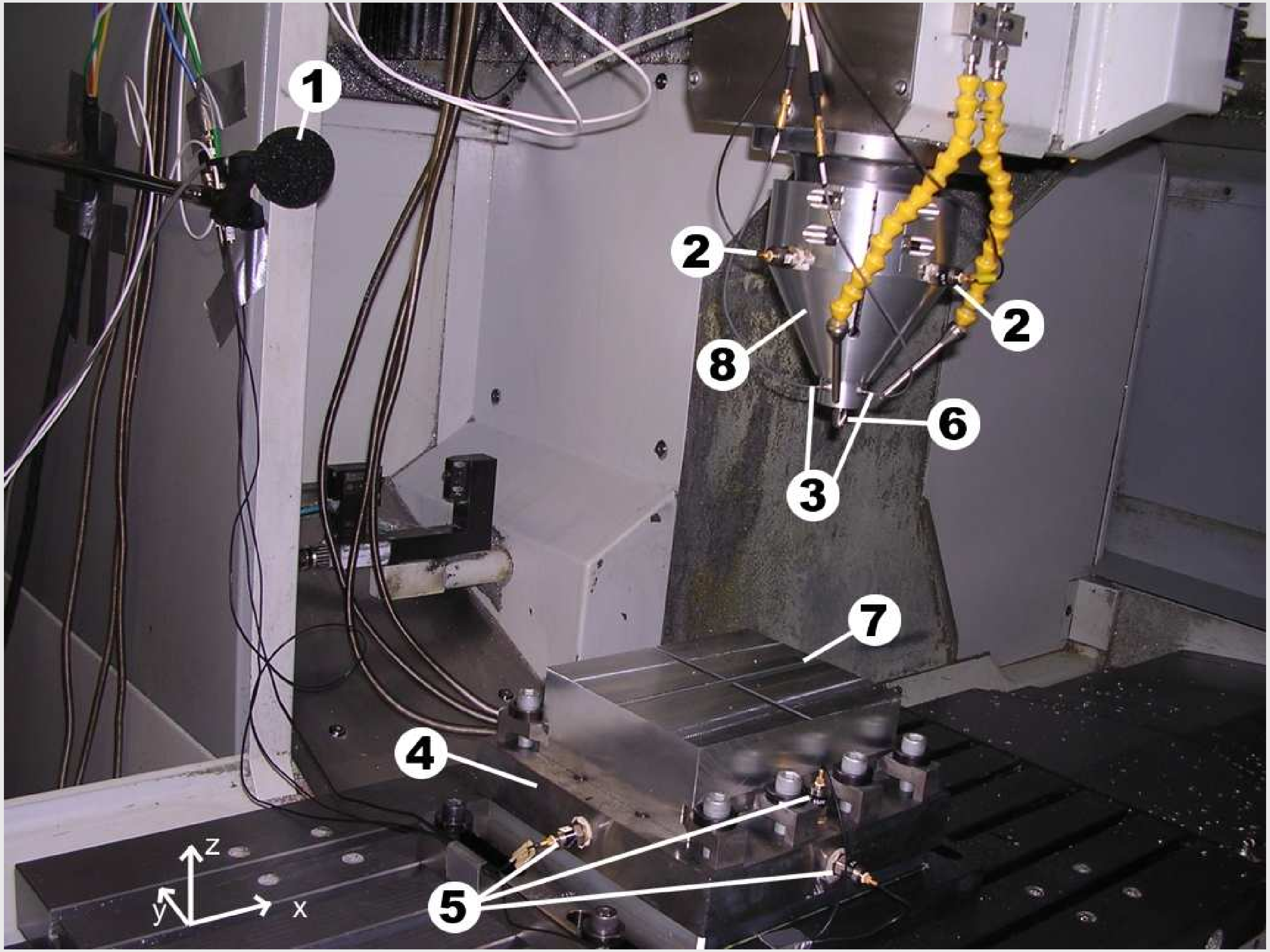
- Demodulation:

$$\begin{aligned}\xi(t)\cos(2\pi f_1 t) = & \xcancel{c_1 \cos(2\pi 2 f_1 t + \phi_1)} \\ & + \xcancel{c_2 \cos\big(2\pi(f_2 + f_1)t + \phi_2\big)} \\ & + \xcancel{c_1 \cos(\phi_1)} \\ & + c_2 \cos\big(2\pi(f_2 - f_1)t + \phi_2\big).\end{aligned}$$

