IL CHATTER E LE VIBRAZIONI NELLE MACCHINE UTENSILI

Origine e modalità di riduzione

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MUSP
Macchine Utensili e Sistemi di Produzione

Agenda

- Machine Tools performance
- Vibration Issues
- Cutting process instability
- Stability Lobes Estimation
- Experimental procedure
- Uncertainty in SDL estimation
- Structural optimization with metal foams
- Vibration Mitigation strategies and Spindle Speed Variation (SSV)
- SSV in turning operations
  - Vibration and cutting forces mitigation effectiveness
  - Industrial feasibility: promising applications
- SSV in milling operations
  - Vibration and cutting forces mitigation effectiveness
  - SSSV parameter selection

Machine tool performances

Finishing operations

Complex geometry components

(3 or more axes)

High feed rates and 3D trajectories precision (tracking requirements)

⇩

High performances axes dynamics

Roughing operations

Components require high cutting capability

“Material Removal Rate” maximization

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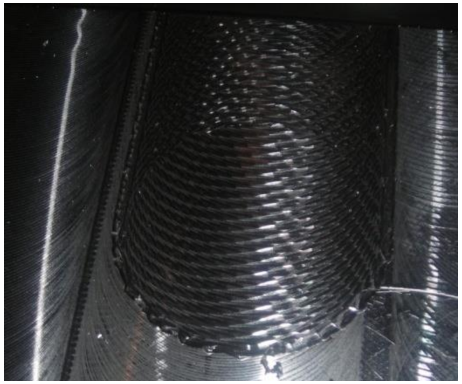
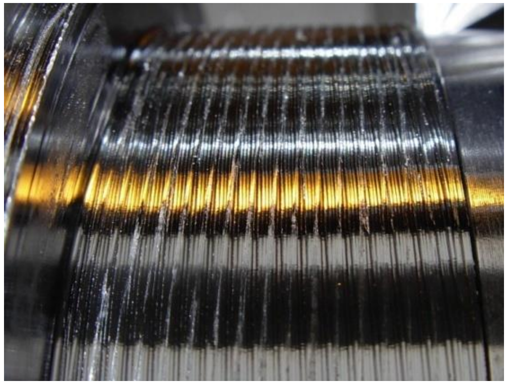
HSM: High Speed Machining
High roughing operation (hard materials)

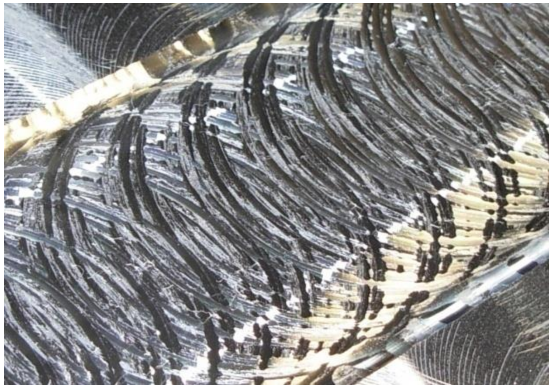
⇘ ⇙

Forces vibrations and auto-regenerative chatter

Effects of vibrations in machine tools



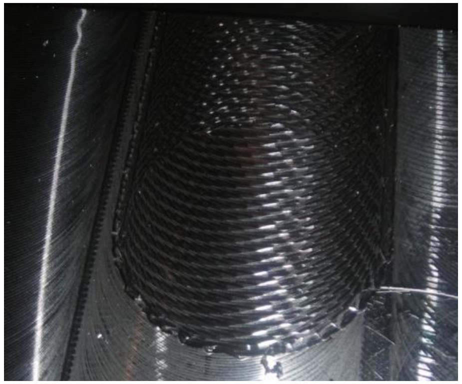
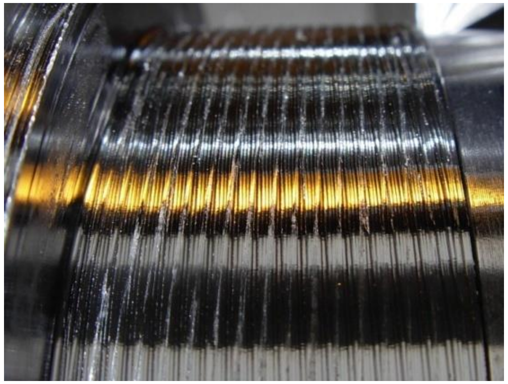
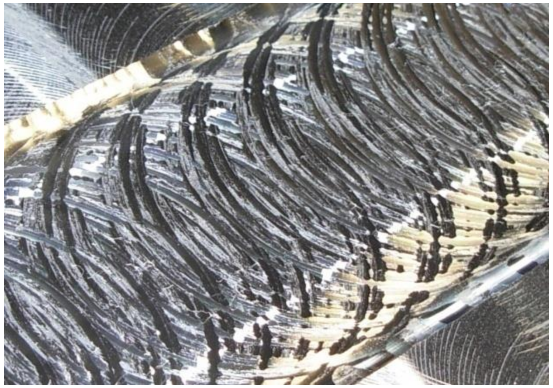




Undesired effects

- Poor surface finish quality
- Increased tool wear and chipping probability
- High spindle bearings load

Effects of vibrations in machine tools

Undesired effects

- Poor surface finish quality
- Increased tool wear and chipping probability
- High spindle bearings load

Commonly accepted approach to reduce vibration effects

Cutting parameter reduction: depth of cut and spindle speed

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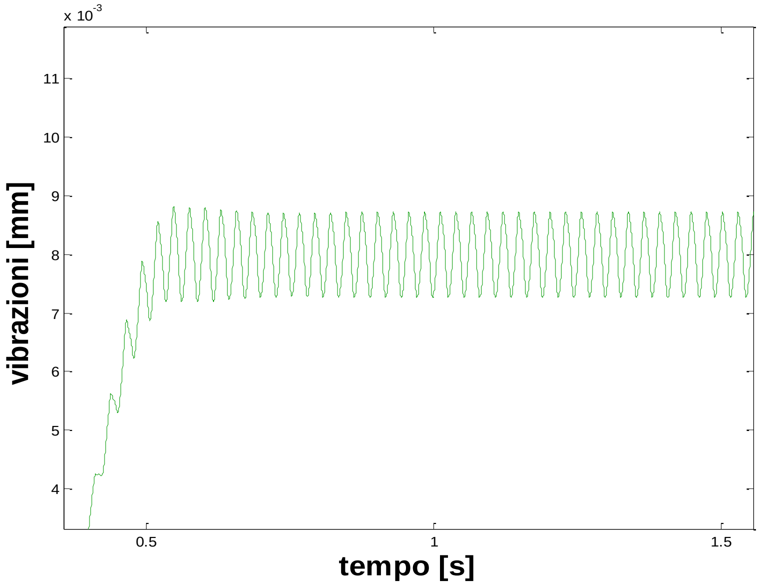
Productivity limitation

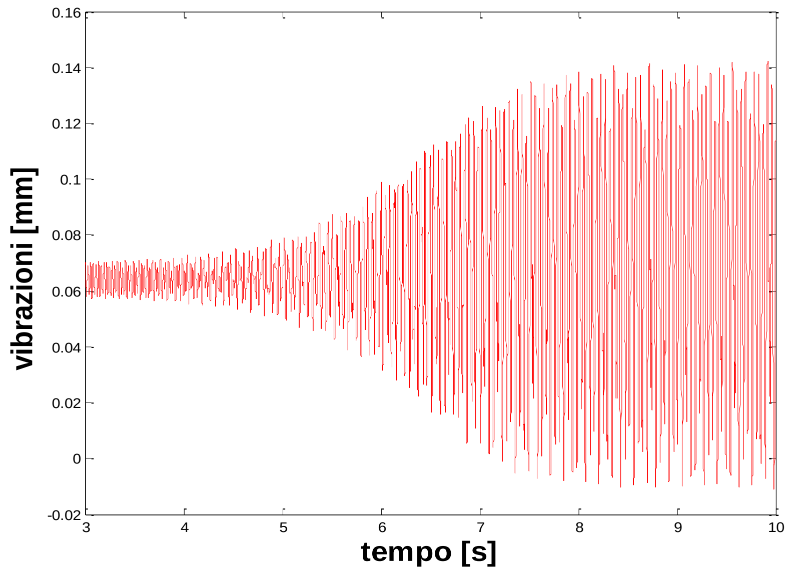
Classification of vibration in machine cutting

Forced vibrations



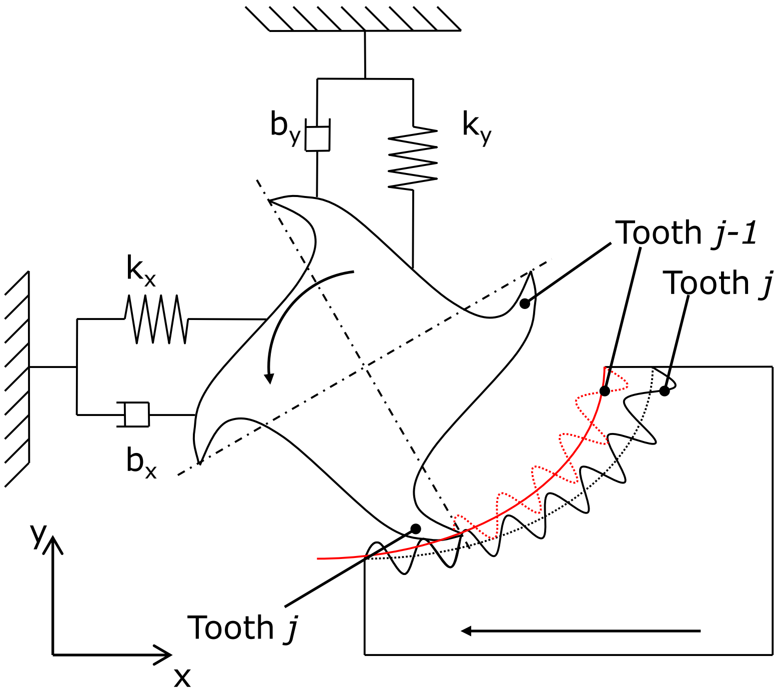
- Directly related to machine dynamics
- Technological signature (waviness) on machine surface

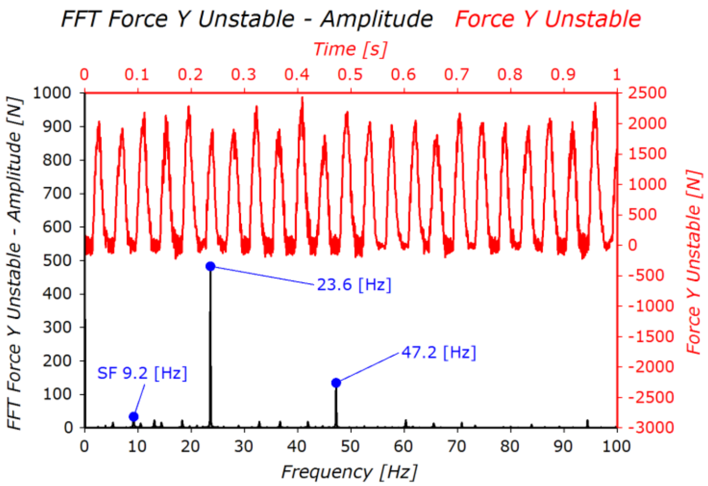
Regenerative vibrations



- Linked to the machine dynamics
- Related to the interaction between successive tooth pass' waviness
- The chip thickness has an unstable dynamic component

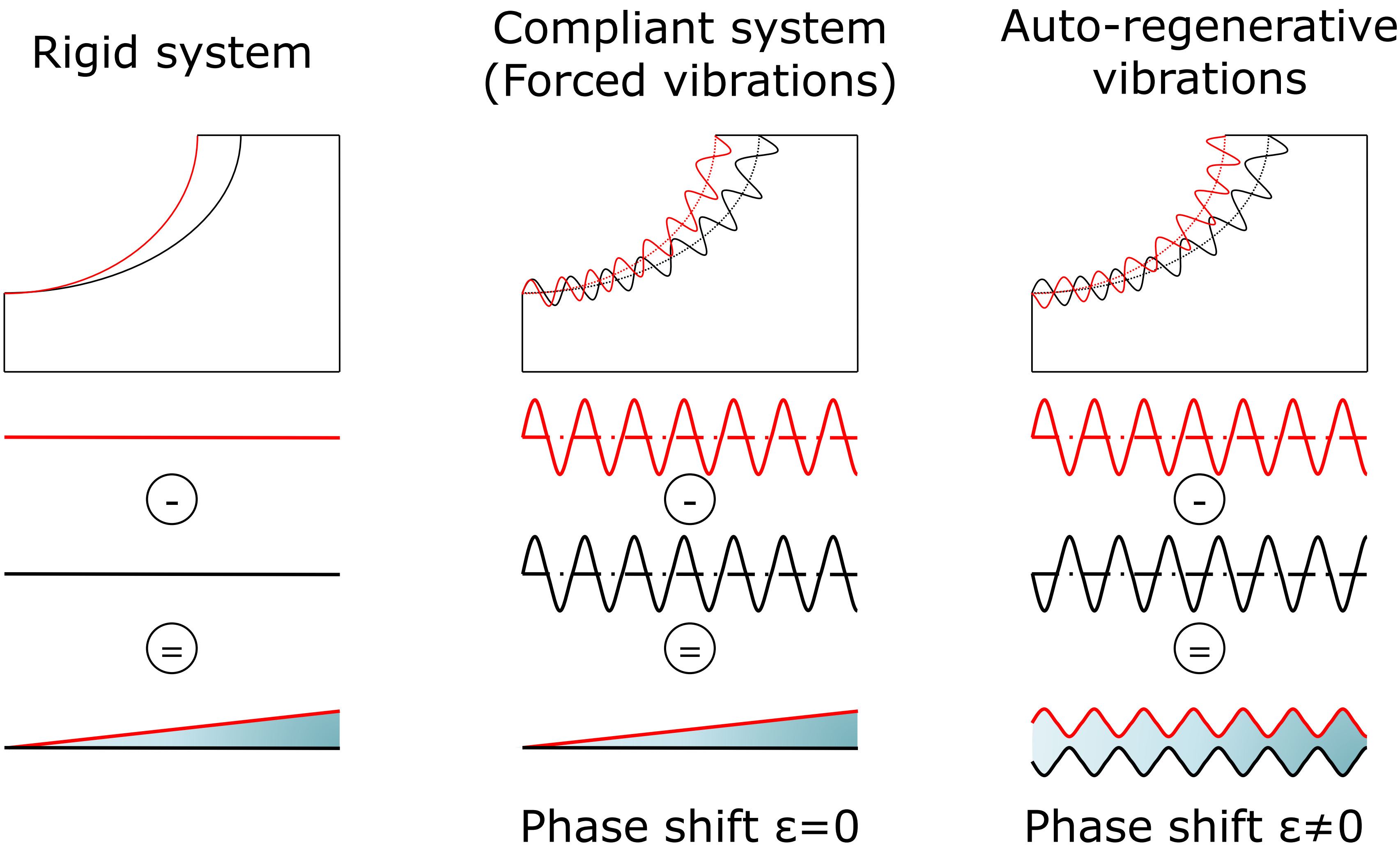
Tooth pass and surface waviness





- Machine tool is not a rigid system
- Cutting forces deforms the machine tool
- Real tooth position can be defined studying the dynamic compliance of the system
- Tooth *j-1* leaves a waviness on the machined surface
- Tooth *j* leaves a waviness that interacts with the previous one
- Chip thickness is modulated

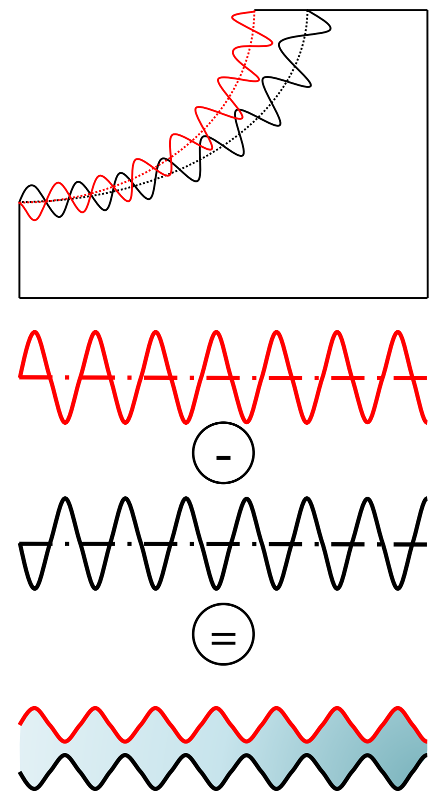
Chip thickness modulation



Chip thickness modulation

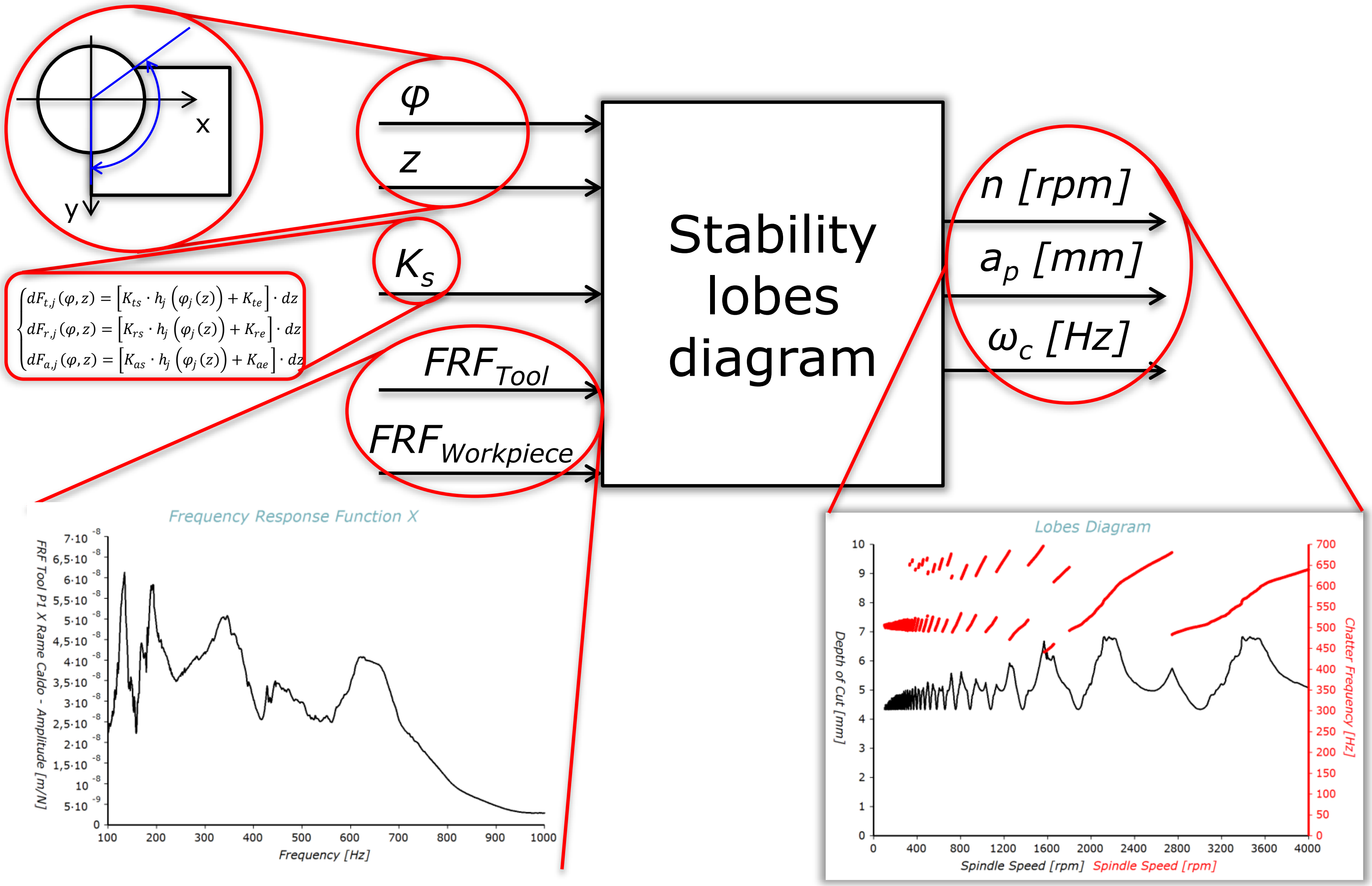
- Cutting forces are proportional to chip thickness
- Vibrations are proportional to cutting forces
- Successive tooth vibrations affects surface waviness
- Chip thickness is proportional to surface waviness

