Enhanced Measurement and Prediction in Sensor-Equipped Metal Cutting Tools

A Model Based Approach for Force Estimation and Tool Wear Monitoring

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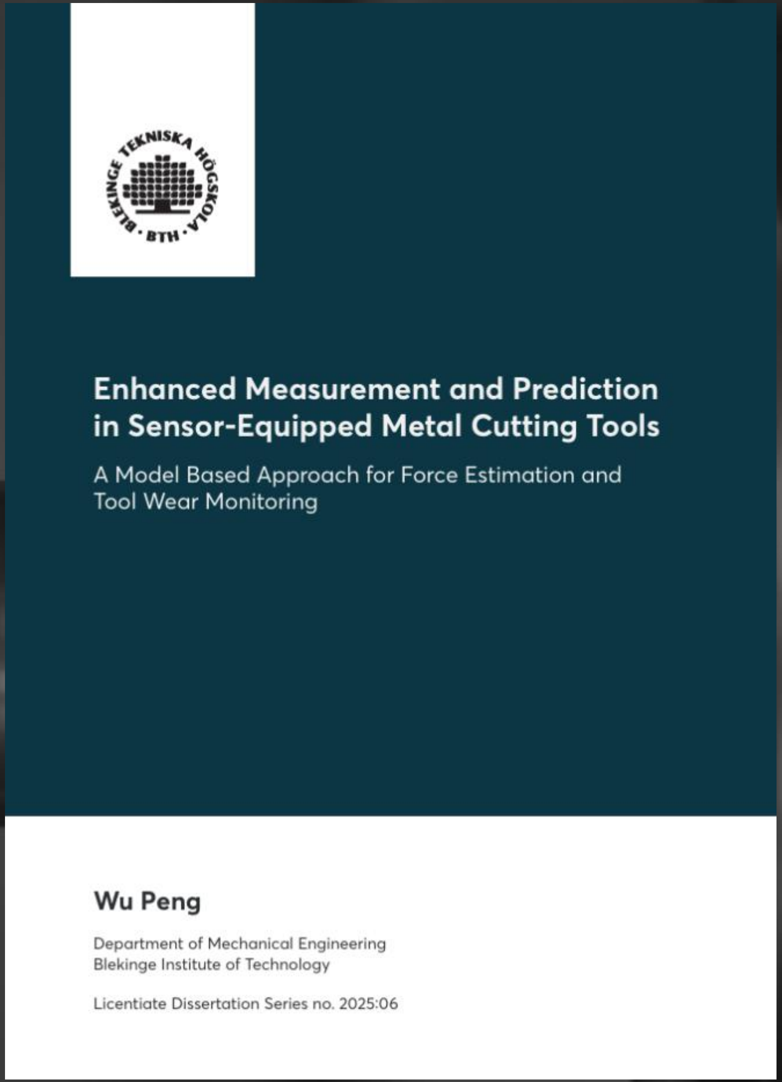
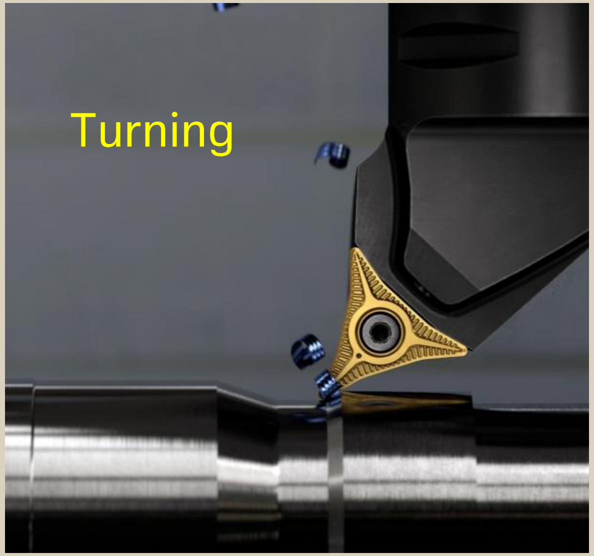
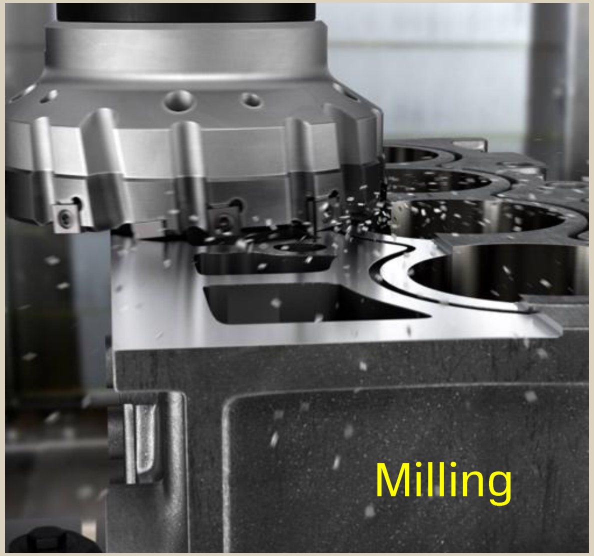