Experimental set-up



Experimental set-up

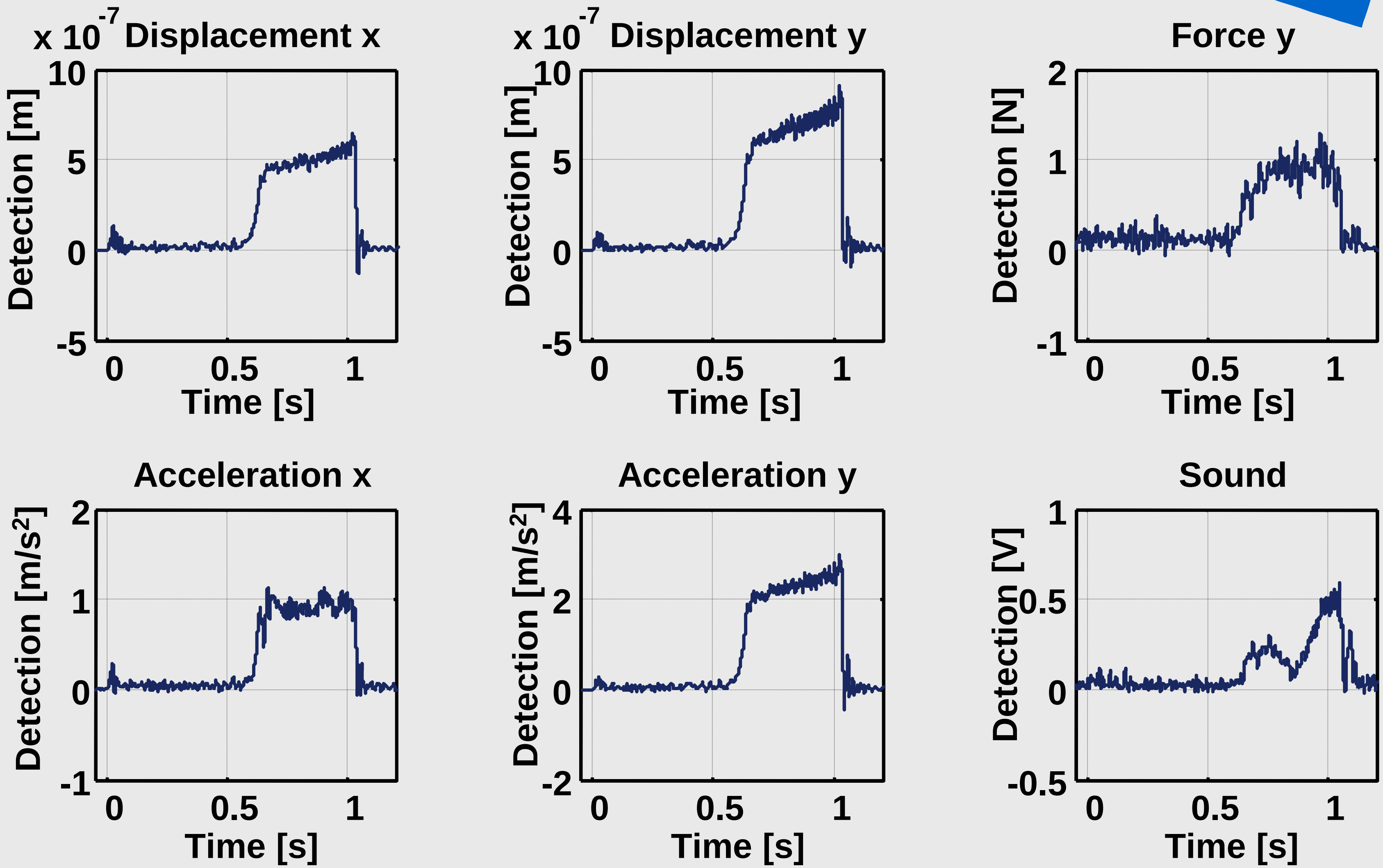


1. Microphone
2. Accelerometer
3. Eddy current
4. Dynamometer
5. Accelerometer
6. Mill
7. Workpiece
8. Mounting device

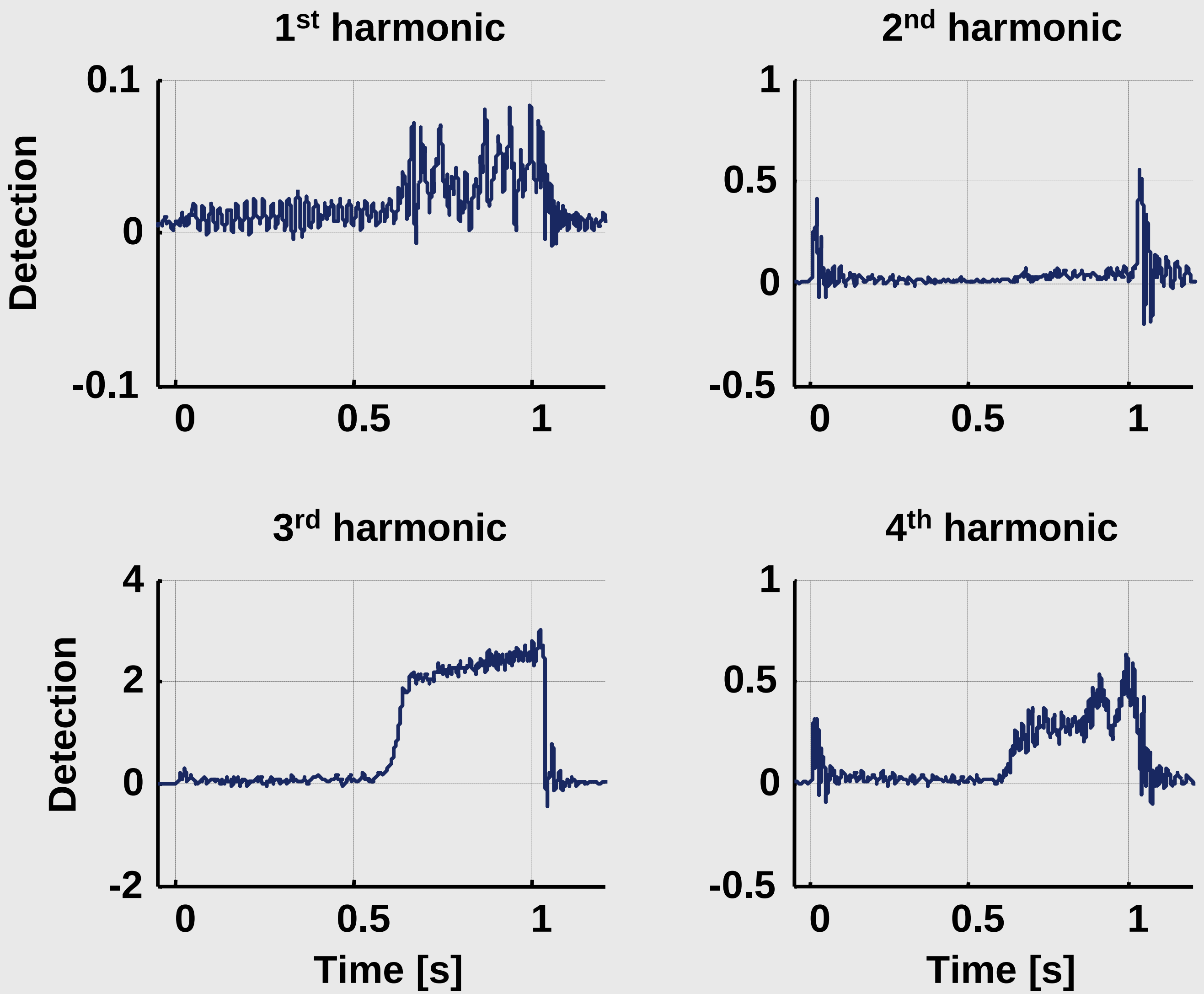
Experiments

- Increasing depth of cut
  - Begin: stable
  - End: chatter
- Apply detection method to different sensors
  - Force
  - Acceleration
  - Displacement
  - Sound
- Compare with workpiece surface