Auto-regenerative vibrations



Phase shift $\varepsilon \neq 0$

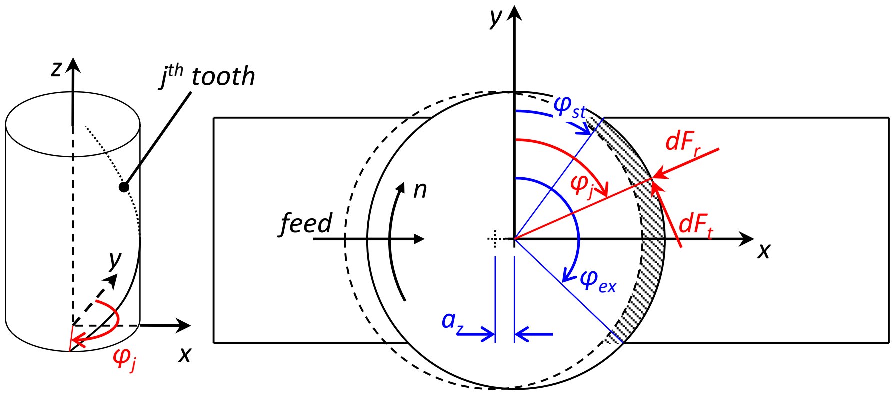
Estimation of the stability lobes diagram



Cutting coefficient determination

$$\begin{cases} dF_{t,j}(\varphi,z) = \left[K_{ts} \cdot h_j(\varphi_j(z)) + K_{te}\right] \cdot dz \\ dF_{r,j}(\varphi,z) = \left[K_{rs} \cdot h_j(\varphi_j(z)) + K_{re}\right] \cdot dz \\ dF_{a,j}(\varphi,z) = \left[K_{as} \cdot h_j(\varphi_j(z)) + K_{ae}\right] \cdot dz \end{cases}$$

$$h_j(\varphi_j(z)) = a_z \cdot \sin\varphi_j(z)$$

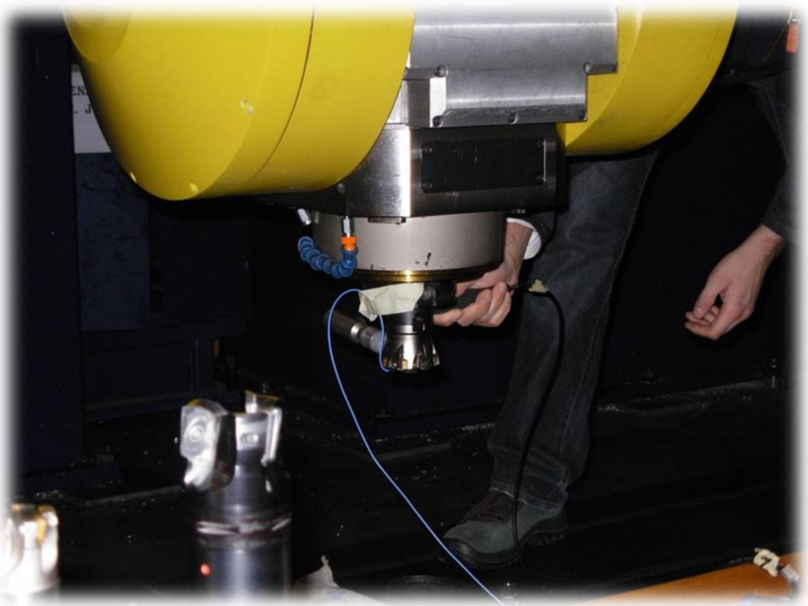


- The select force model is the mechanicistic one
- Mean cutting forces are estimated as a function of a_z
- A regression of the mean forces as a function of the a_z allows to determine the cutting coefficients

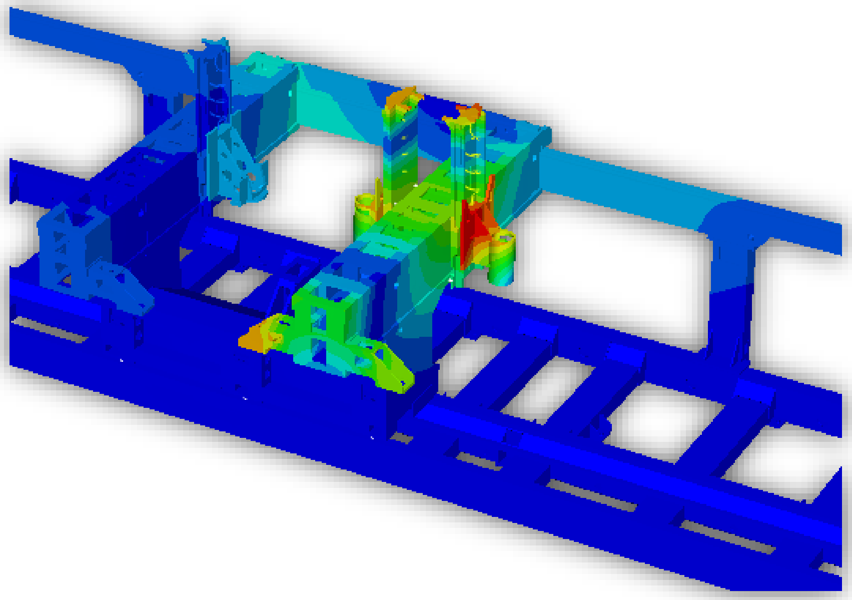
Determination of structure dynamics

- The dynamic compliance at the tool allows to describe system behavior
- There are two ways for *Frequency Response Function* (FRF) determination

(1) Experimental measurement



(2) Finite Element Modeling

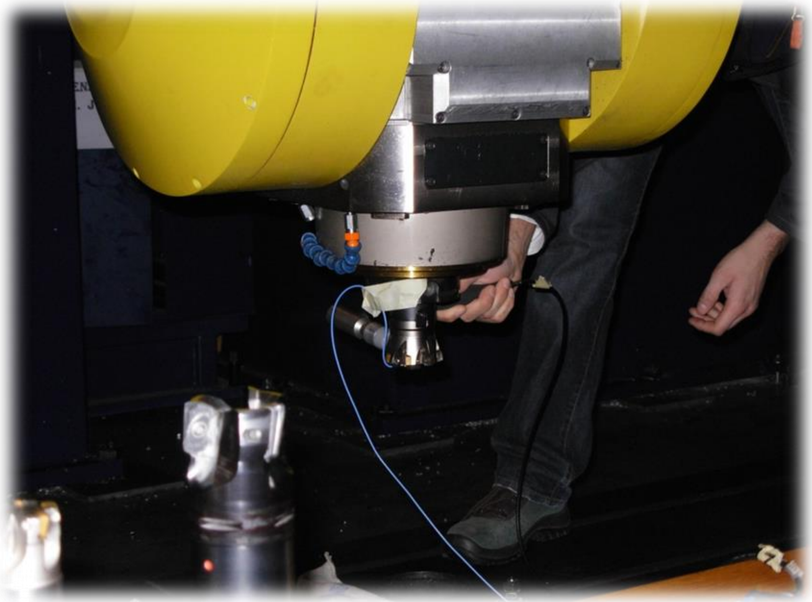


Experimental FRF measurement

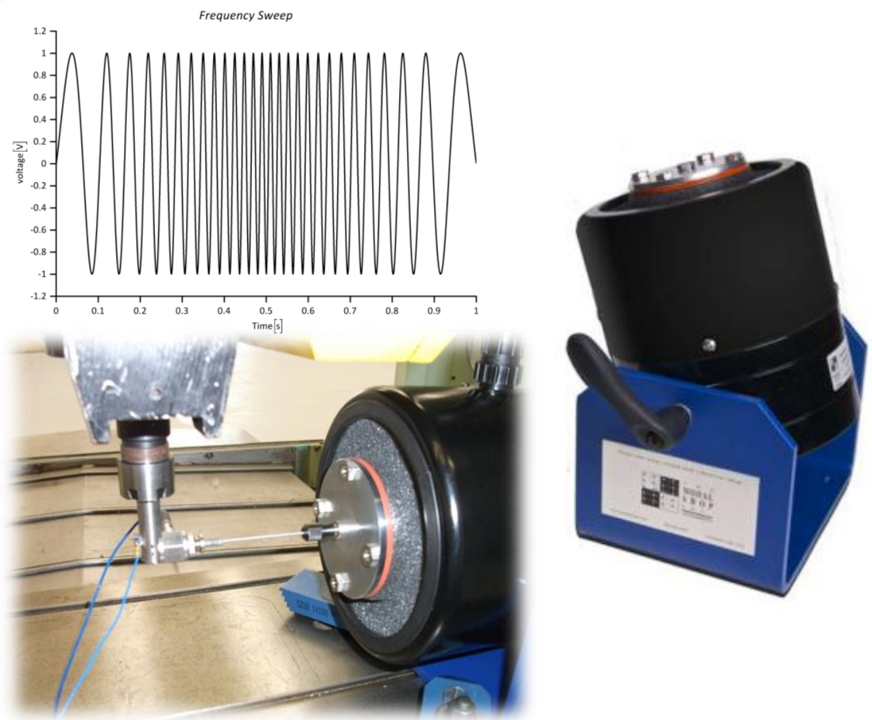
Two typologies of measurement

- Impact test: instrumented hammer and accelerometers
- Measurement with actuators: complex function with force sensor and actuator

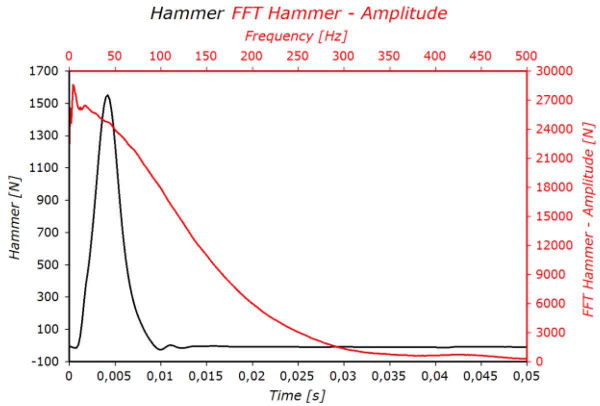
(1.1) Impact testing



(1.2) Measurement with actuator



Impact testing

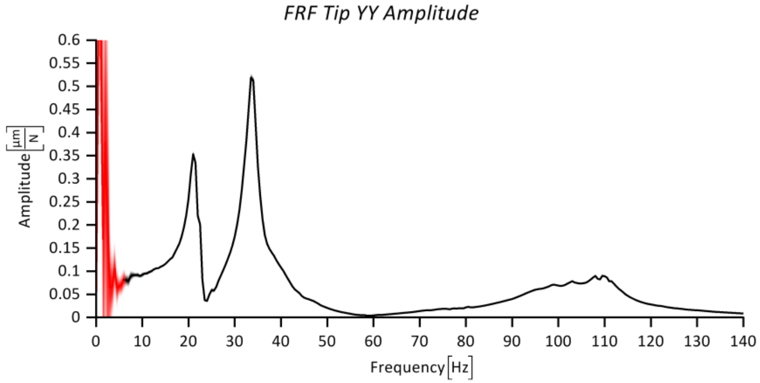


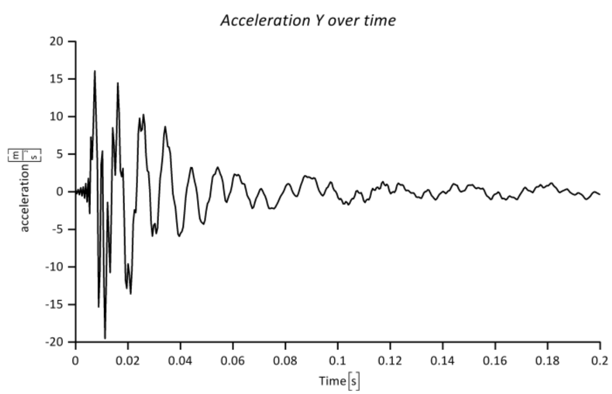
Solicitation → Frequency Response Function estimation → FRF

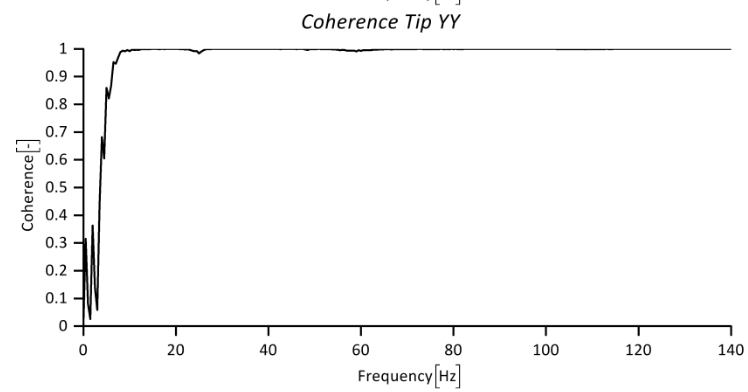
Displacement → Frequency Response Function estimation

(double integration)

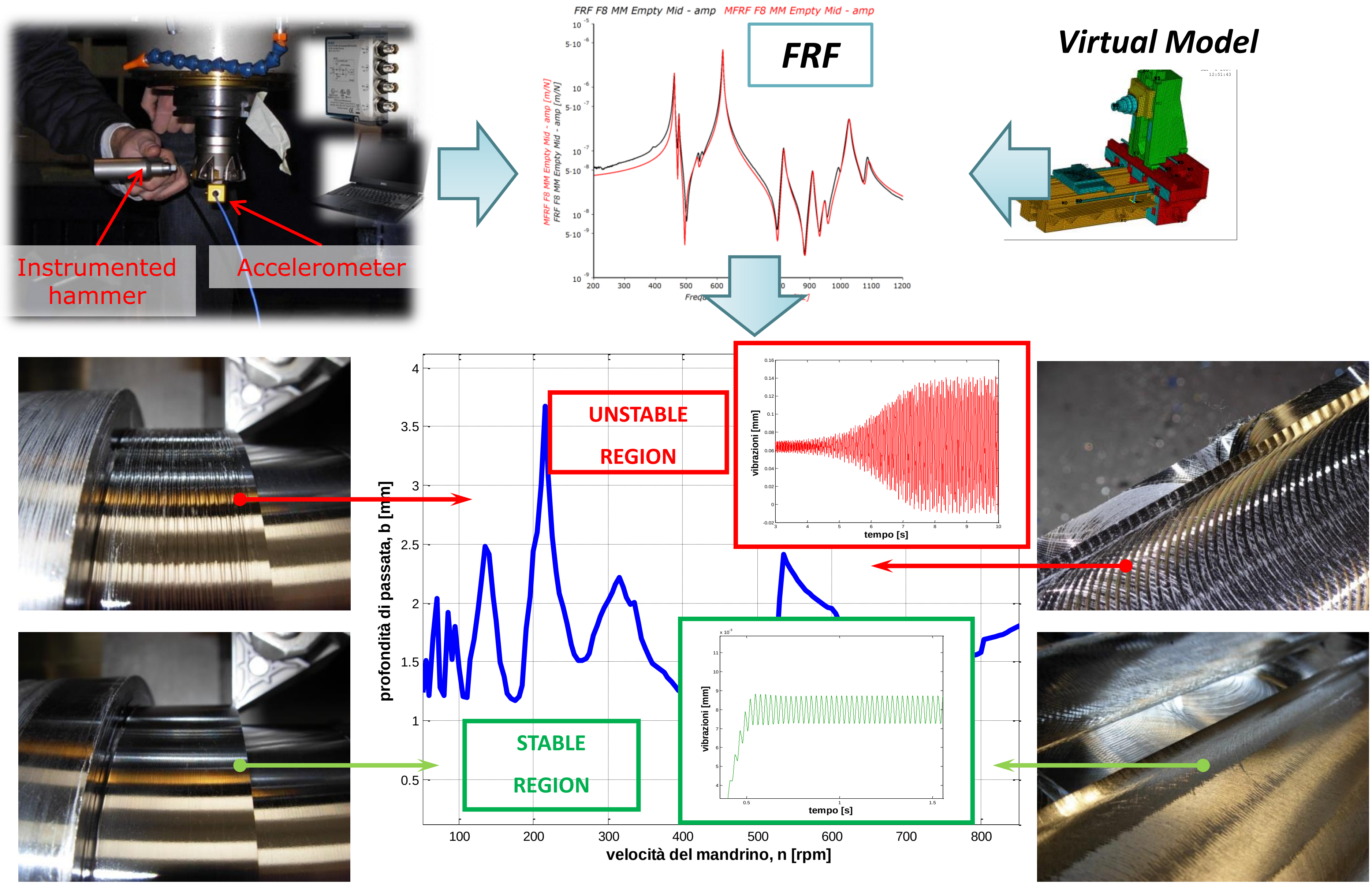
Acceleration



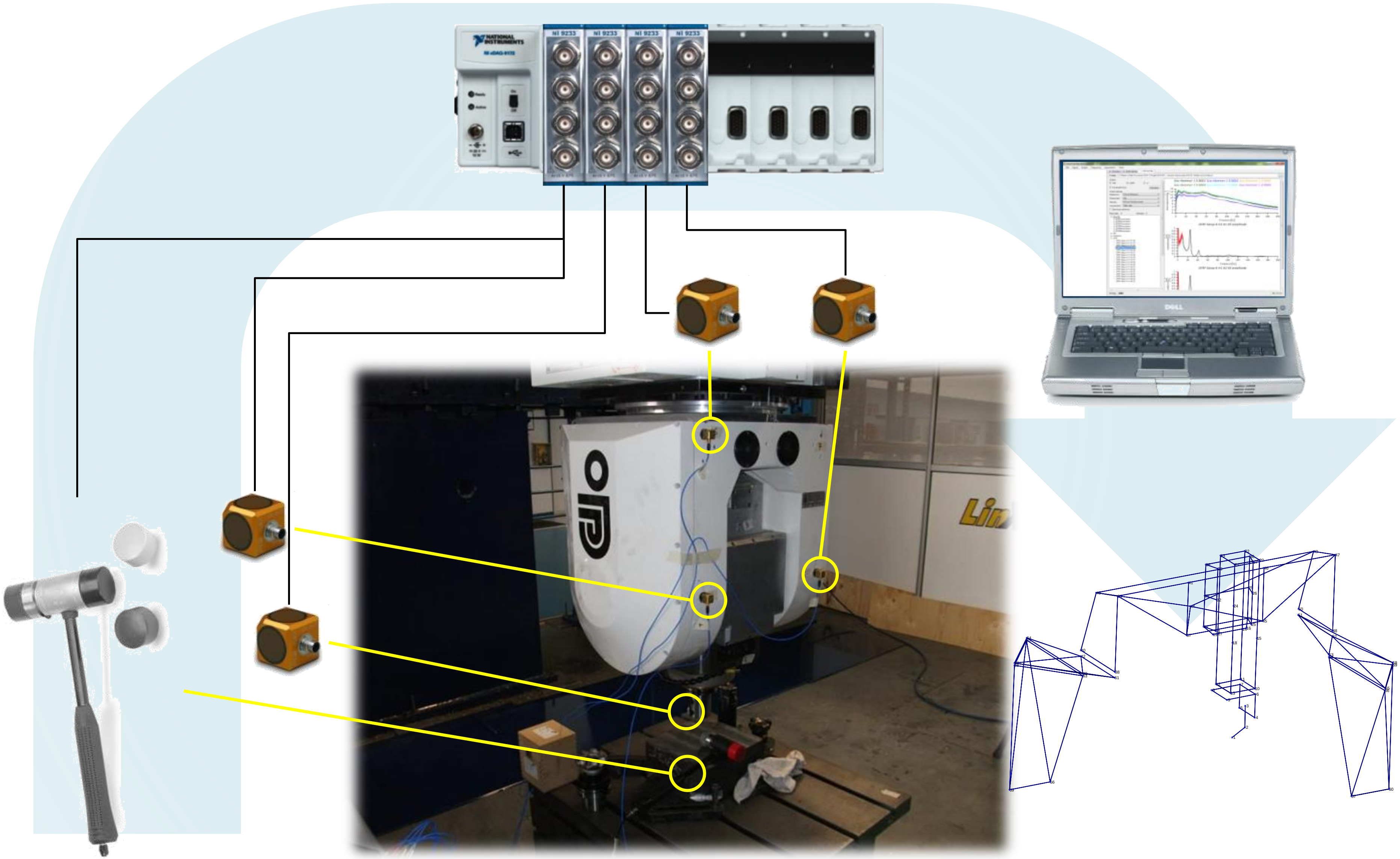




Stability lobes diagram



Experimental modal analysis



Why the Lobes Diagram is not widely applied?

Comments

- The Stability Lobes Diagram (SLD) is not reliable
- Whenever used it is experimentally verified

Needs

- Quantify the “errors” on SLD estimation
- Quantify the errors is SLDalgorithm

Proposed approach

- Propagation of uncertainty

Propagation of uncertainty

- Uncertainty of y is calculated as the composition of uncertainties of the various inputs x_i
- The ***combined uncertainty*** is computed as follows:

$$(1) \quad y = f(x_1, x_2, \ldots, x_N)$$

$$(2) \quad u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 \cdot u^2(x_i) + 2 \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \cdot \frac{\partial f}{\partial x_j} \cdot u(x_i, x_j)$$

- This equation is the ***law of propagation of uncertainty***

UNI CEI ENV 13005:2000. *Guida all'espressione dell'incertezza di misura.* Milano: UNI – CEI, 2000.