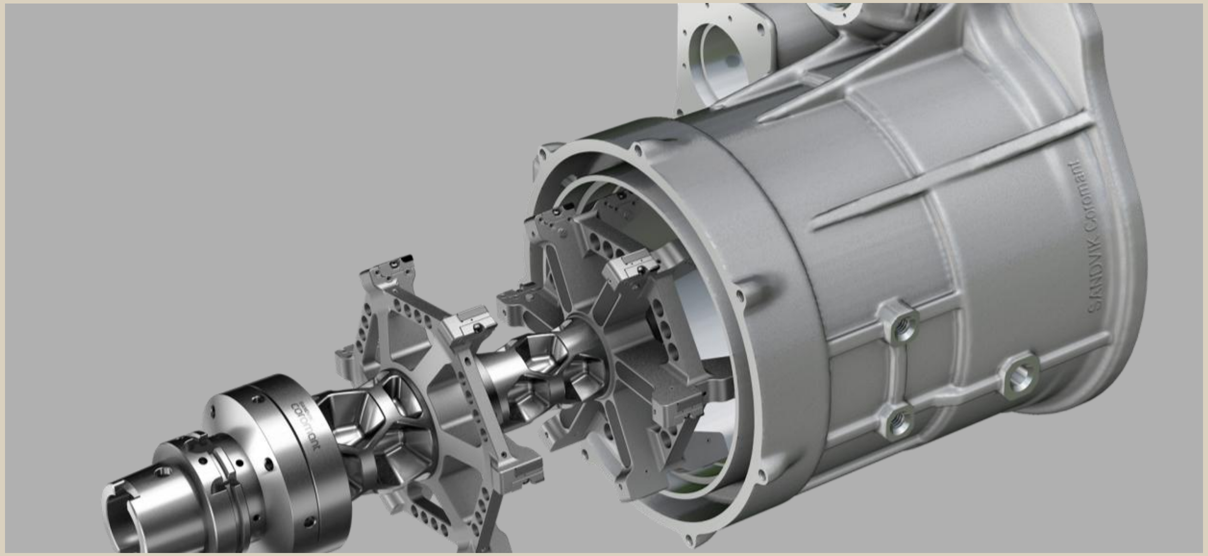
Metal Cutting Tools ?

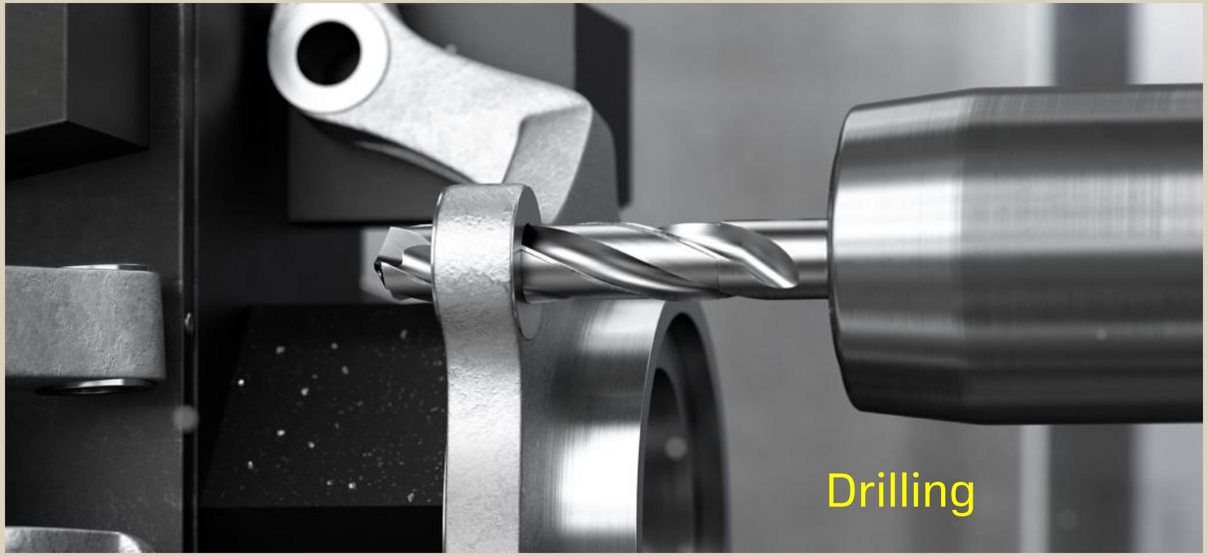
Why Do We Use Them?