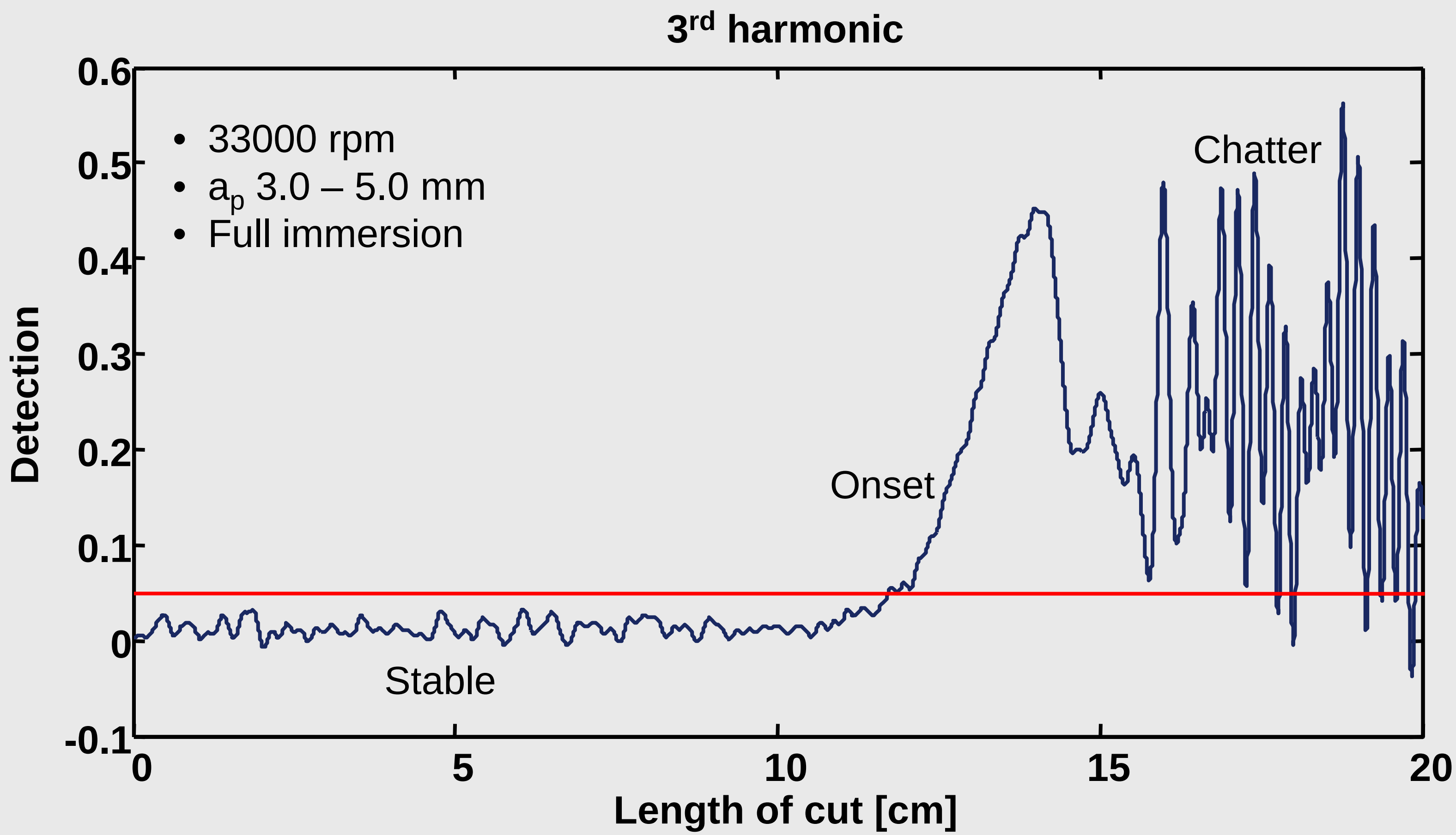
Sensor choice



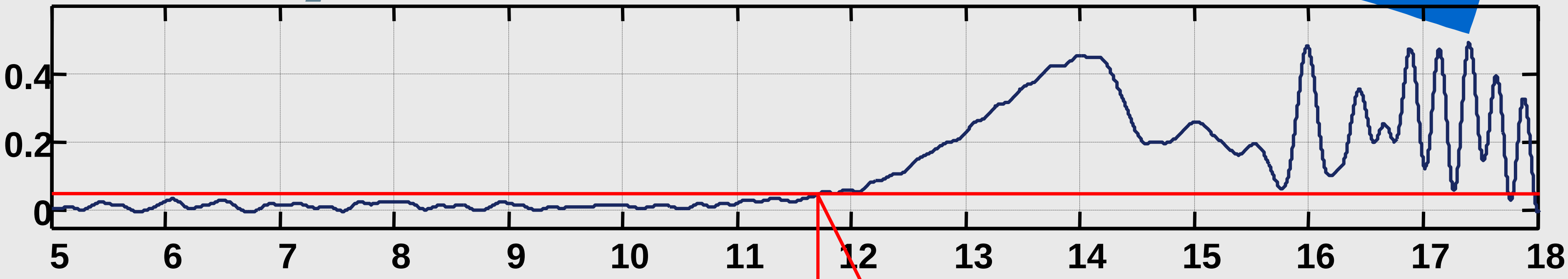
Choice of frequency

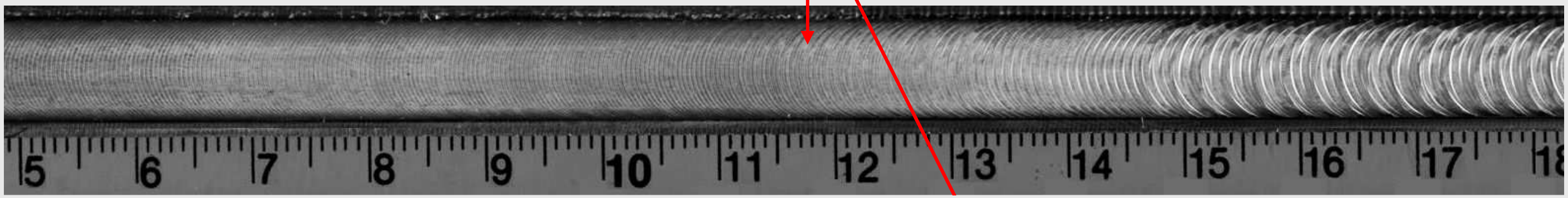


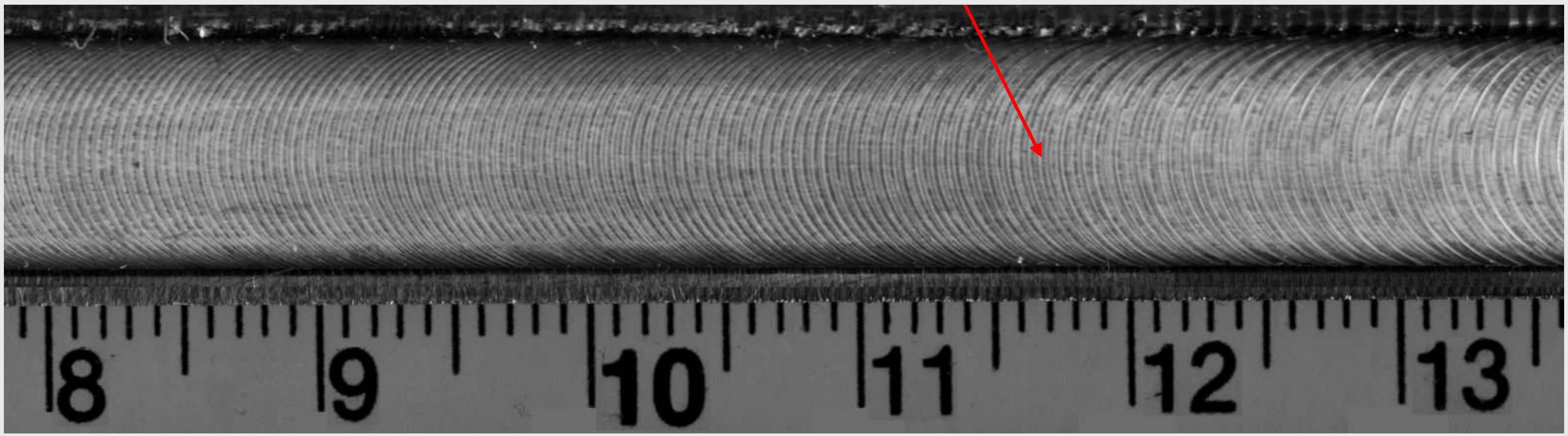
Experimental results



Comparison with workpiece

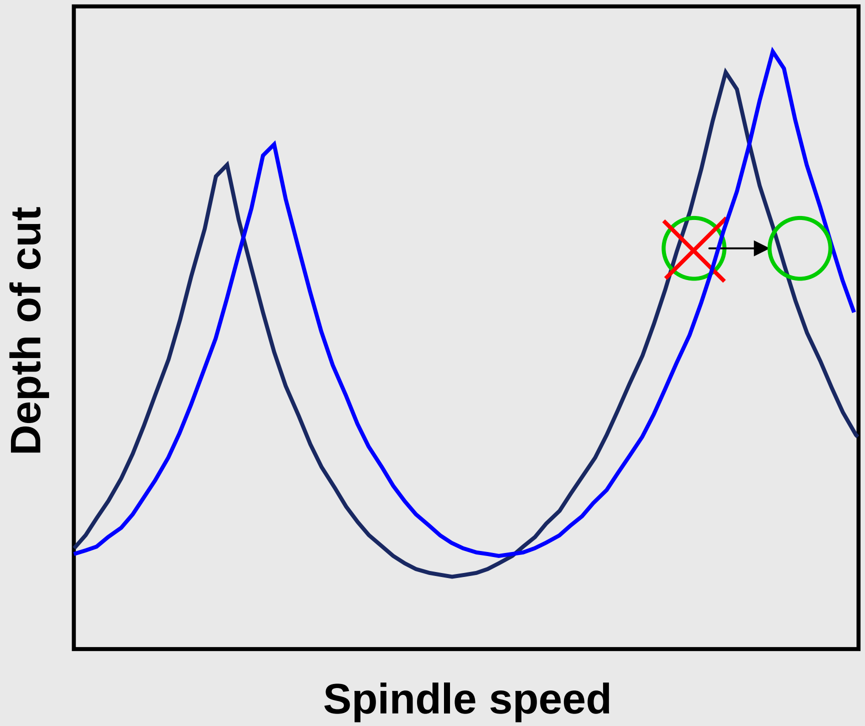






Chatter control

- Change spindle speed and feed



Conclusions (1)

- Model can be used to predict chatter boundary
- Model gives insight to chatter from a non-linear dynamics point of view
  - Chatter is born through a bifurcation
  - After the bifurcation a broad frequency range exists
  - One frequency, close to natural frequency, is dominant
- Simulations coincide well qualitatively with experimental results

Conclusions (2)

- Chatter can be detected online by various sensors
  - Accelerometer preferable < Accurate / Cost effective
- A priori choice of proper demodulation frequencies
  - Using two sensors, detection can run at four different harmonics in parallel at 20 kHz
  - Avoid higher harmonics of tooth passing frequency
- Early detection of onset of chatter
  - Time for control actions to avoid chatter
  - Change spindle speed