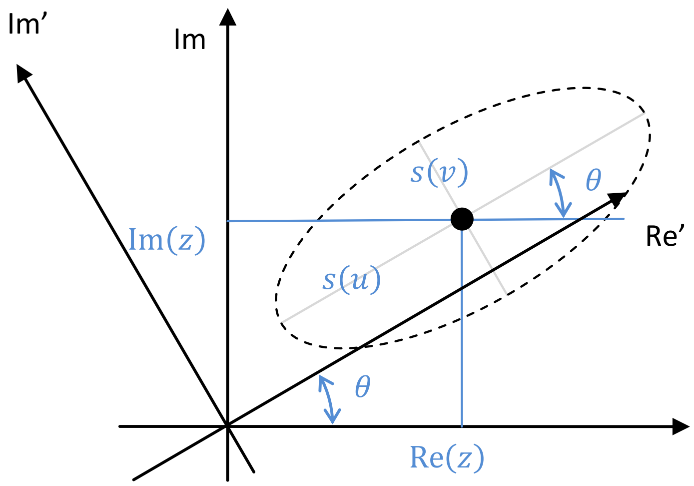
Multivariate propagation of uncertainty

- The covariance matrix of the output variables (matricial version of the *law of propagation of uncertainty*) is:

$$\underbrace{\begin{Bmatrix} u^2(y_1) & \cdots & u(y_1, y_M) \\ \vdots & \ddots & \vdots \\ u(y_M, y_1) & \cdots & u^2(y_M) \end{Bmatrix}}_{M*M} = \underbrace{\begin{Bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_M}{\partial x_1} & \cdots & \frac{\partial f_M}{\partial x_N} \end{Bmatrix}}_{M*N} \cdot \underbrace{\begin{Bmatrix} u^2(x_1) & \cdots & u(x_1, x_N) \\ \vdots & \ddots & \vdots \\ u(x_N, x_1) & \cdots & u^2(x_N) \end{Bmatrix}}_{N*N} \cdot \underbrace{\begin{Bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_M}{\partial x_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_1}{\partial x_N} & \cdots & \frac{\partial f_M}{\partial x_N} \end{Bmatrix}}_{N*M}$$

- The uncertainty region in a plane of two correlated factor is an ellipse (with normality assumption)

$$\theta = \frac{1}{2} \cdot \operatorname{atan2}\left(\frac{2s(\bar{x}, \bar{y})}{s^2(\bar{x}) - s^2(\bar{y})}\right)$$



Analysis of the input and output variables

- Uncertainty affected input quantities
  - Cutting coefficients
  - Frequency Response Functions
- Output quantities (with uncertainty)
  - Depth of cut
  - Spindle speed
- Independent variable (without uncertainty)
  - Chatter frequency

$$a_{lim}(\omega_c) = -\frac{2\pi \cdot \mathrm{Re}(\Lambda)}{N \cdot K_t} \cdot (1+\kappa^2)$$

$$\varepsilon = \pi - 2\tan^{-1}(\kappa)$$

$$\kappa = \frac{\mathrm{Im}(\Lambda)}{\mathrm{Re}(\Lambda)}$$

$$n = \frac{60}{z \cdot T} = \frac{60}{z} \cdot \frac{2\pi\omega_c}{\varepsilon + 2k\pi}$$

Uncertainty for cutting coefficients

- A regression of mean forces as a function of a_z is needed
- Uncertainty of the predictors can be estimated with regression

Feed Regression

Source	DF	SS	MS	F
Regression	1	1465502,7	1465502,684	122,5613
Error	16	191316,9	11957,306	
Total	17	1656819,6		

$$\overline{F}_x = \overline{F}_{xs} \cdot a_z + \overline{F}_{xe}$$

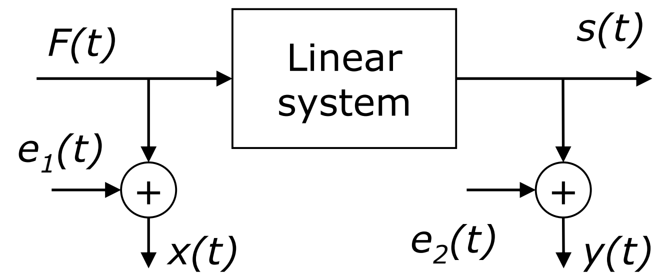
Cutting coefficient

K_{ts}= 1911±53 [N/mm^2]
K_{rs}= 747,7±19 [N/mm^2]
K_{as}= 7,696±12 [N/mm^2]
K_{te}= 17,18±9,3 [N/mm]
K_{re}= 65,04±3,4 [N/mm]
K_{ae}= -21,07±1,6 [N/mm]

- From the cutting force model it is possible to estimate the cutting coefficients with uncertainty
- Hypothesis testing must be done after regression analysis

Uncertainty in Frequency Response Function estimation

- Frequency Response Function is the result of a series of repeated measurements
- The quantities *F(t), s(t)* are noise affected
- Estimators minimize these measurement noises
- The *coherence function* shows the linearity of the measure as a function of frequency



$$\hat{H}_1(\omega) = \frac{\hat{G}_{xy}(\omega)}{\hat{G}_{xx}(\omega)}$$

$$\hat{H}_2(\omega) = \frac{\hat{G}_{yy}(\omega)}{\hat{G}_{yx}(\omega)}$$

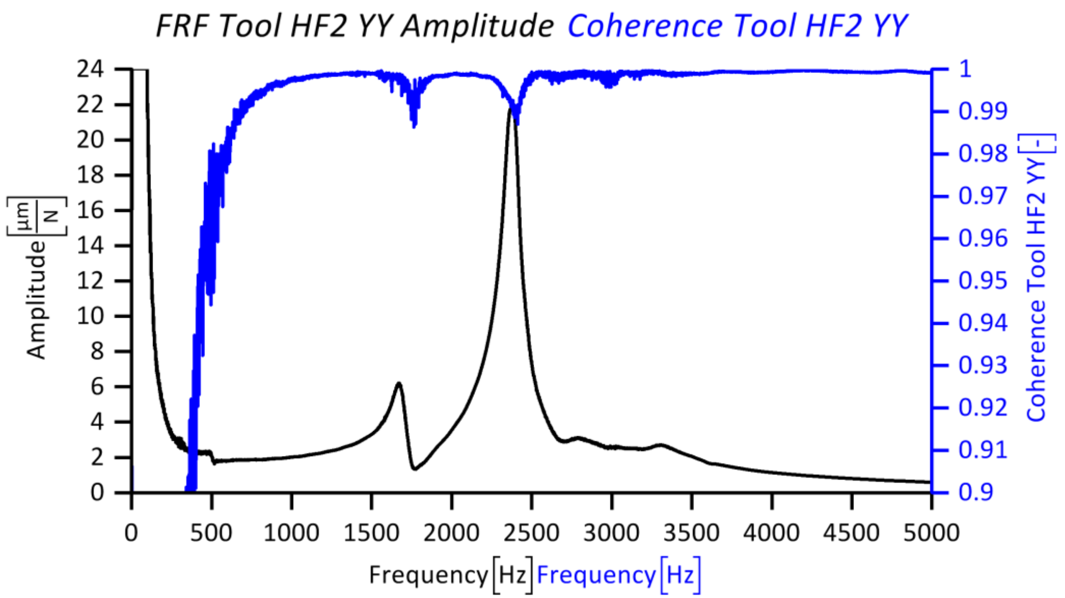
$$\hat{\gamma}^2(\omega) = \frac{\left|\hat{G}_{xy}(\omega)\right|^2}{\hat{G}_{xx}(\omega)\cdot\hat{G}_{yy}(\omega)}$$

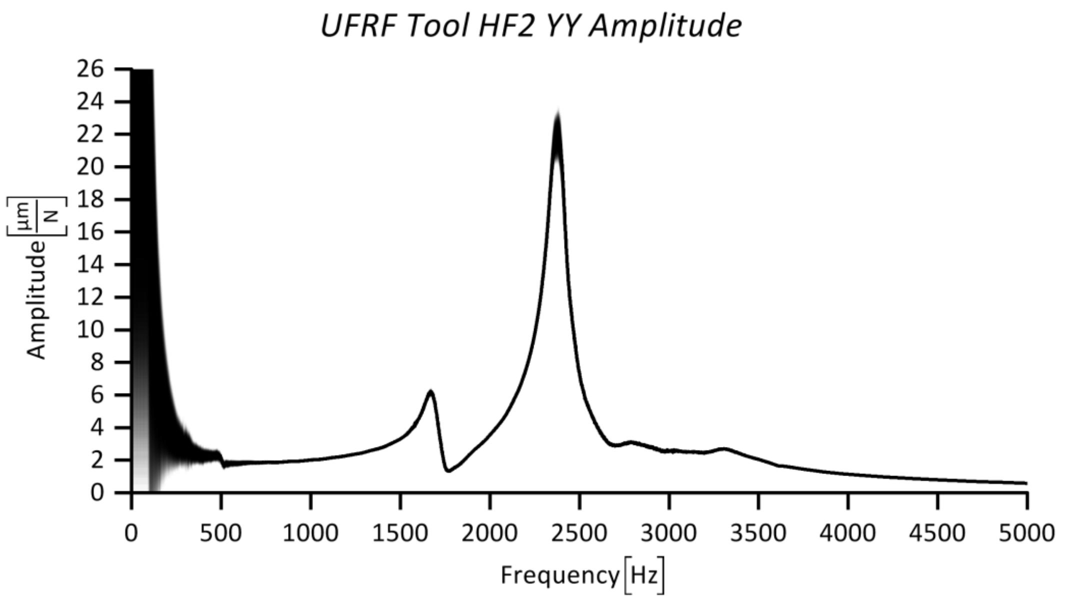
Uncertainty in Frequency Response Function estimation

- There is a formulation for the estimation of uncertainty for H_1 FRF estimator as a function of coherence function

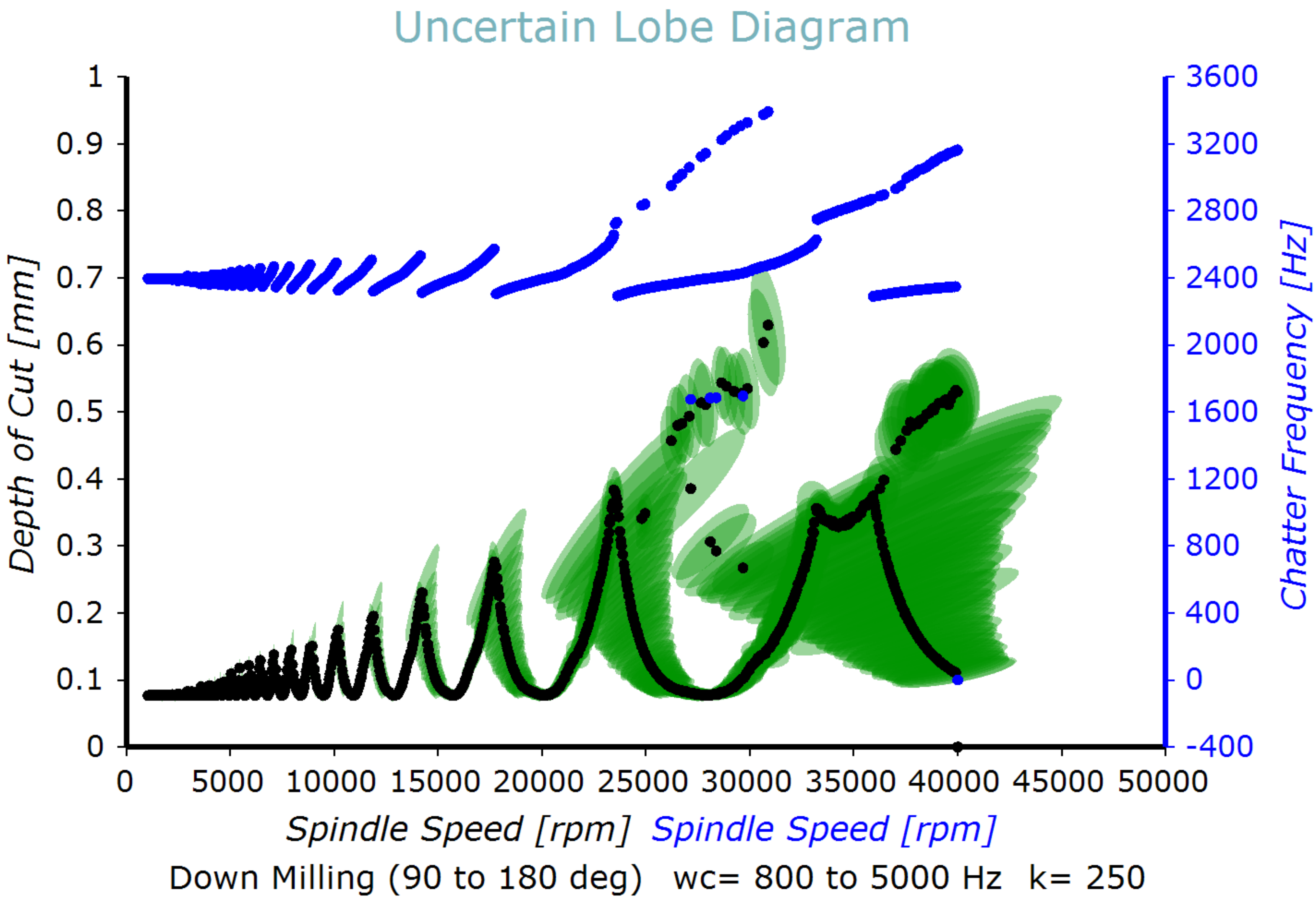
$$\sigma(\angle H_1(\omega)) = \sin^{-1}\left(\frac{\sqrt{1-\gamma^2(\omega)}}{|\gamma(\omega)|\sqrt{2n_d}}\right)$$

$$\sigma(|H_1(\omega)|) = \frac{\sqrt{1-\gamma^2(\omega)}}{|\gamma(\omega)|\sqrt{2n_d}}|H_1(\omega)|$$





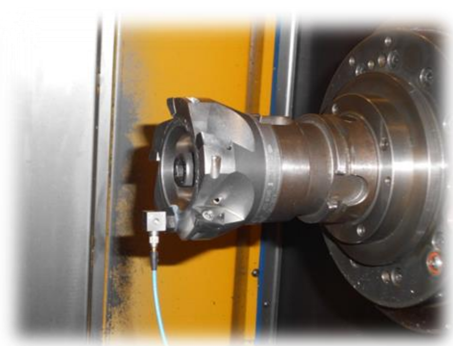
Stability Lobes Diagram with uncertainty (HSM)

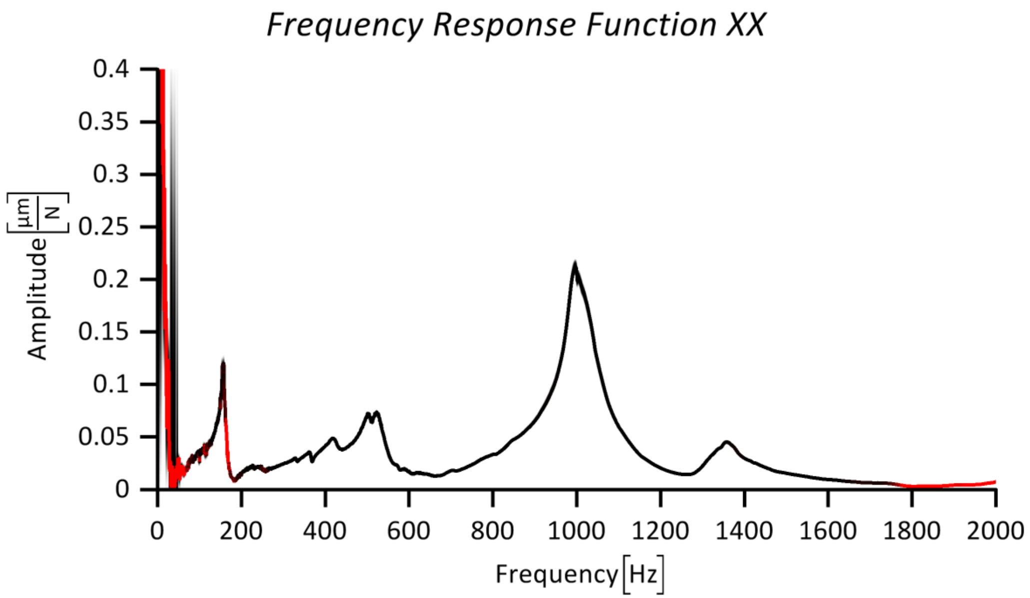


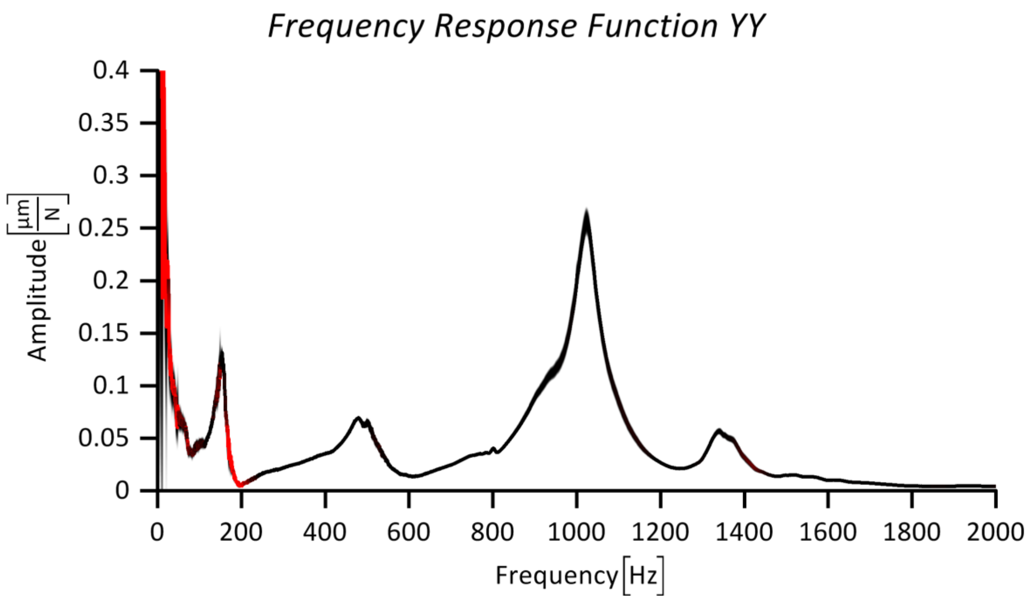
Stability Lobes Diagram with uncertainty (example)

- Spindle speed 3000 rpm
- Axial depth of cut 1.5 mm
- Slot milling on aluminum
- Three different milling tests with a_z: 0.1 - 0.2 - 0.3 mm/z

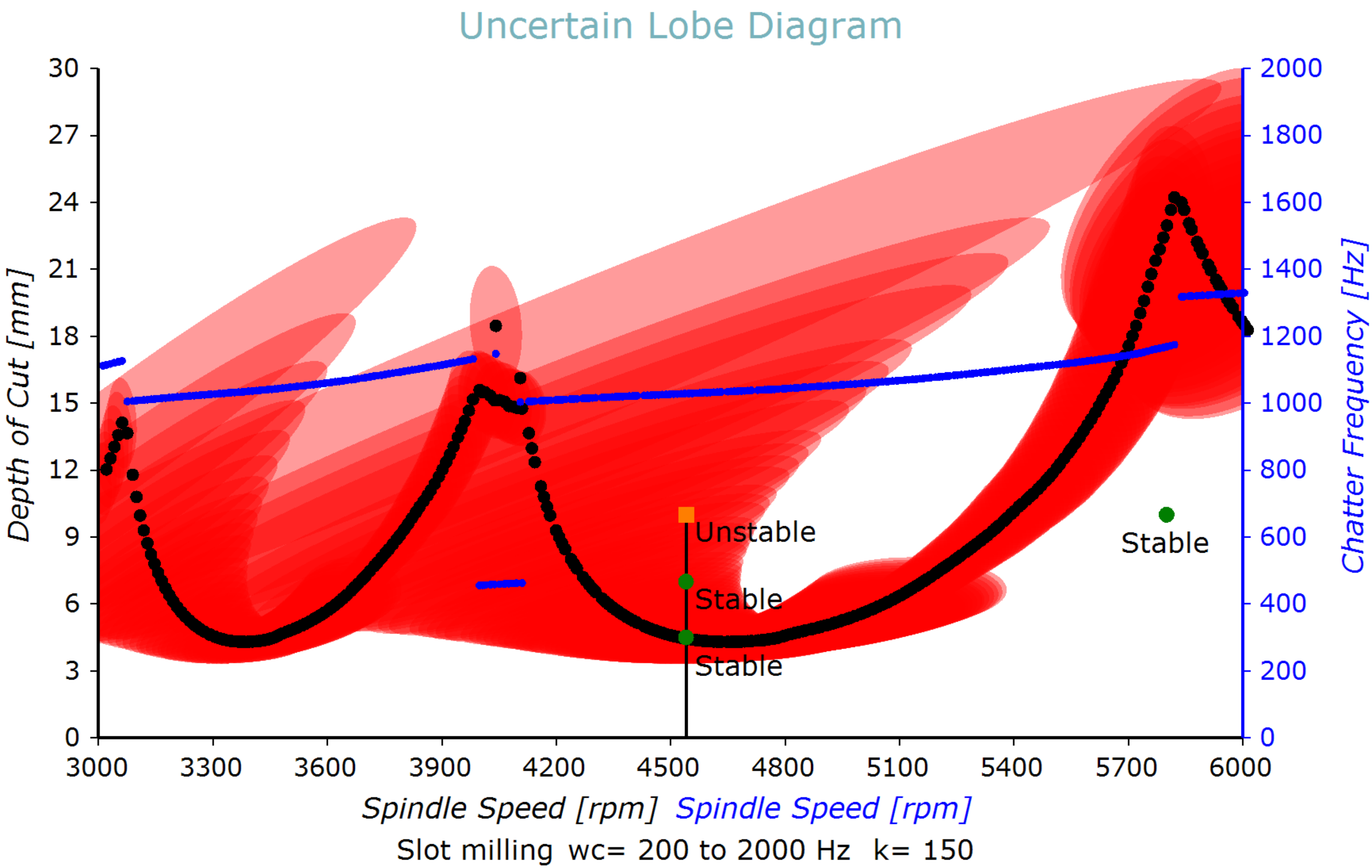
K_{ts}= 575,8±27 [N/mm^2]
K_{rs}= 74,79±4,2 [N/mm^2]
K_{as}= -10,01±5,4 [N/mm^2]
K_{te}= 24,94±4,1 [N/mm]
K_{re}= 21,37±0,64 [N/mm]
K_{ae}= 13,84±0,67 [N/mm]





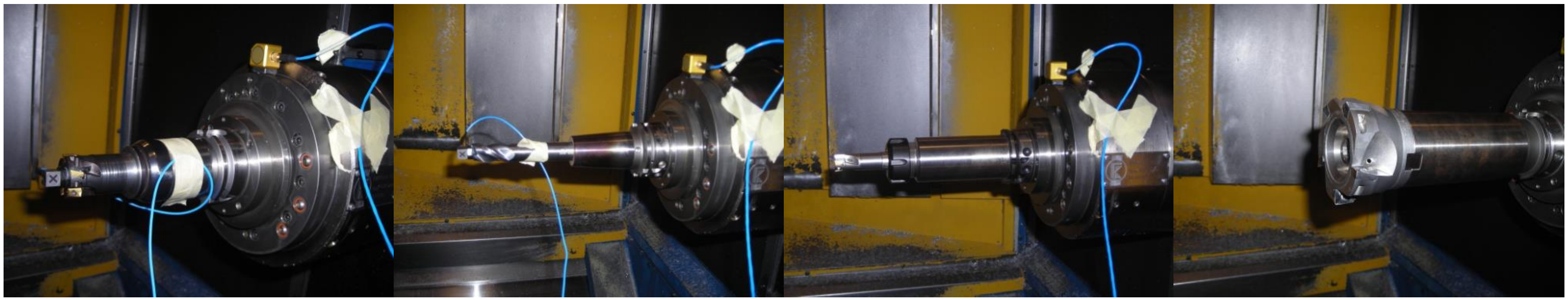


Stability Lobes Diagram with uncertainty (example): performed tests

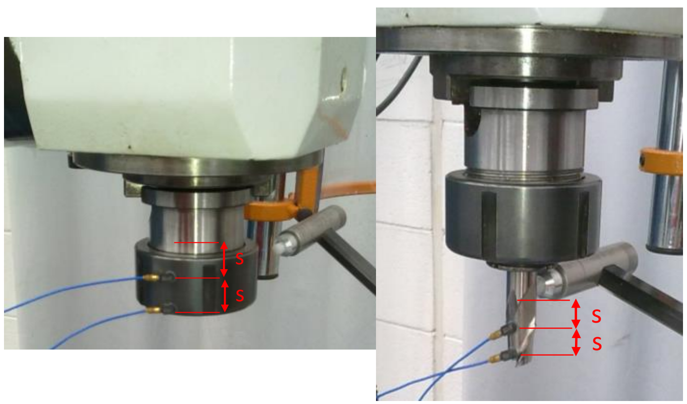


Receptance Coupling Substructure Analysis (RCSA)

- Need to save time: ***complex industrial*** productive scenarii



Known case:



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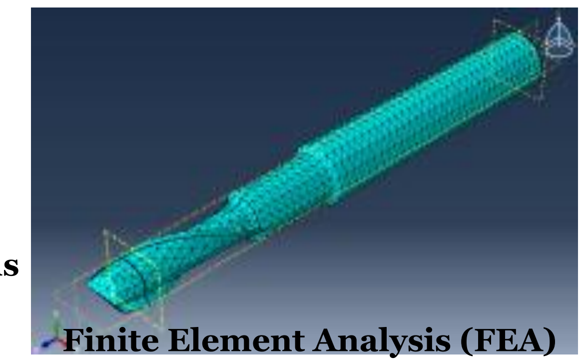
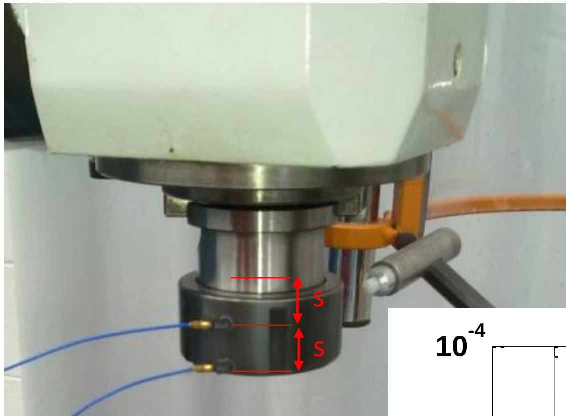
Coupling dynamic systems

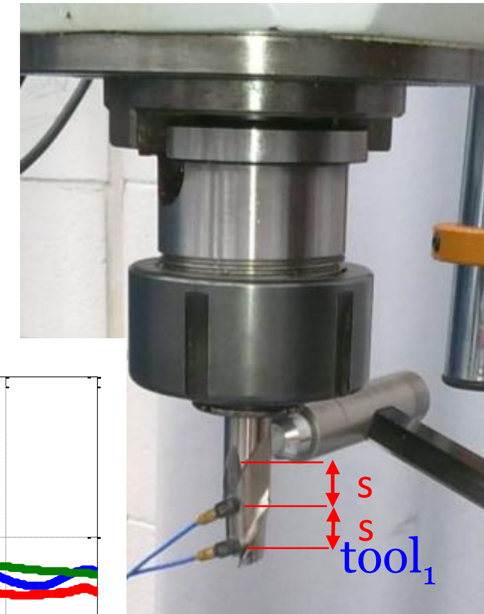


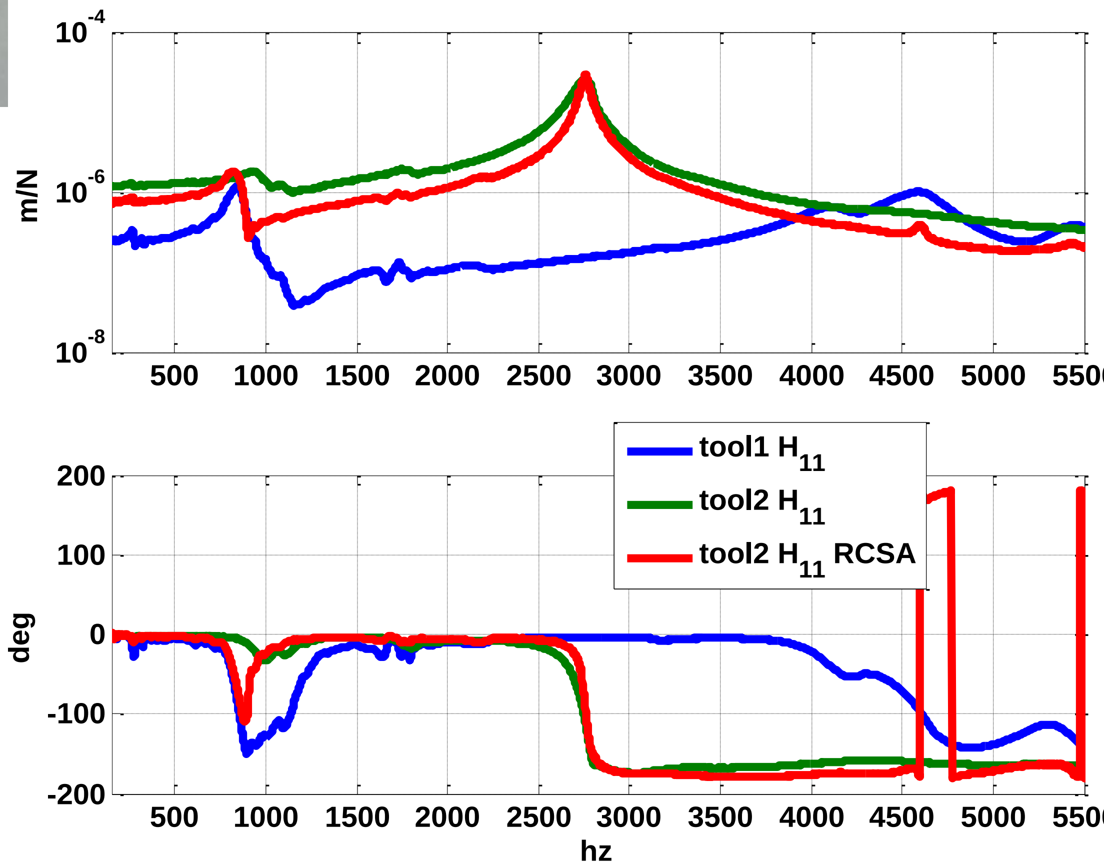
Finite Element Analysis (FEA)

- A lot of research have been done but the RCSA technique still shows important limitation due to the dynamics prediction accuracy
- Different RCSA techniques were developed

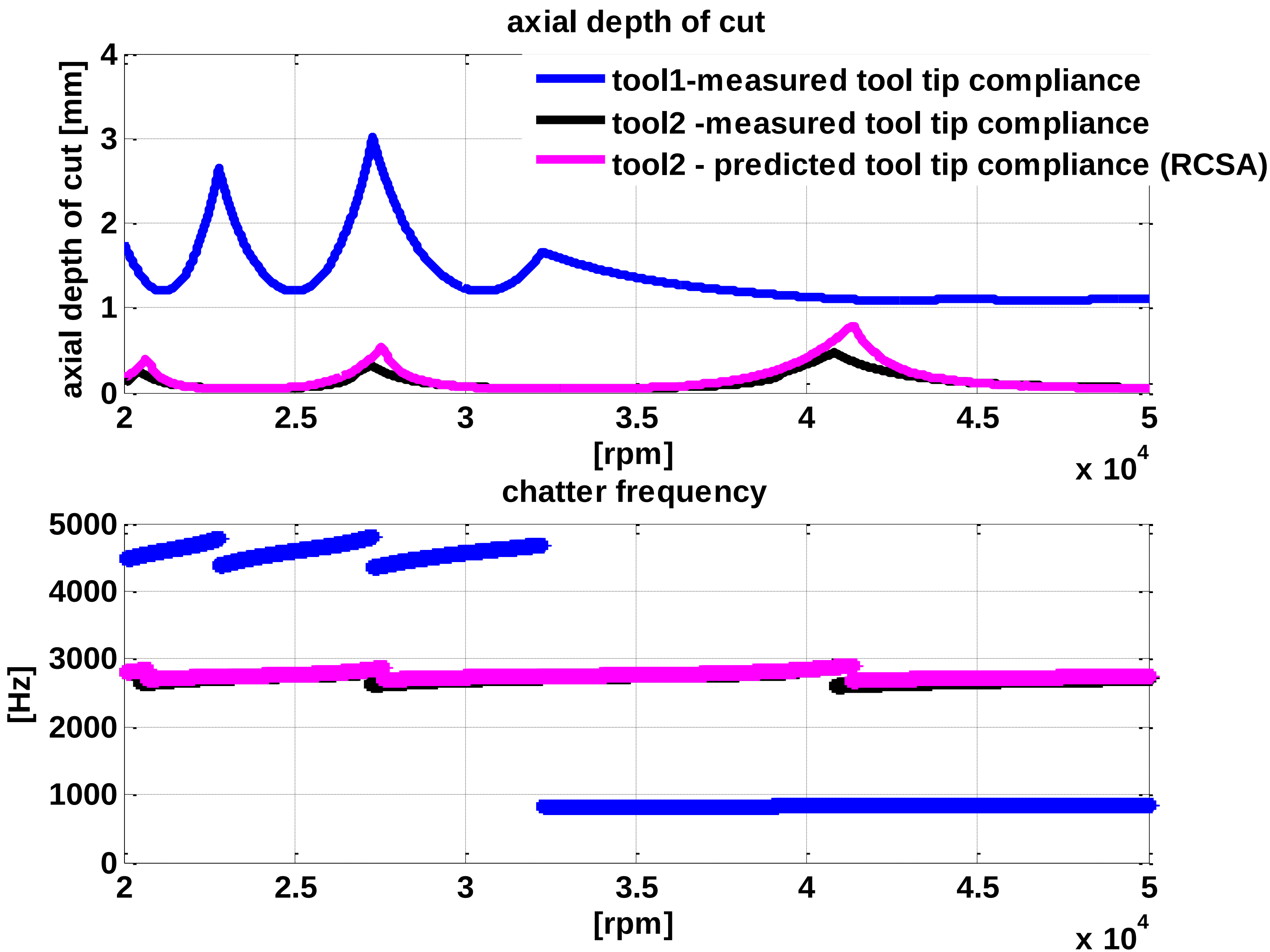
Tool tip dynamic prediction properties: RCSA evaluation





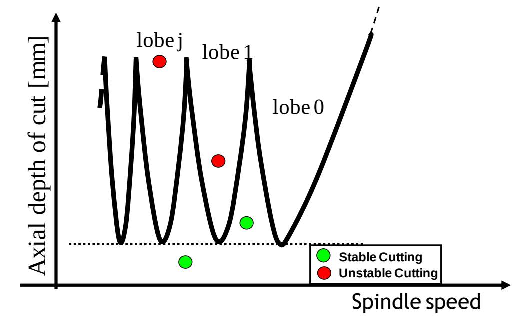


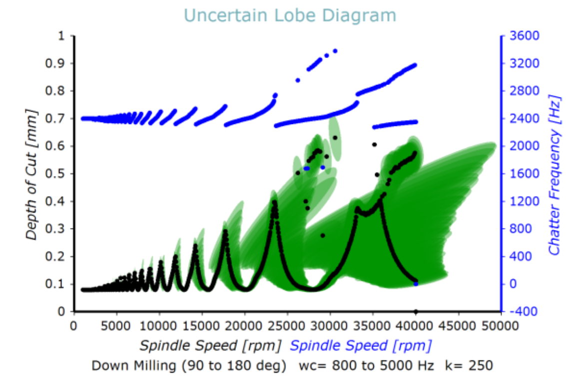
Stability Lobes Prediction: RCSA evaluation

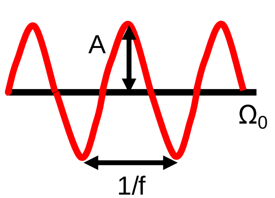


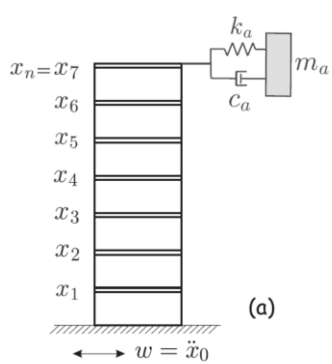
Facing regenerative chatter

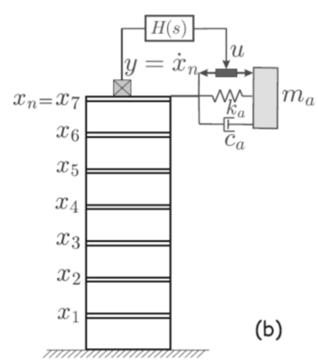
- **Cutting parameters (spindle speed) selection**
  - Regenerative chatter modelling and stability prediction accuracy (process damping, low mill engagement)
  - Stability Lobes Diagram (SLD) uncertainties
  - Fast SLD prediction-Receptance Substructuring Analysis
- **Improve the Machine Tool dynamics**
  - cutting process oriented MT and components design
  - increase structural damping
    - Active or passive damping solutions
    - Smart materials
    - Metal foams
- **Spindle Speed Modulation**

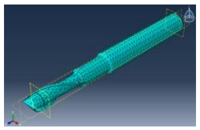


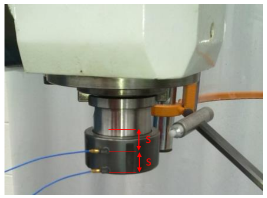










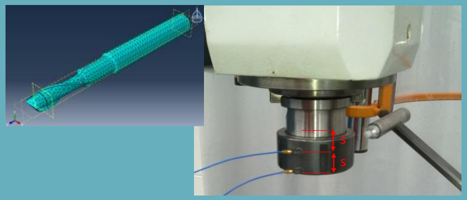


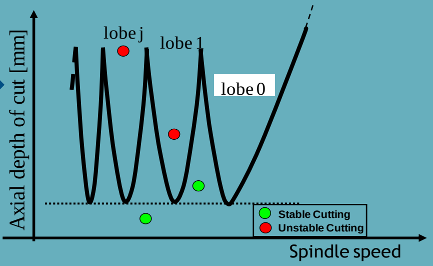
Machine tool Performance enhancement

Cutting performance prediction and parameters selection

Stability Lobes estimation

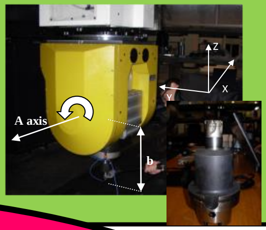
- *Uncertainty and SLD estimation*
- *Receptance Coupling Sub-structuring Analysis*

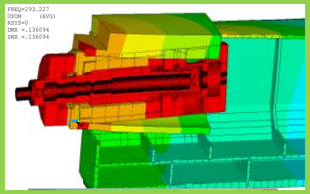




Machine Tool Dynamics improvement through subsystems dynamic interaction exploitation

- *Spindle-Machine Tool Structure interaction*
- *Spindle-Control Interaction*

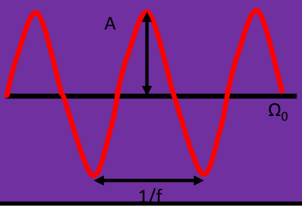




Machine Tools
performance enhancement
&
chatter vibration mitigation

Spindle Speed Variation and vibration controller

- *SSV turning*
- *SSV milling*



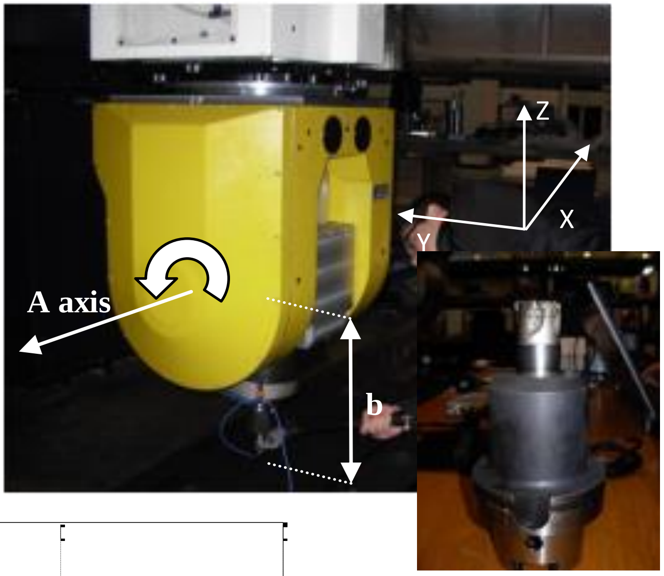
Innovative Materials

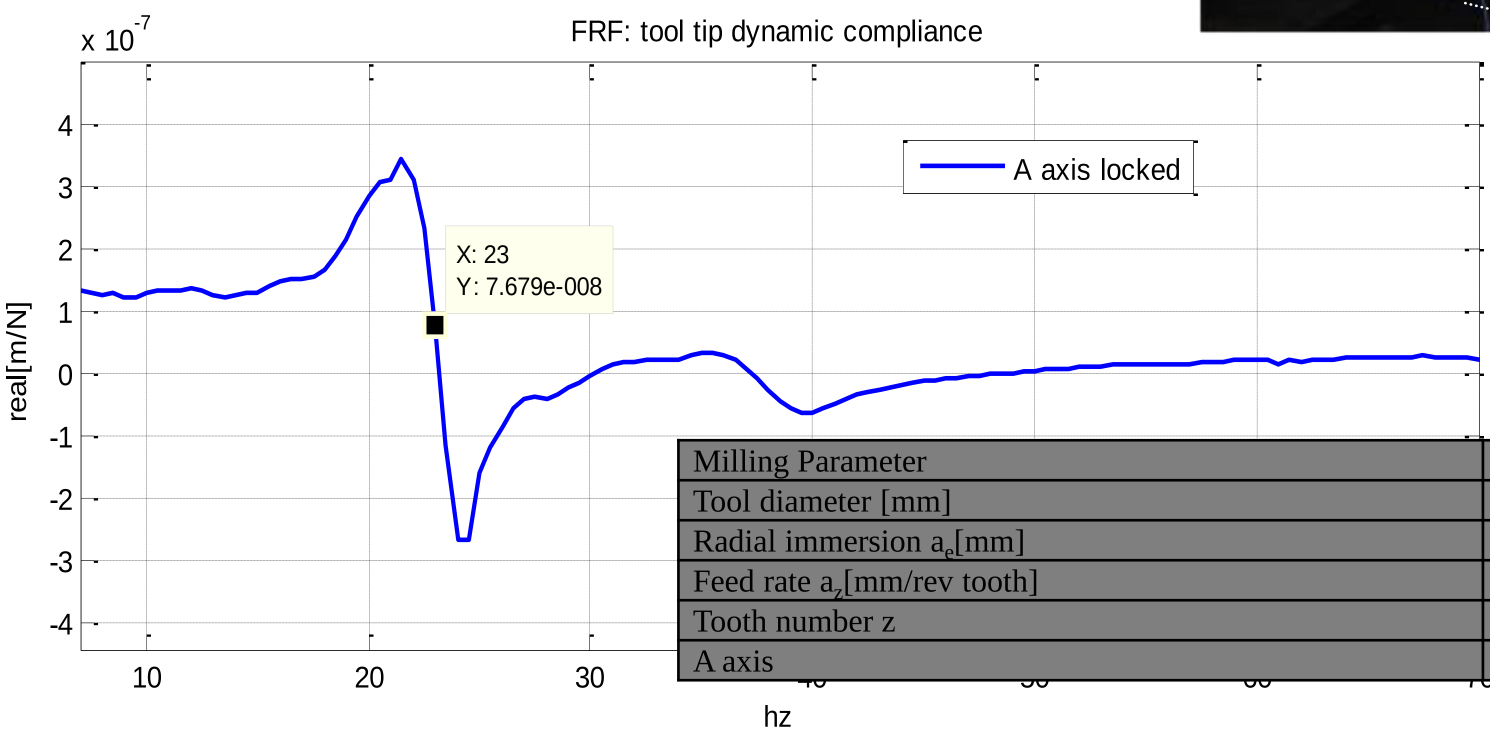
Increase the machine tool structural damping (metal foams)

Machine Tool Dynamics improvement through subsystems dynamic interaction exploitation

Machine Tool Structure – Control interaction

Is it possible to exploit the regulator tuning to improve the cutting process stability?
a) increase the damping (loop velocity)
b) introduce a quasi-static compliance contribute

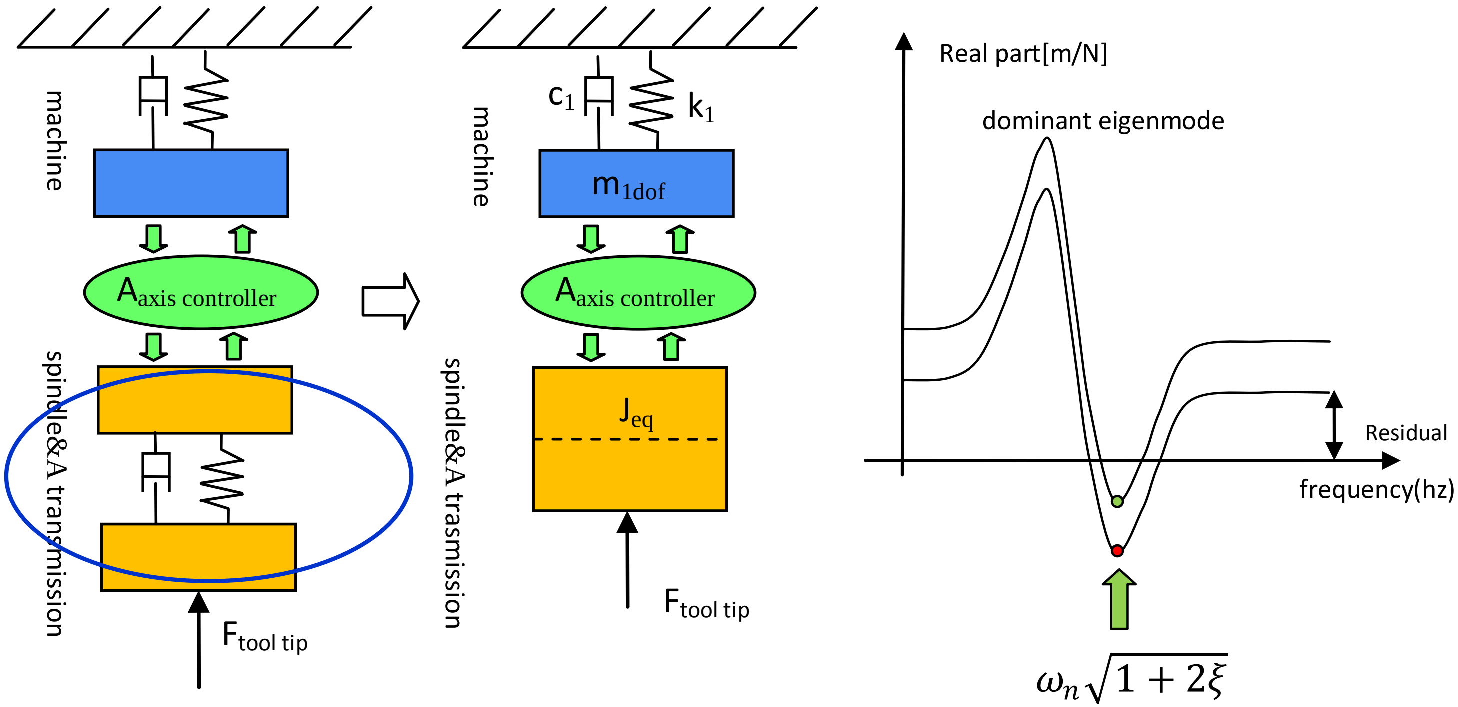




Titanium milling

Milling Parameter	Value
Tool diameter [mm]	32
Radial immersion a_e[mm]	32
Feed rate a_z[mm/rev tooth]	0.9
Tooth number z	5
A axis	Locked (2 brakes)

Machine Tool Dynamics improvement through subsystems dynamic interaction exploitation

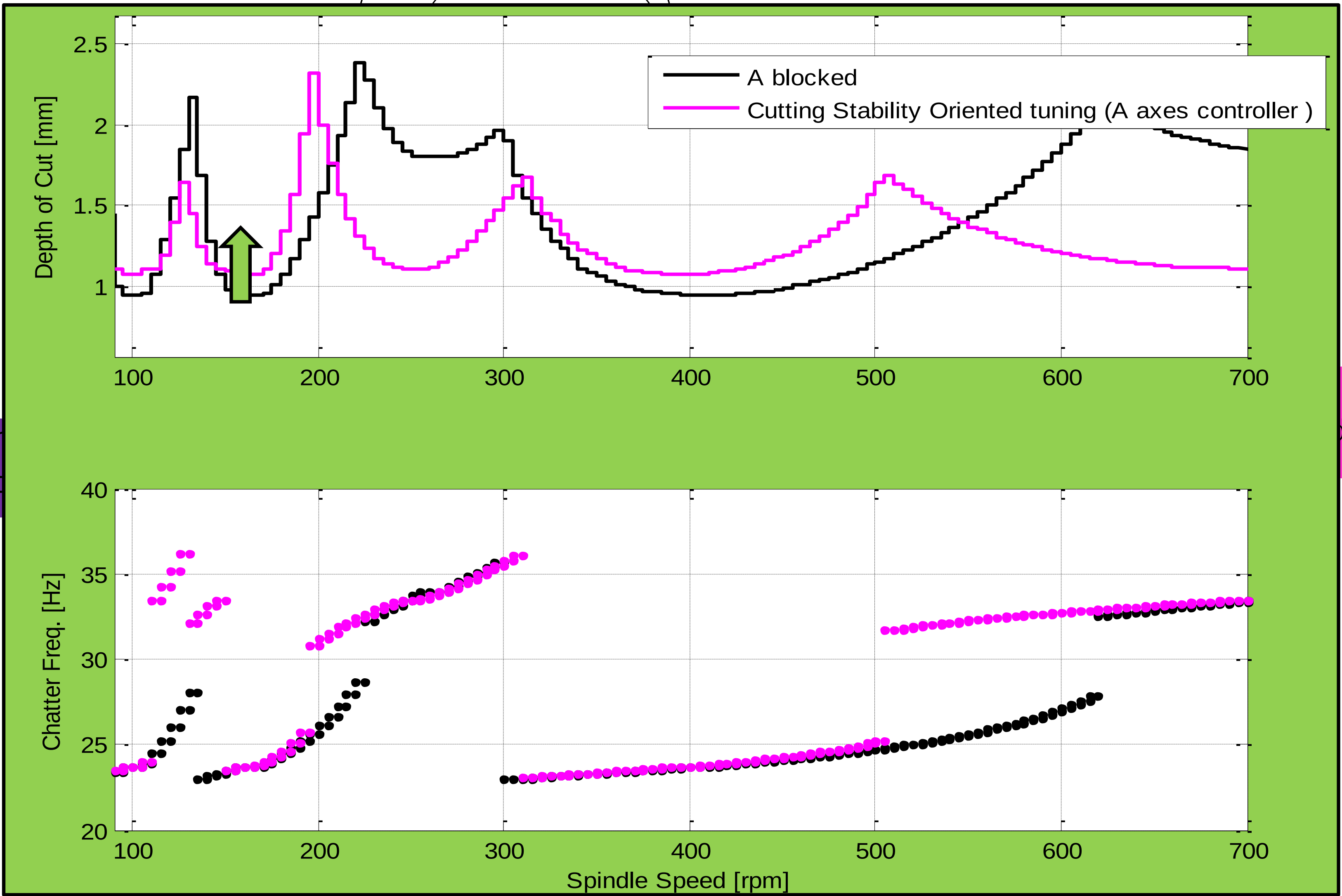


Goal: Define some tuning criteria to enhance the cutting stability

Machine Tool Dynamics improvement through subsystems dynamic interaction exploitation

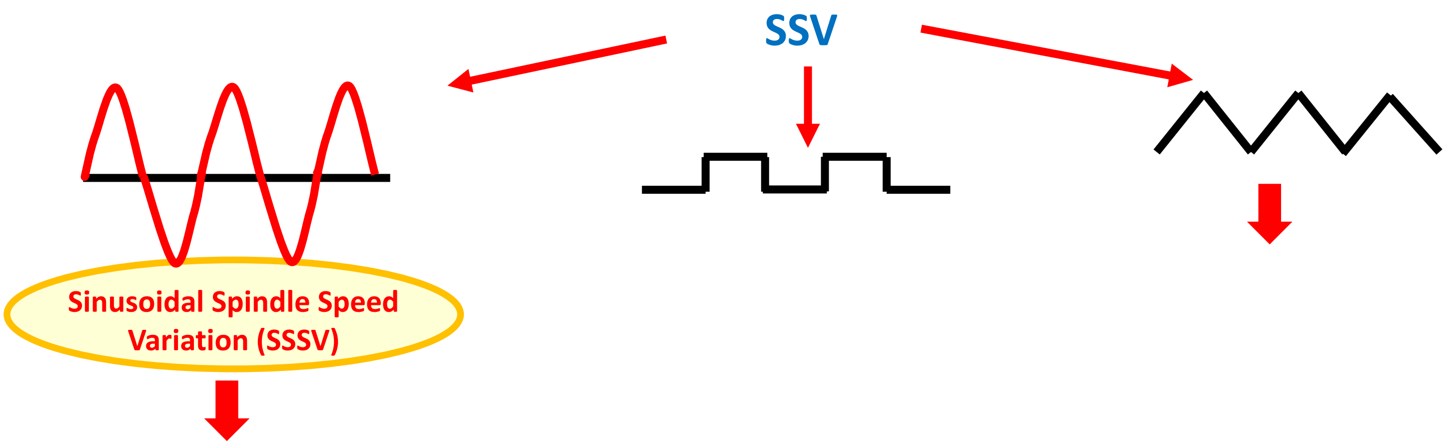
Tool com
identified

criteria



10
10
hz

Spindle Speed Variation

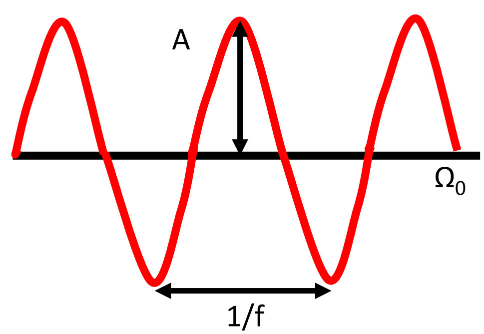


- Infinite acceleration values are not required
- Can be easily tracked by Numerical Control systems

$$\Omega(t) = \Omega_0 + \Omega_0 \cdot RVA \cdot sen(\Omega_0 \cdot RVF \cdot t)$$

W_0 = nominal spindle speed

$$RVA = \frac{A}{\Omega_0} \qquad RVF = \frac{2\pi f}{\Omega_0}$$

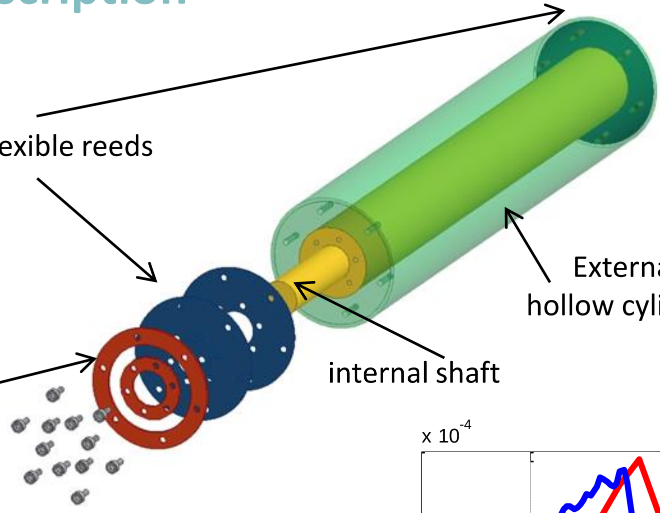


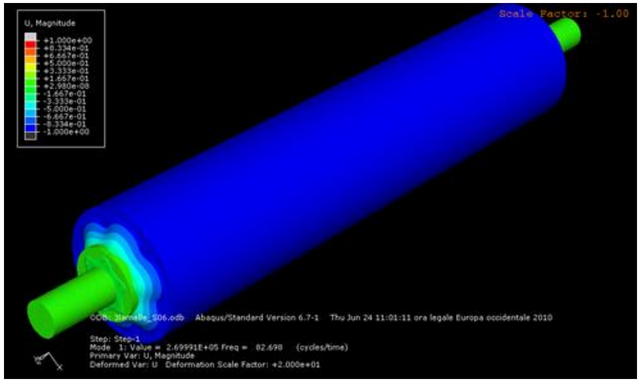
reasonable values

RVA = 0 ÷ 40%
RVF = 0 ÷ 40%

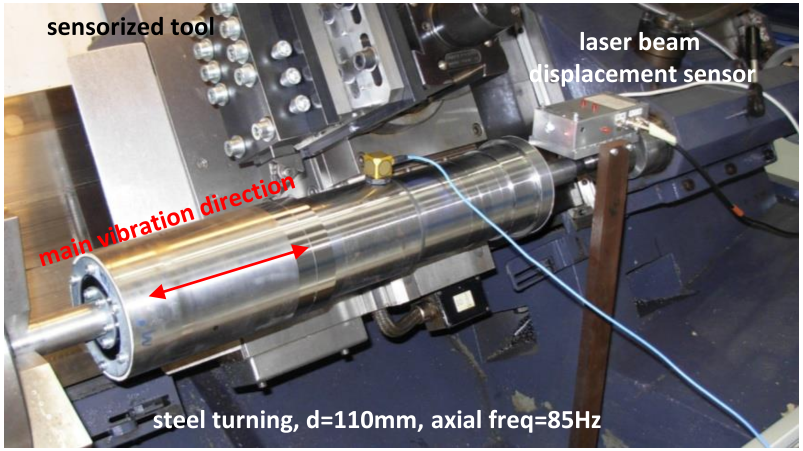
Spindle Speed Variation

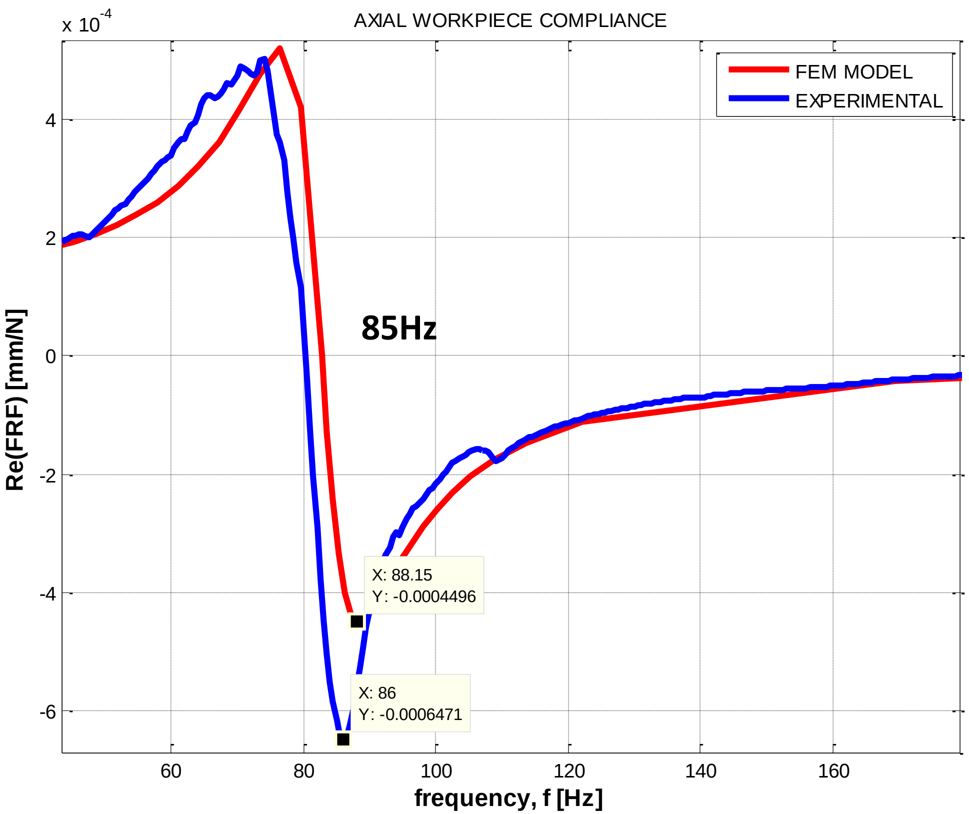
Experimental set-up description





design of a specific workpiece with a calibrated compliance



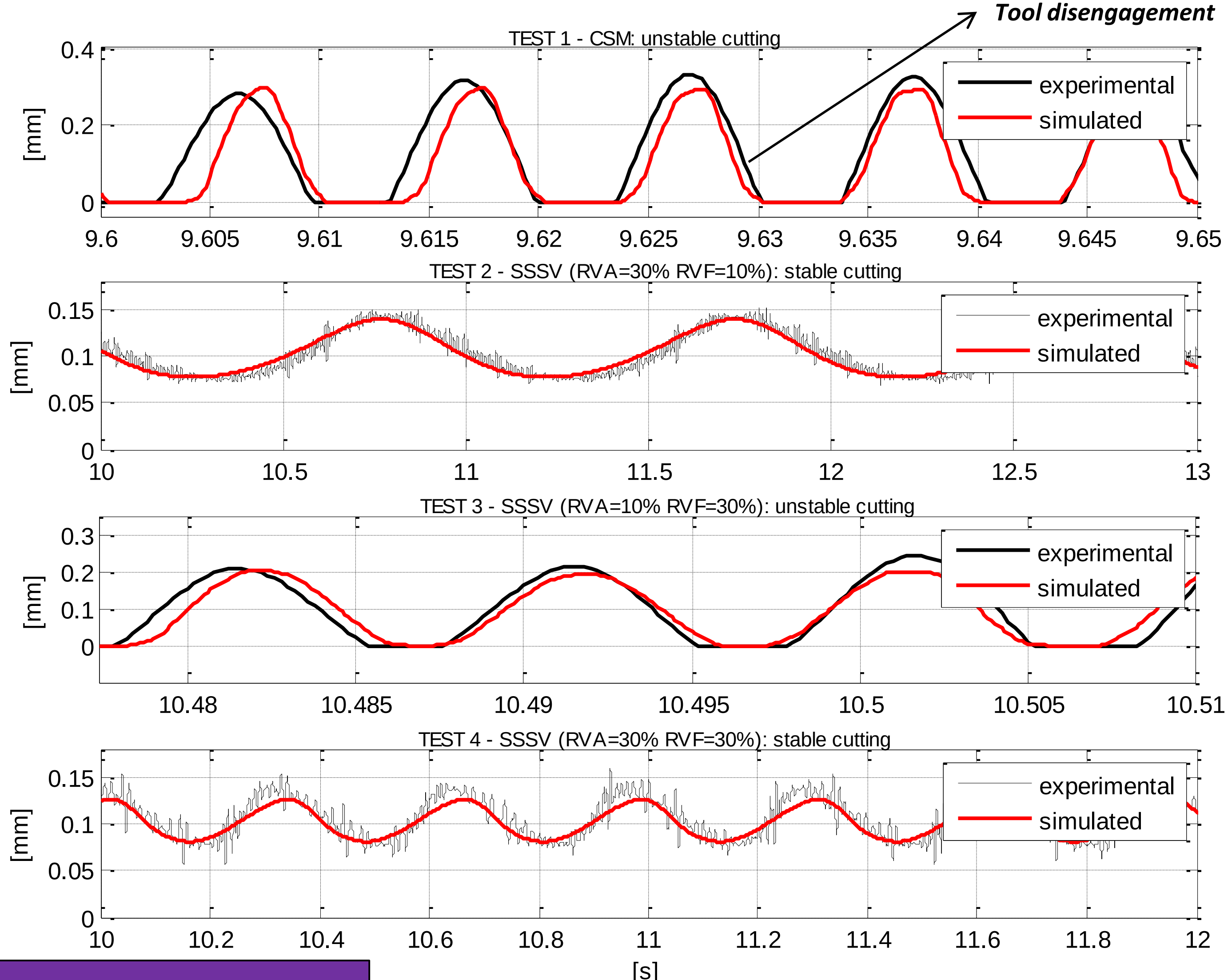


The SSSV seems to be effective for high dominant frequency/nominal spindle speed

Spindle Speed Variation

Turning Model Validation

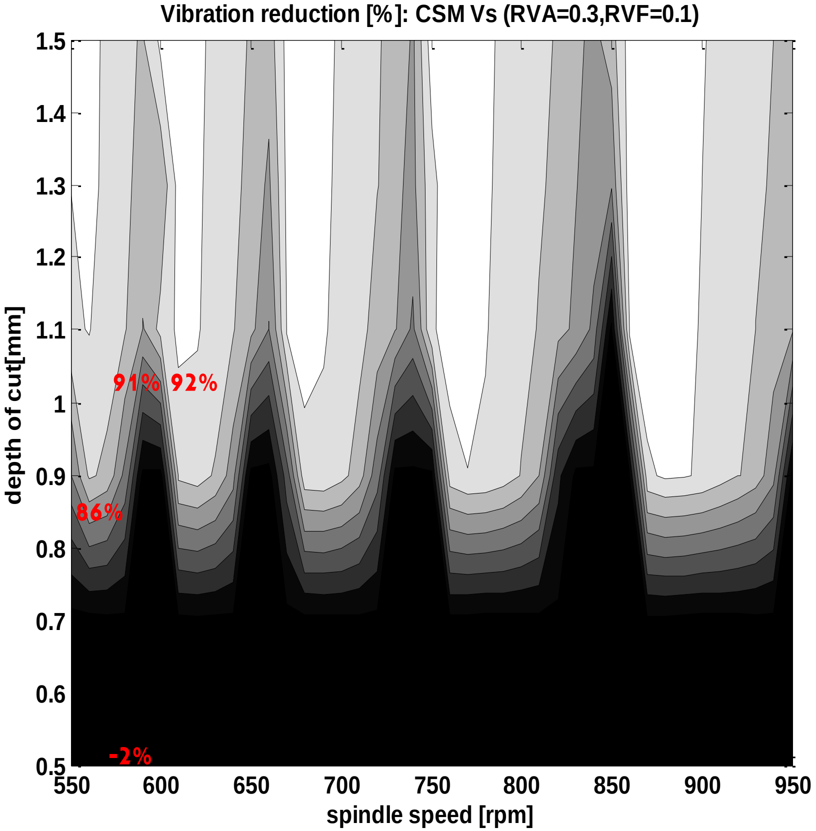
Chip thickness reconstruction: from laser measurement

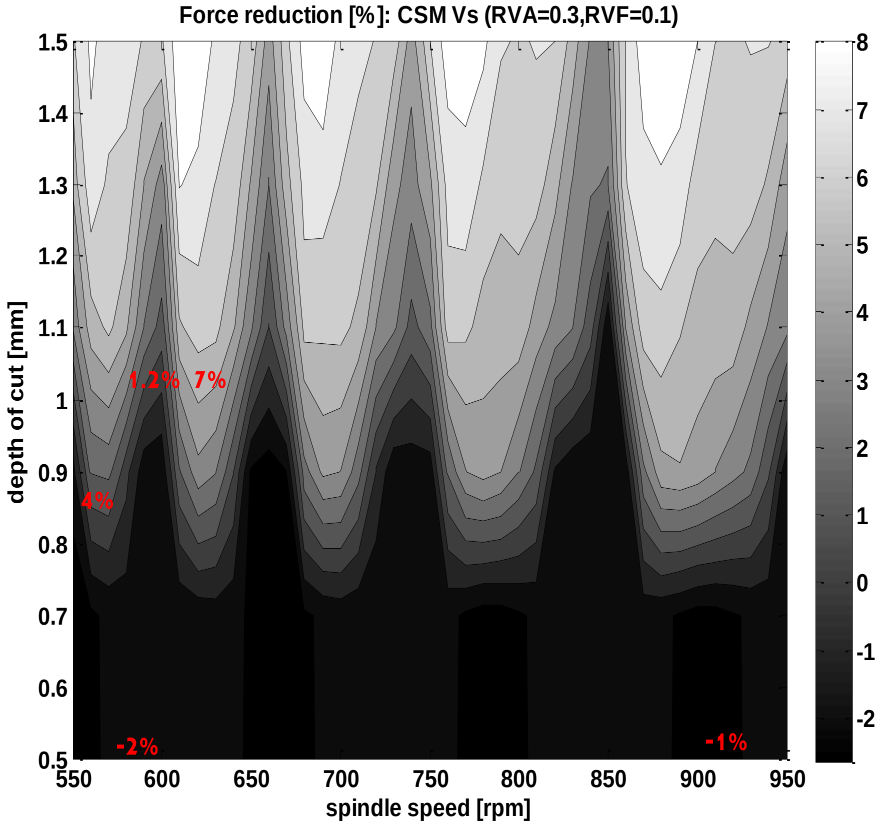


Spindle Speed Variation

Turning: simulation results

- Tool load → force (Root Mean Square)
- Surface quality → Workpiece vibration (Root Mean Square)
- RVA=0.3, RVF=0.1

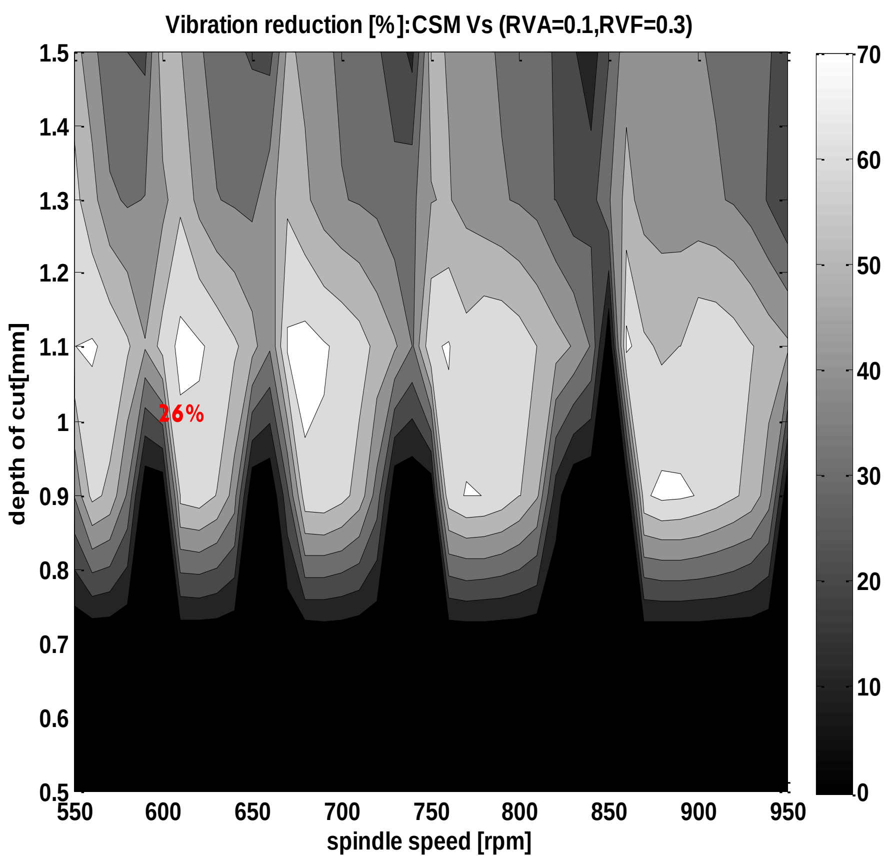


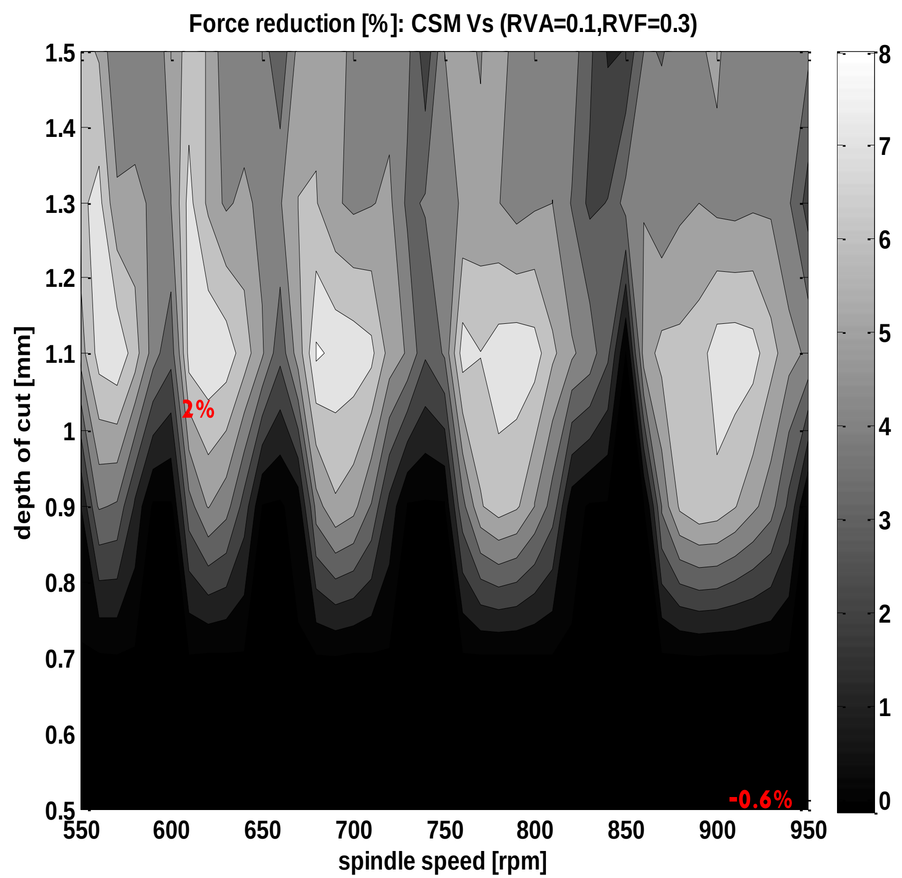


Spindle Speed Variation

Turning: simulation results

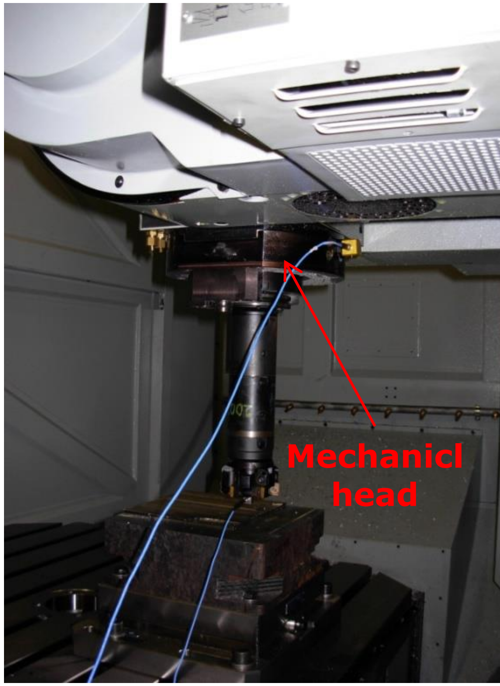
- Tool load → force (Root Mean Square)
- Surface quality → Workpiece vibration (Root Mean Square)
- RVA=0.1, RVF=0.3

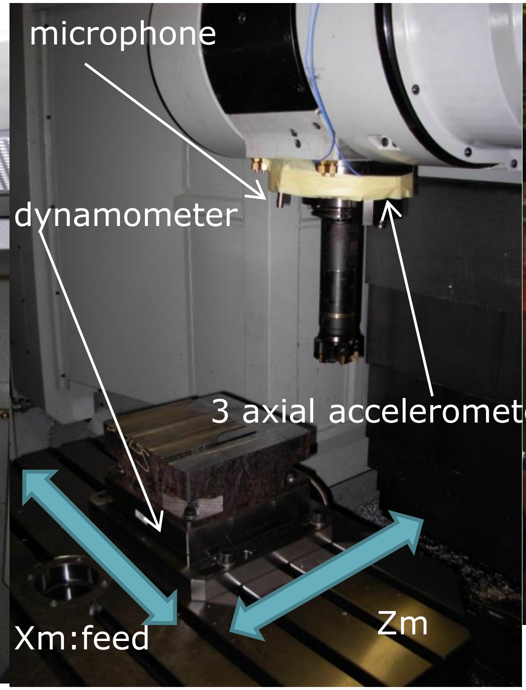


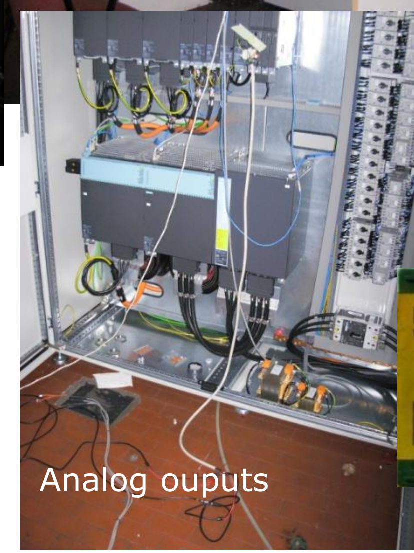


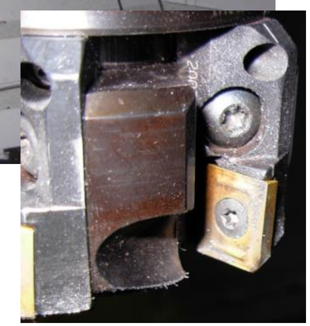
Spindle Speed Variation

Milling application





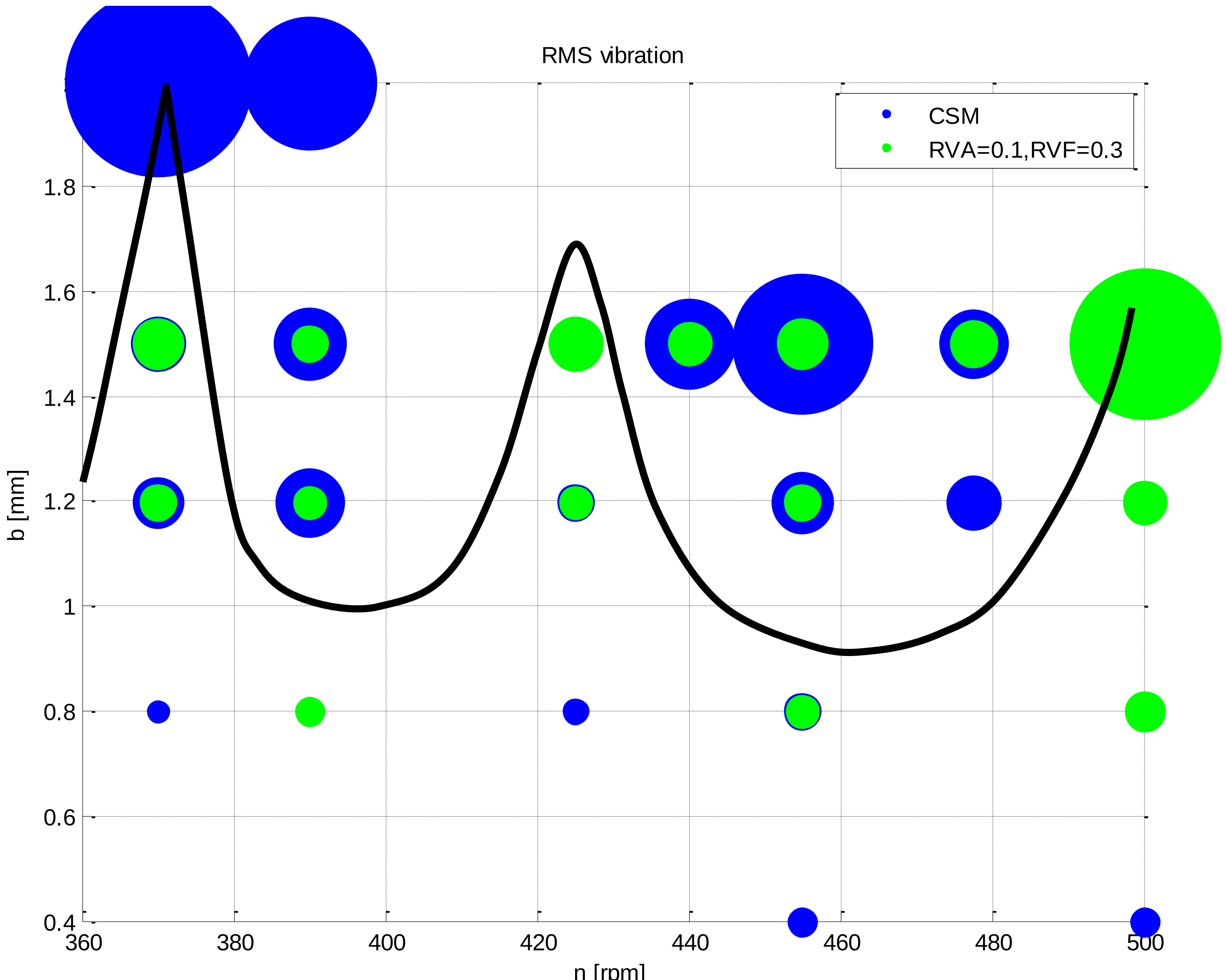




Tool type	
Tool lenght	270mm
Tool diameter	80mm
Z	6
Insert Walter	P27275-3R WTL71

Spindle Speed Variation

Head Vibration (Resultant RMS value): CSM Vs (RVA=0.1,RVF=0.3)



Spindle Speed Variation

Interesting cases

n=455rpm
b=1.5mm
RVA=0.1, RVF=0.3

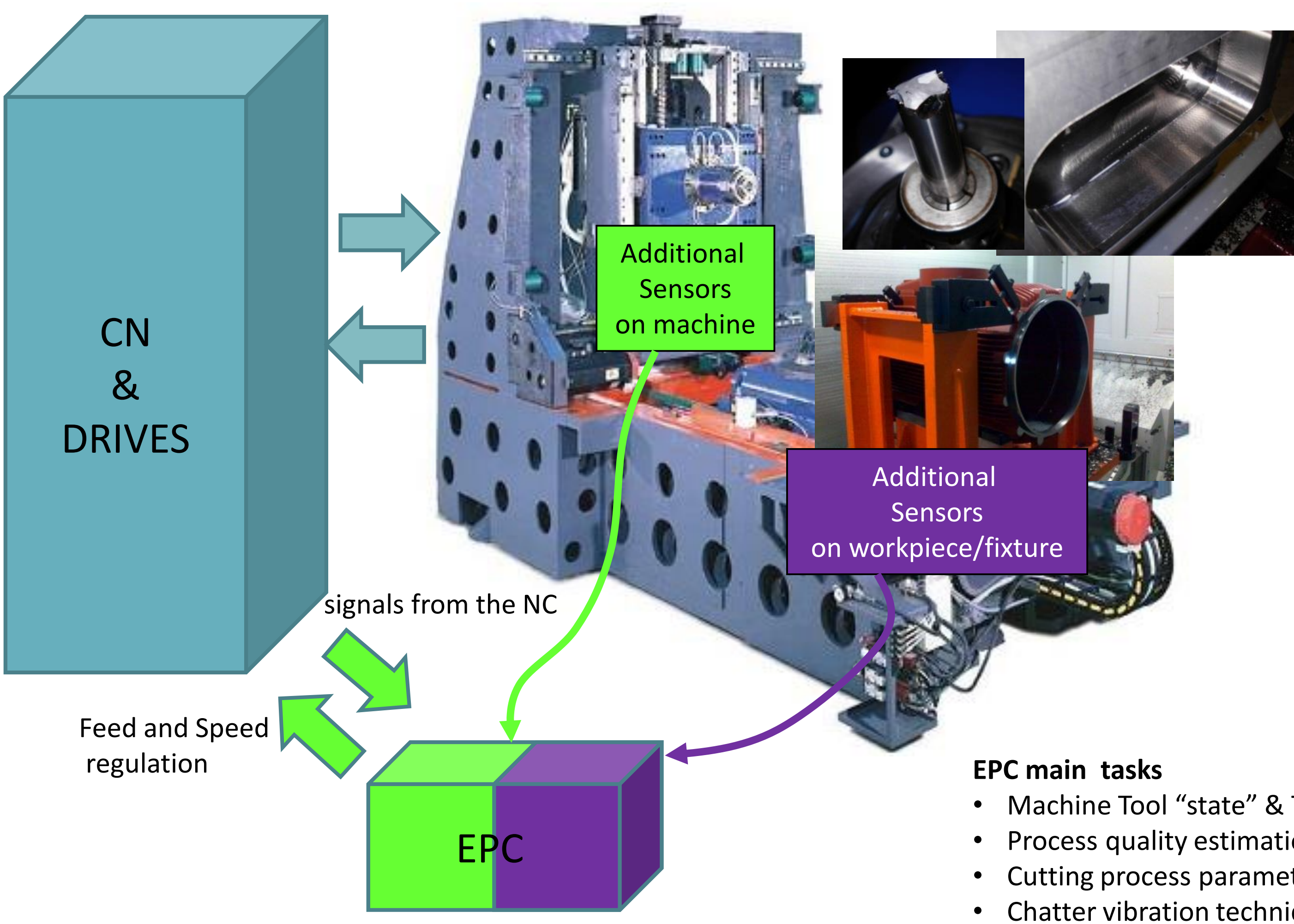
Spindle Speed Variation

Iteresting cases

n=500rpm
b=1.5mm
RVA=0.1, RVF=0.3

Spindle Speed Variation

Mandelli



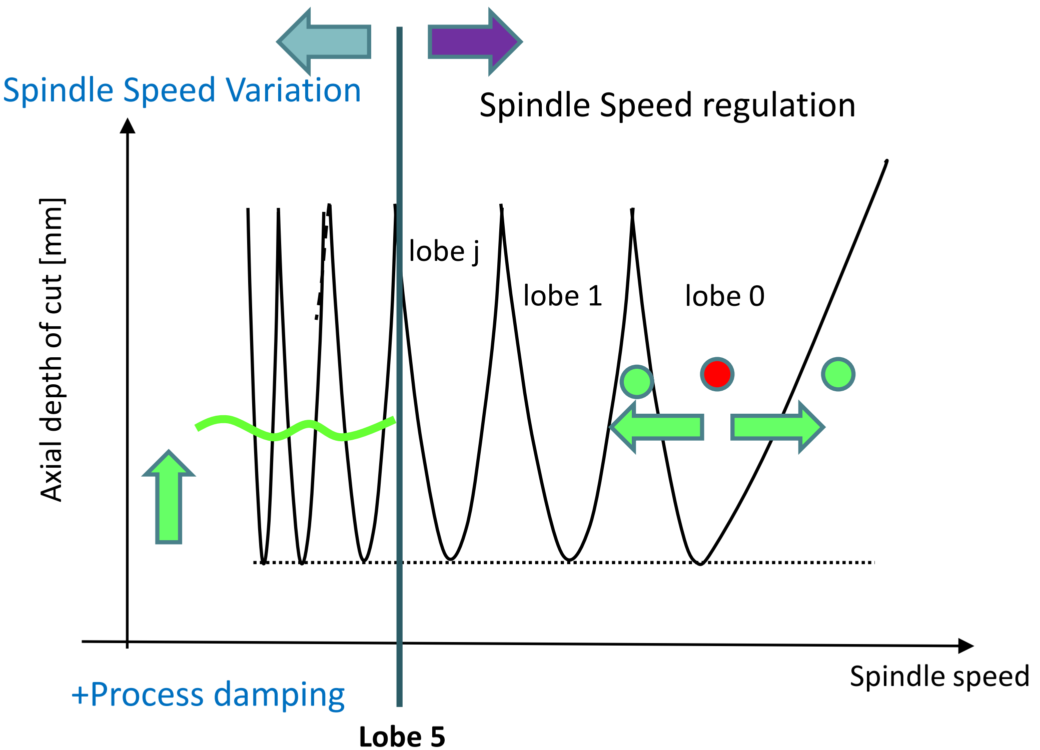
EPC main tasks

- Machine Tool "state" & Tool "state" reconstruction
- Process quality estimation
- Cutting process parameters automatic regulation
- Chatter vibration techniques (i.e. SSV) implementation
- Active vibration damping system (workpiece) control
- Data logging

Spindle Speed Variation

Vibration Mitigation Strategies

Regenerative chatter → S parameter



Forced Vibration
→ feed parameter regulation

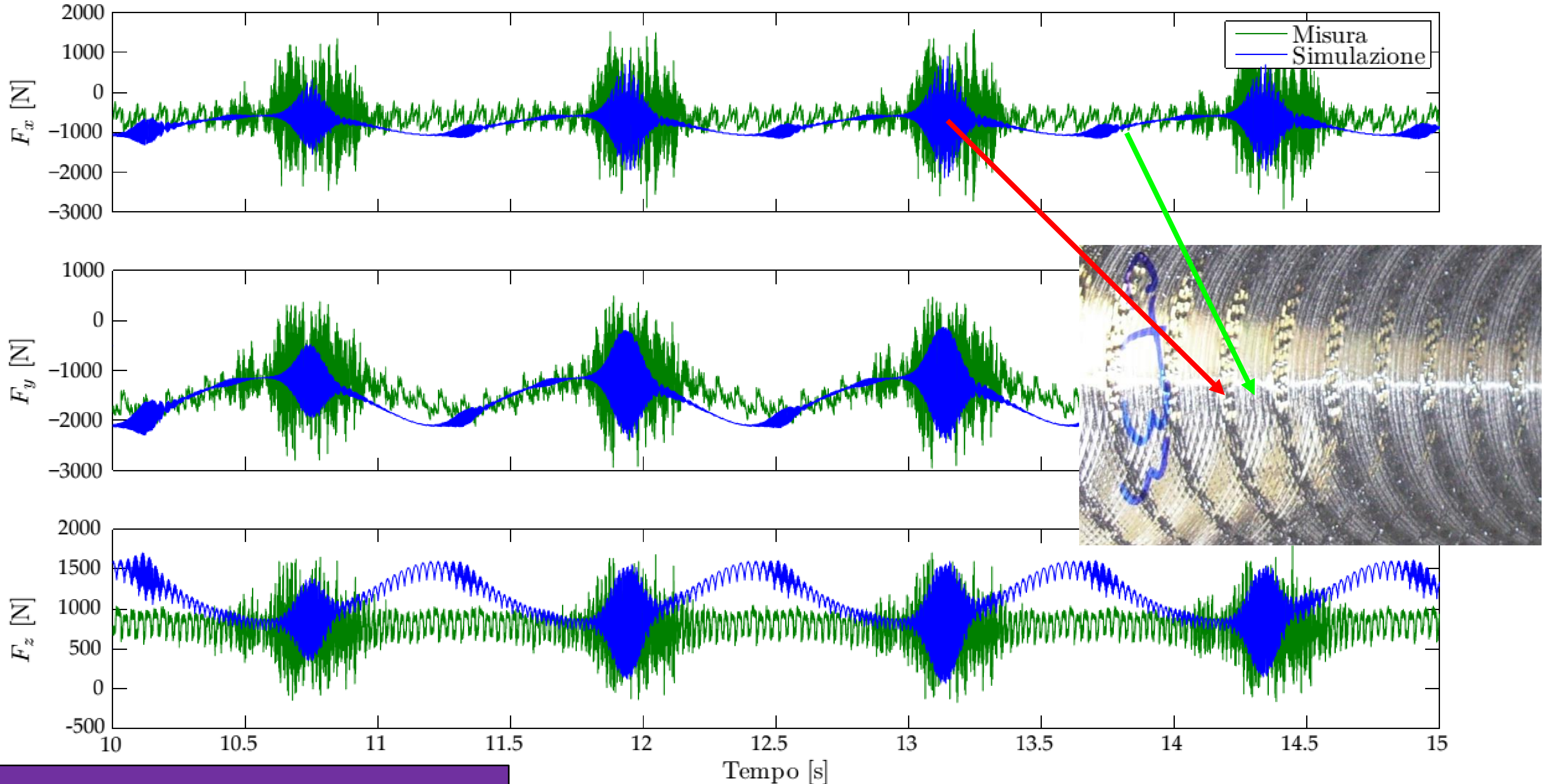
SSV can be a vibration suppression solution @ low spindle speeds (even if process damping exists). It is more flexible than variable pitch tools. SSV probably is non effective when high feed tools are used.

Spindle Speed regulation: automatic spindle speed tuning → algorithm definition (robustness)

Spindle Speed variation: continuously spindle speed modulation → parameter selection(Sinusoidal Spindle Speed Variation)

Spindle Speed Variation

Control strategy development on updated models
The model reproduces well the real behaviour

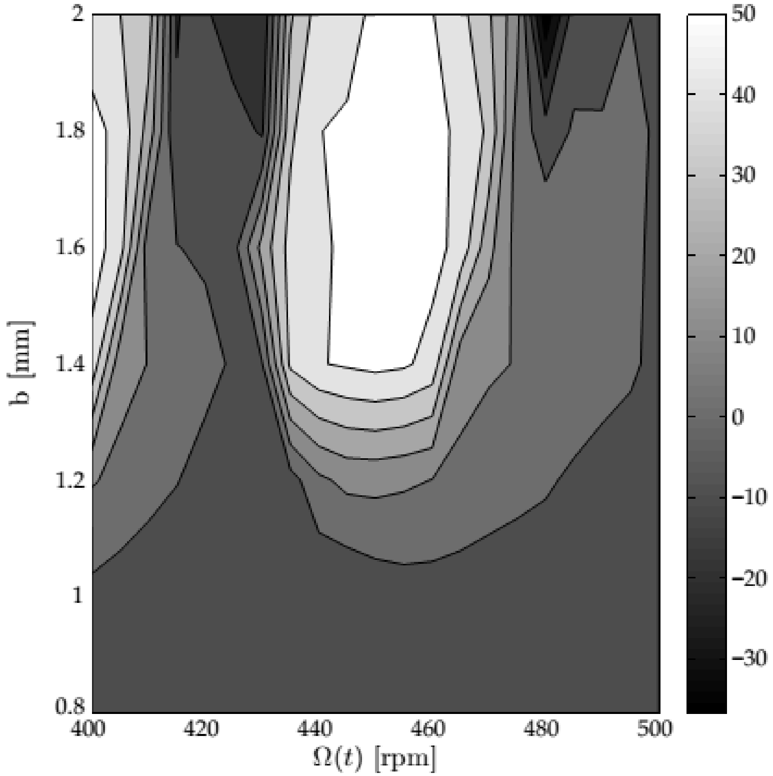


Spindle Speed Variation

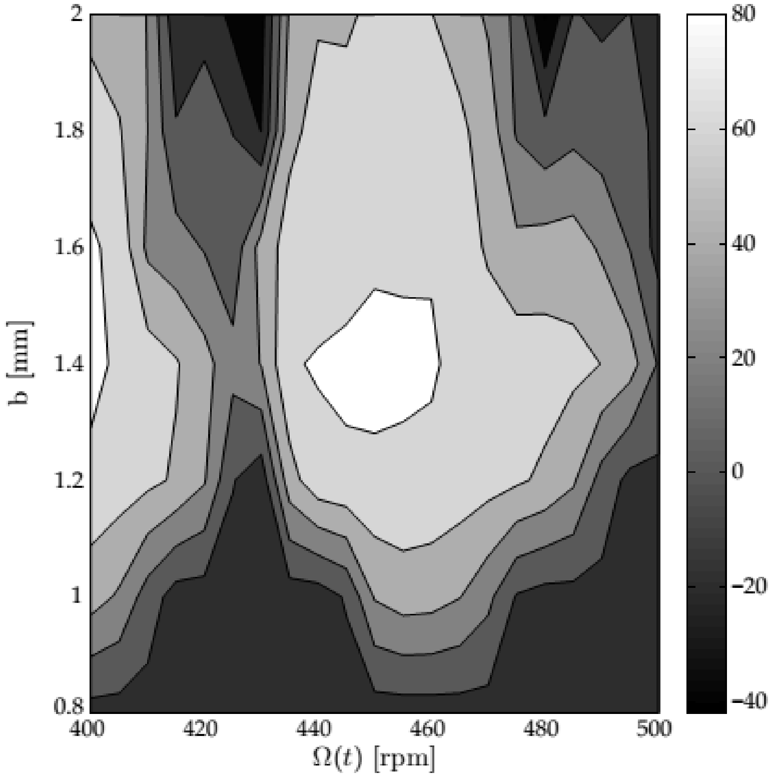
Control strategy development on updated models

SSSV parameters: RVA=0.3; RVA=0.1

Rms cutting forces



Rms tool vibratiojn



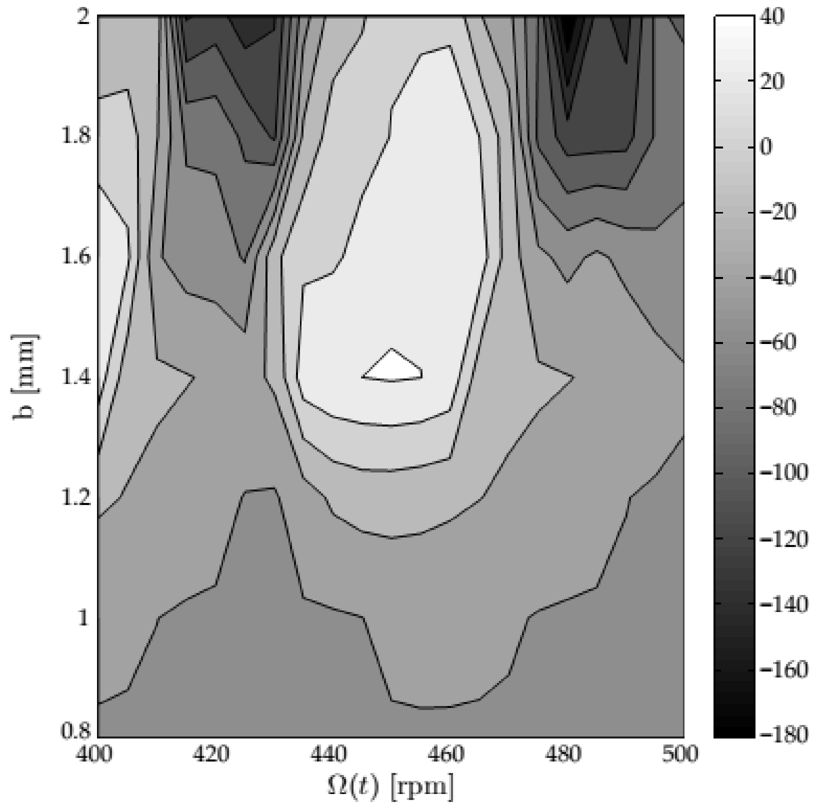
Spindle Speed Variation

Control strategy development on updated models

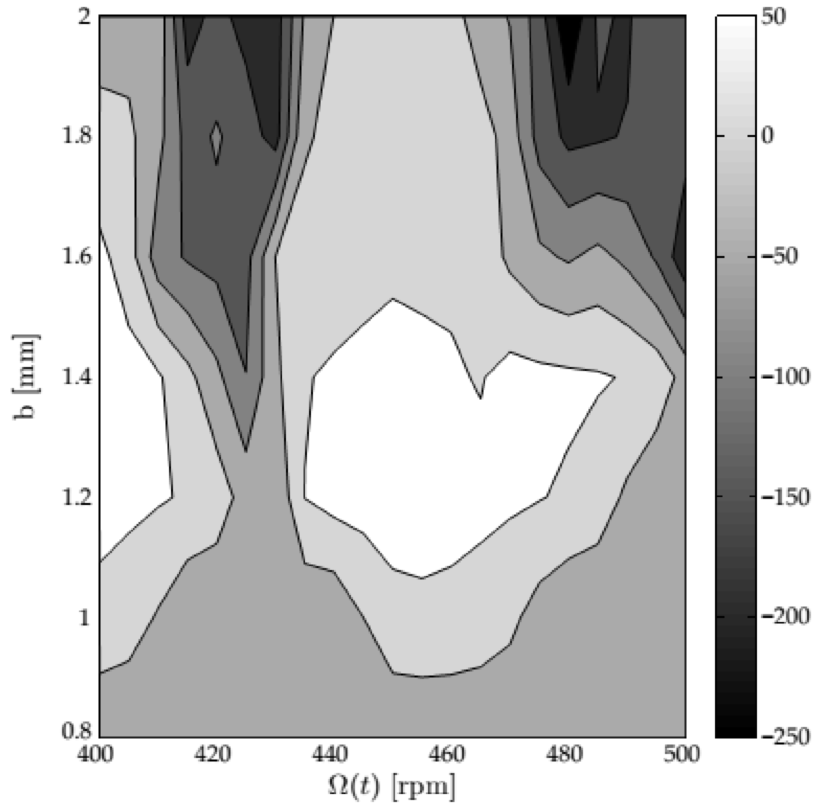
Considering also the pulsing vibrations

SSSV parameters: RVA=0.3; RVA=0.1

Rms (moving window) cutting forces



Rms tool (moving window) vibration

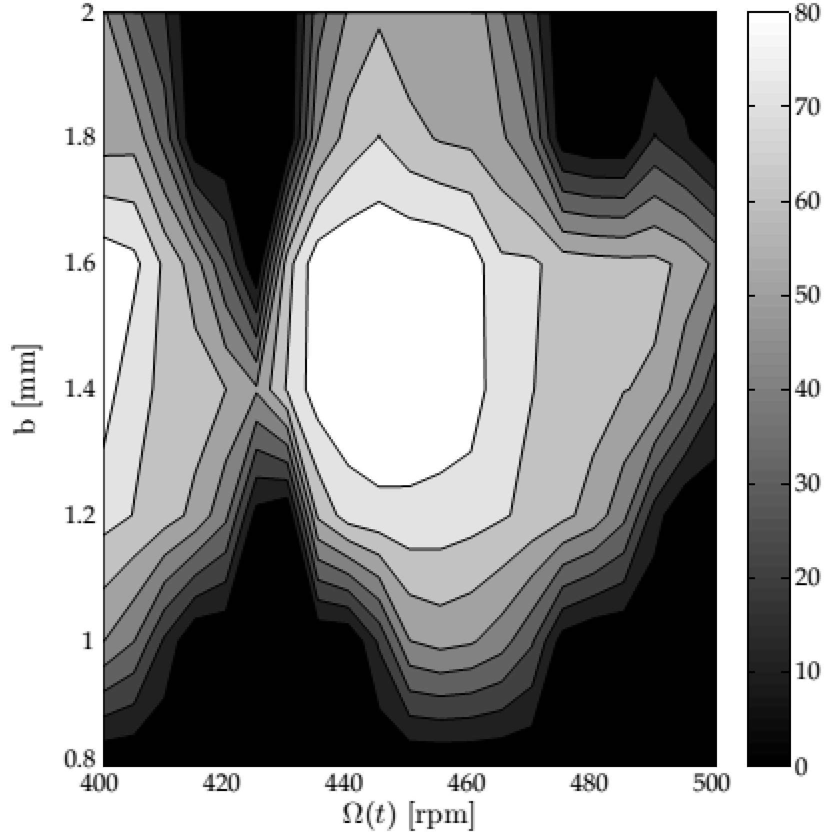


Spindle Speed Variation

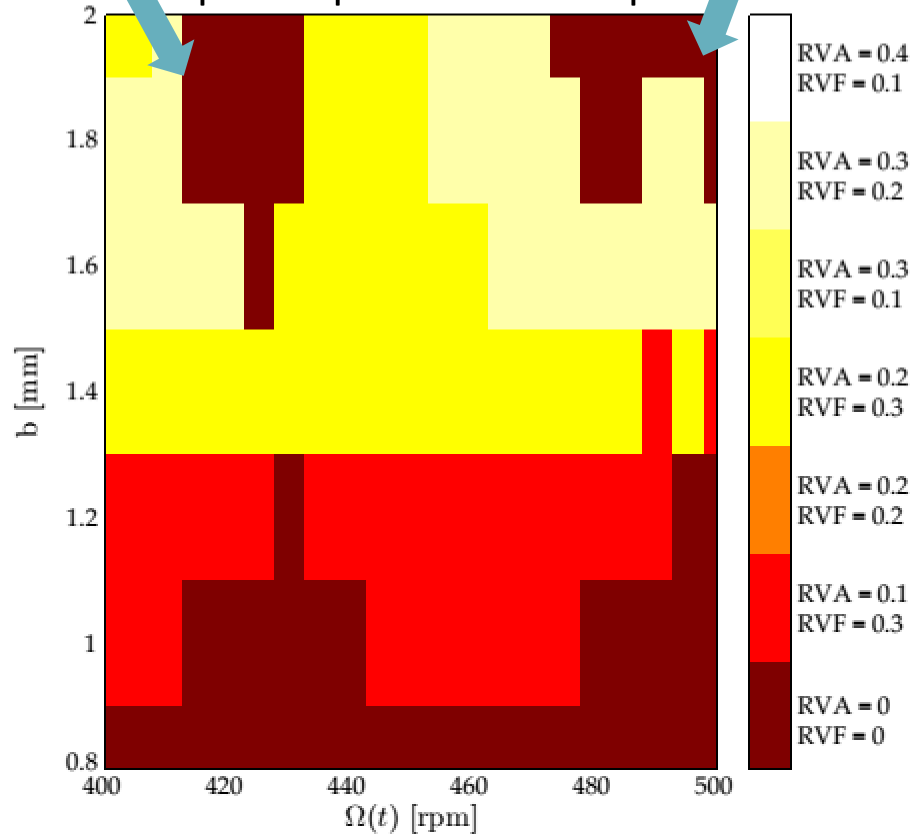
Control strategy development on updated models

SSSV parameters selection Optimization

Rms tool (moving window) vibration

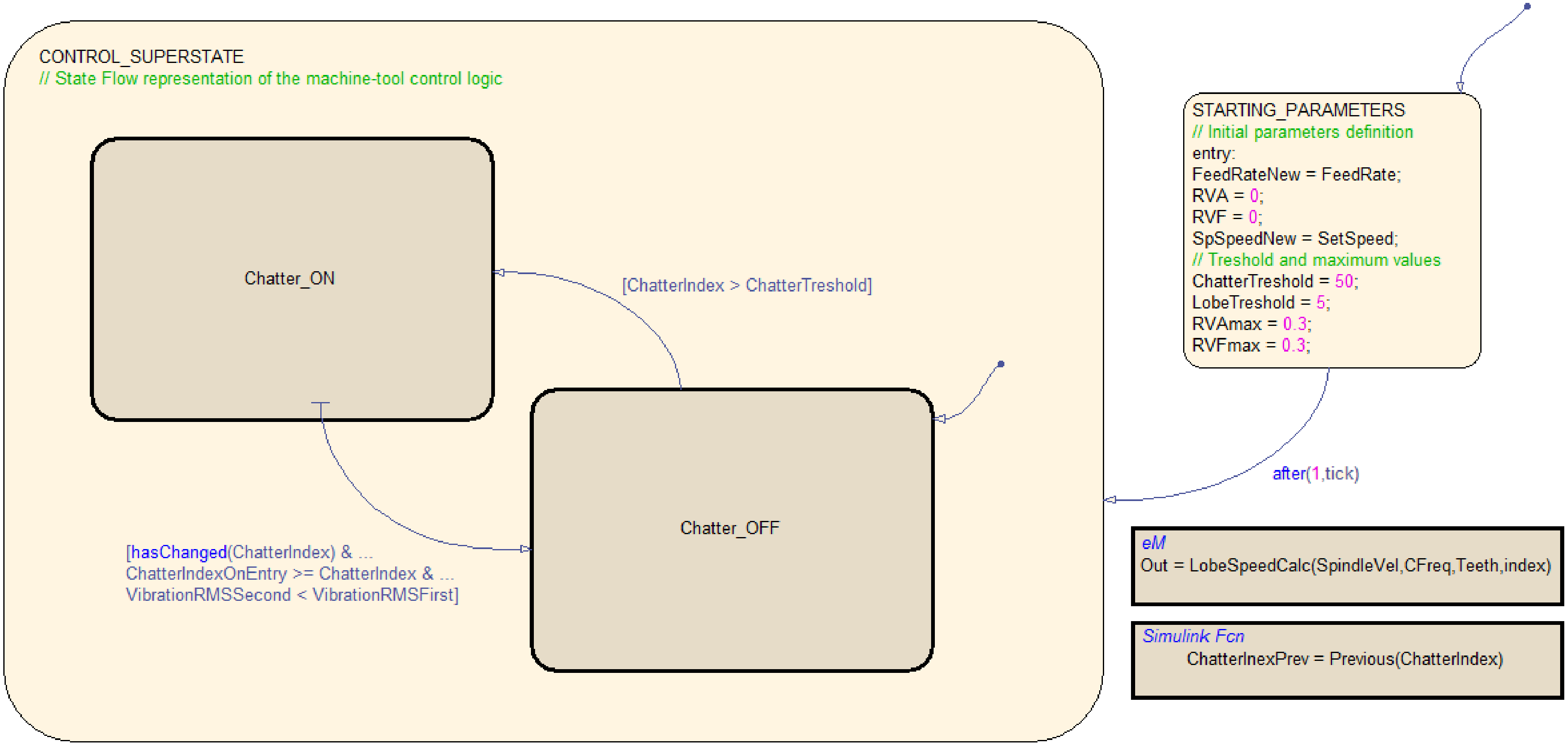


Optimal parameters map



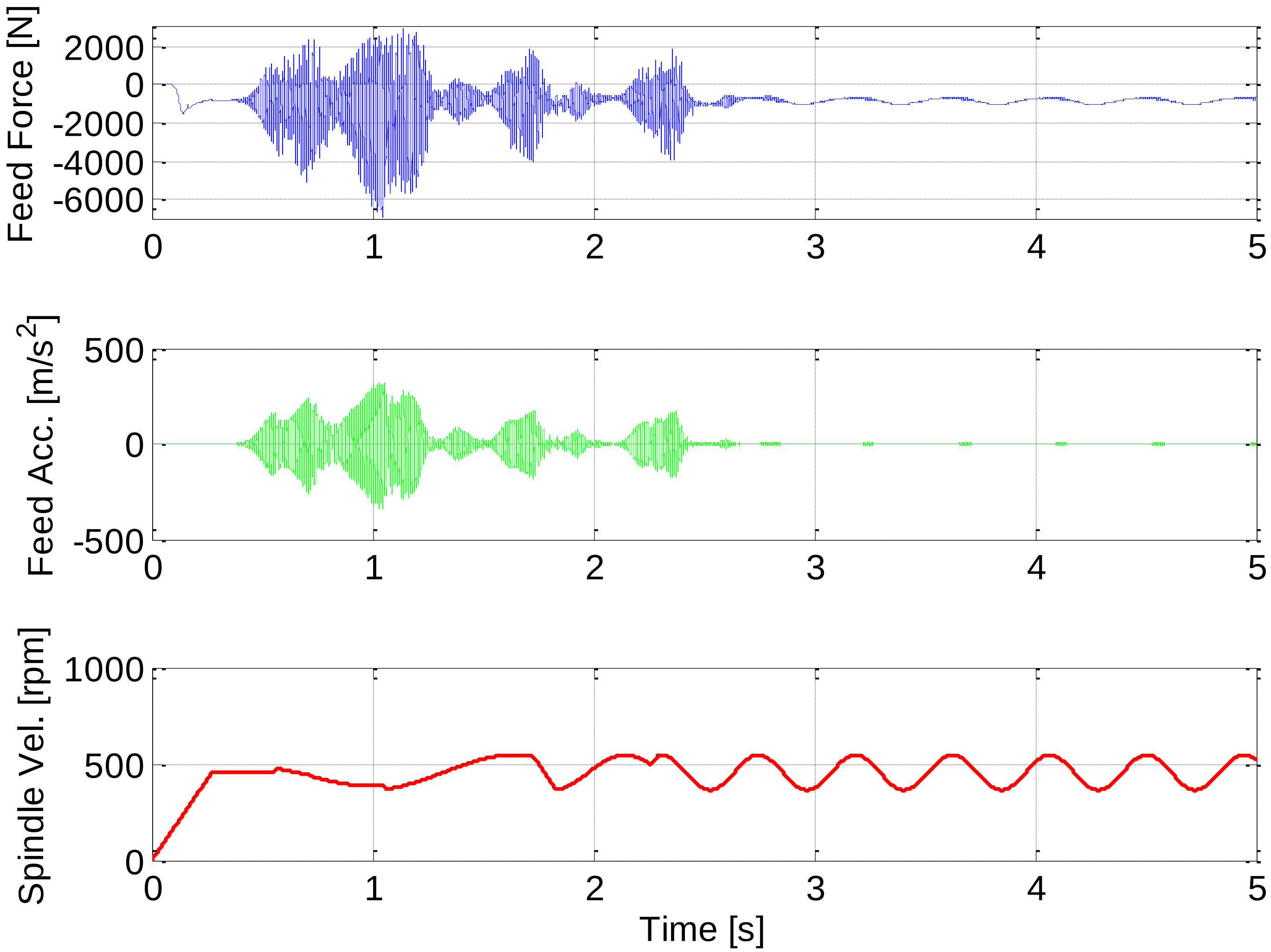
Spindle Speed Variation

Representation of the machin-tool control logic



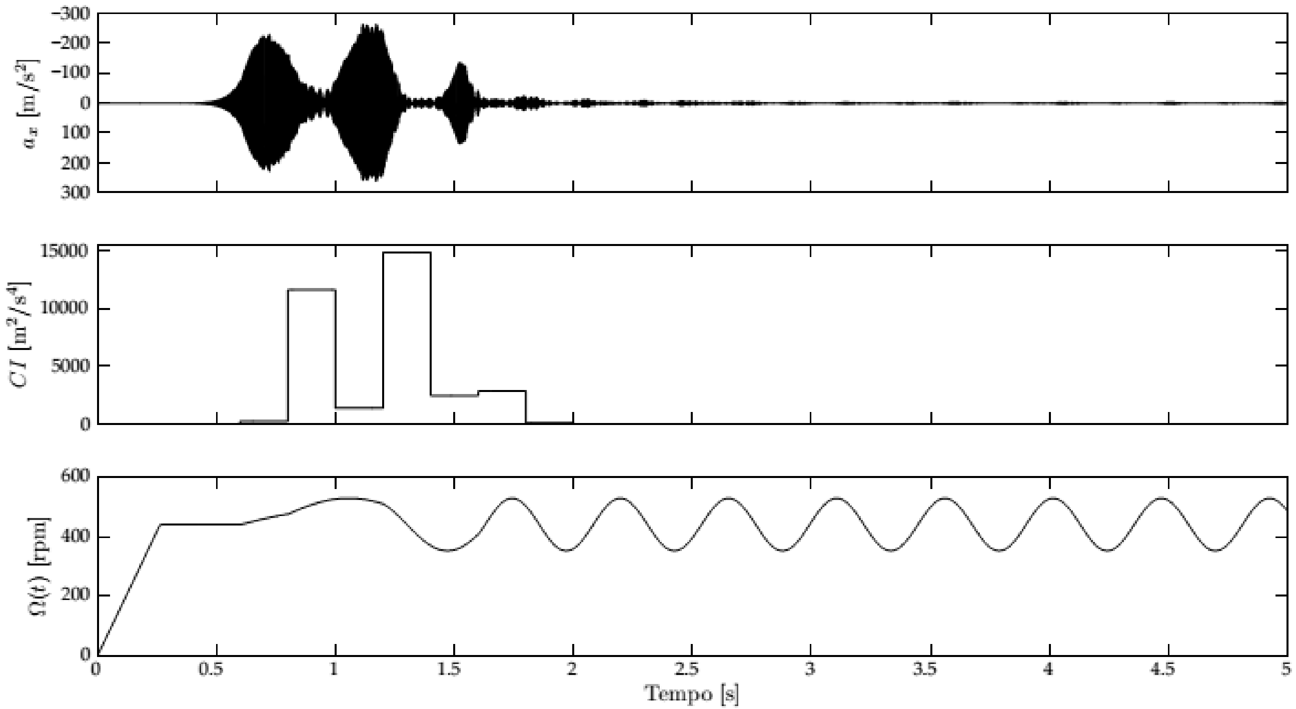
Spindle Speed Variation

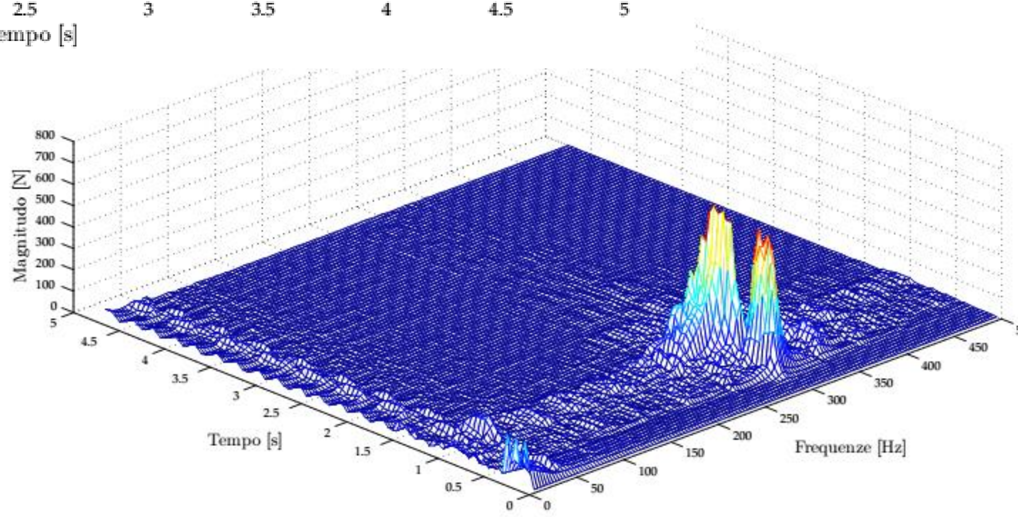
Numerical Results



Spindle Speed Variation

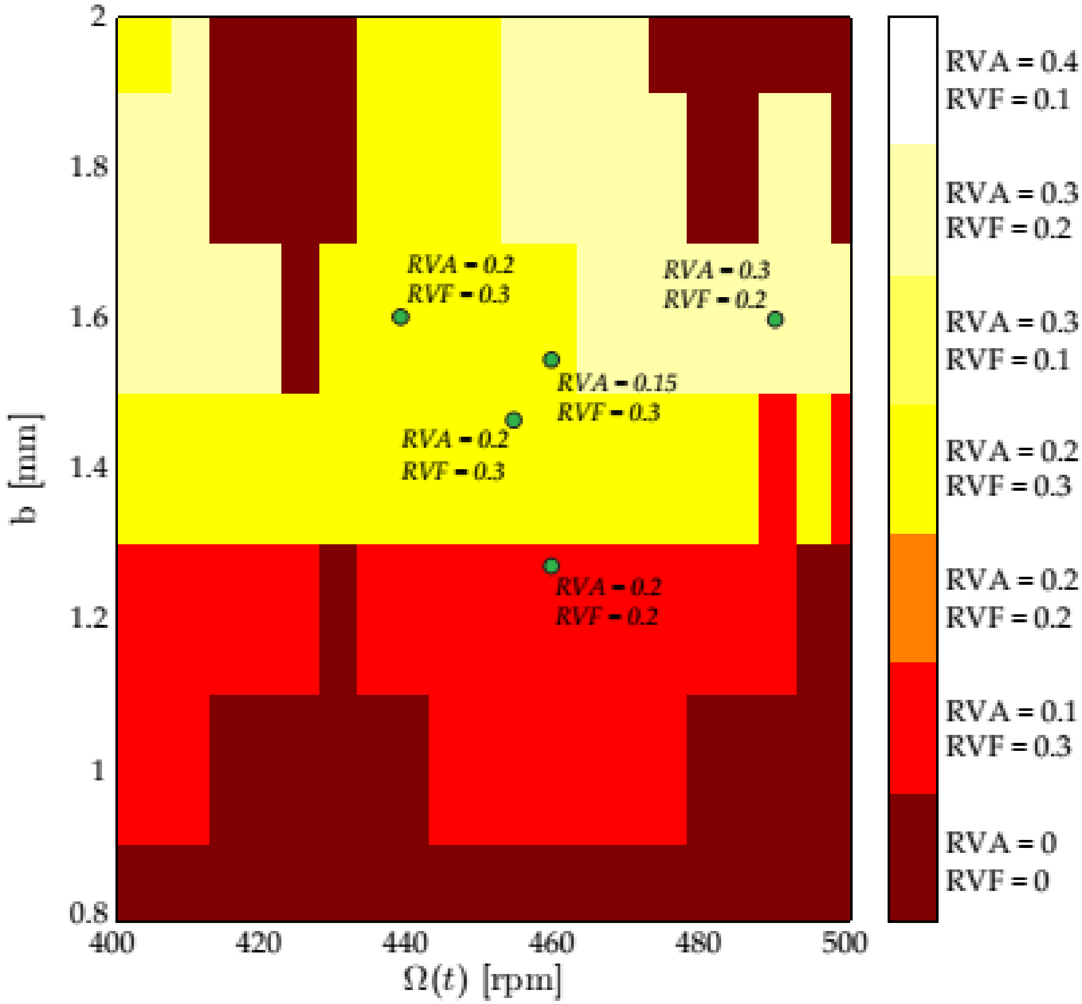
Control action tested on the updated numerical model





Spindle Speed Variation

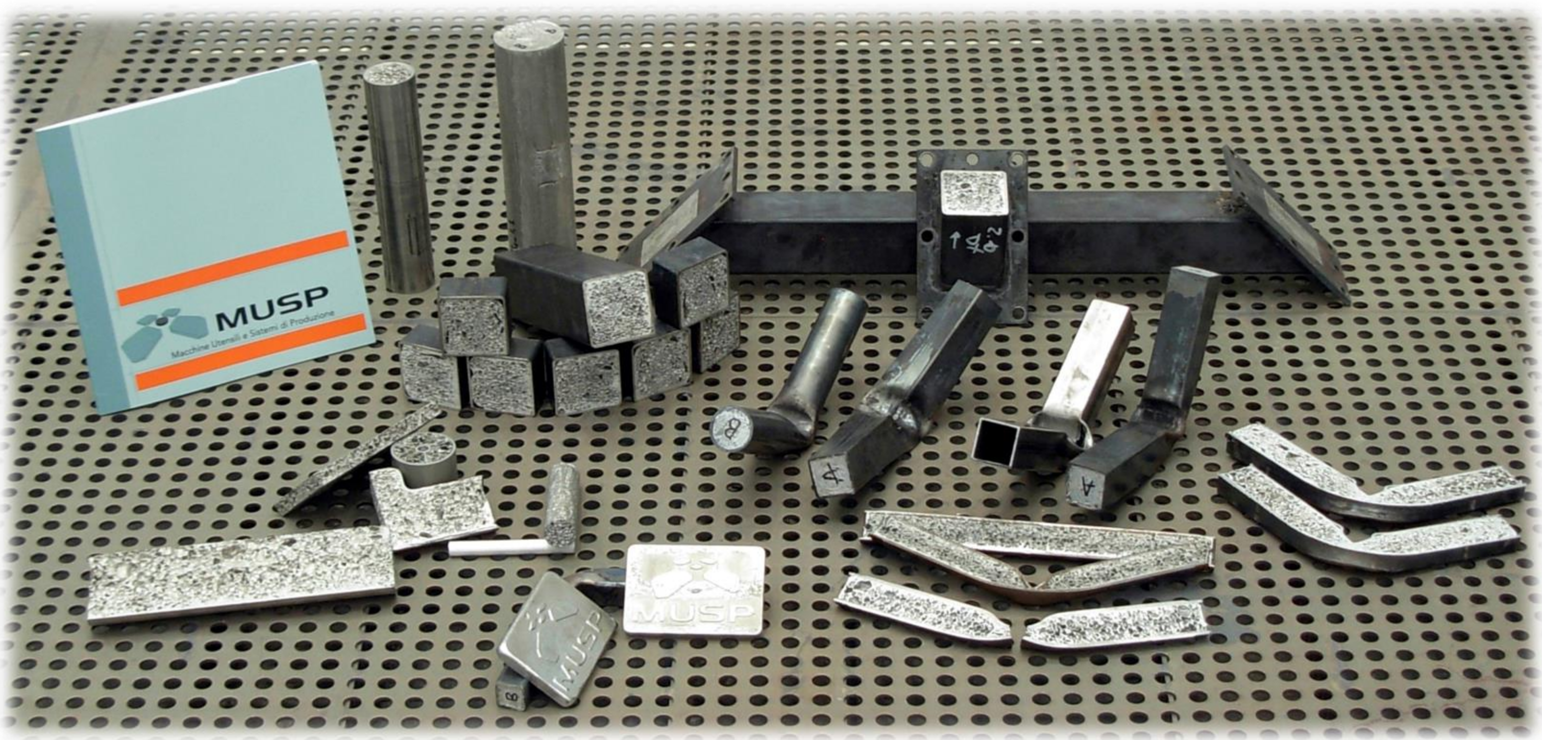
State flow implementation control action (SSSV) – results resuming



Spindle Speed Variation

Metal Foams

1 min | 2 min | 3 min | 4 min | 5 min | 6 min | 7 min | 8 min | 9 min



Grazie per l'attenzione

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