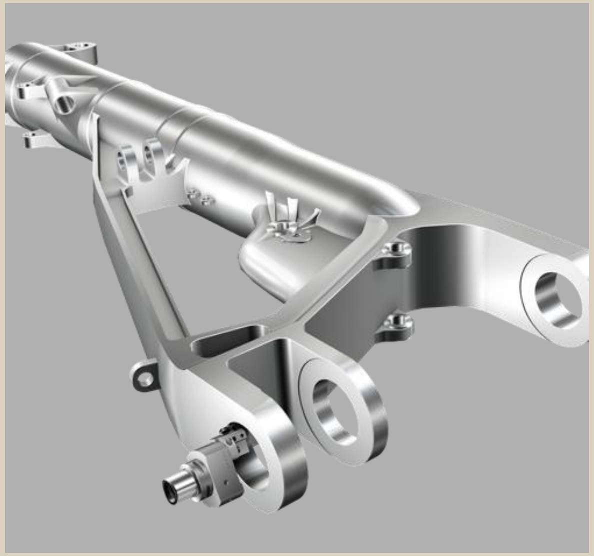
There are a vast number of cutting tools existing in the world, widely used in Turning, Milling and Drilling operations in the manufacturing industries.



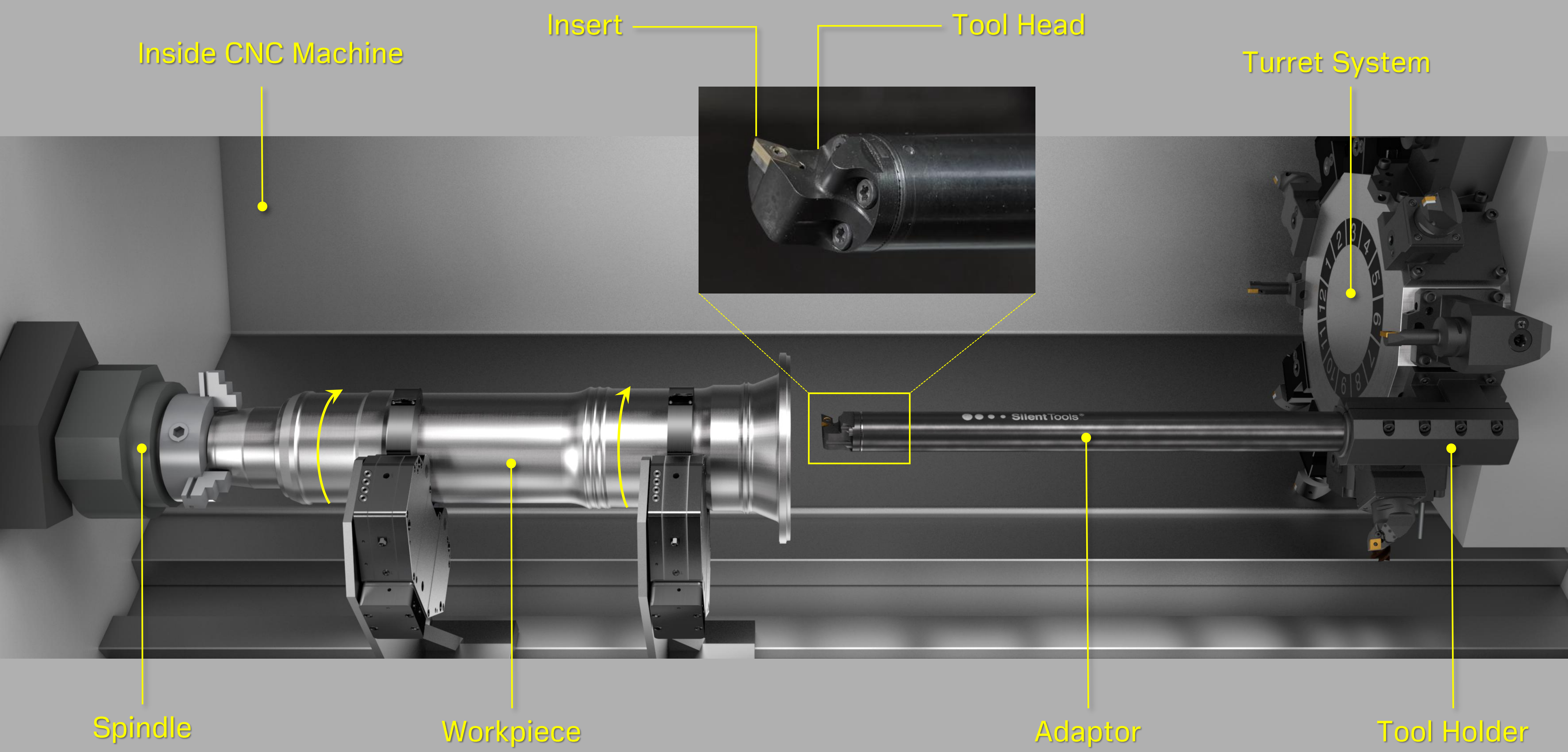




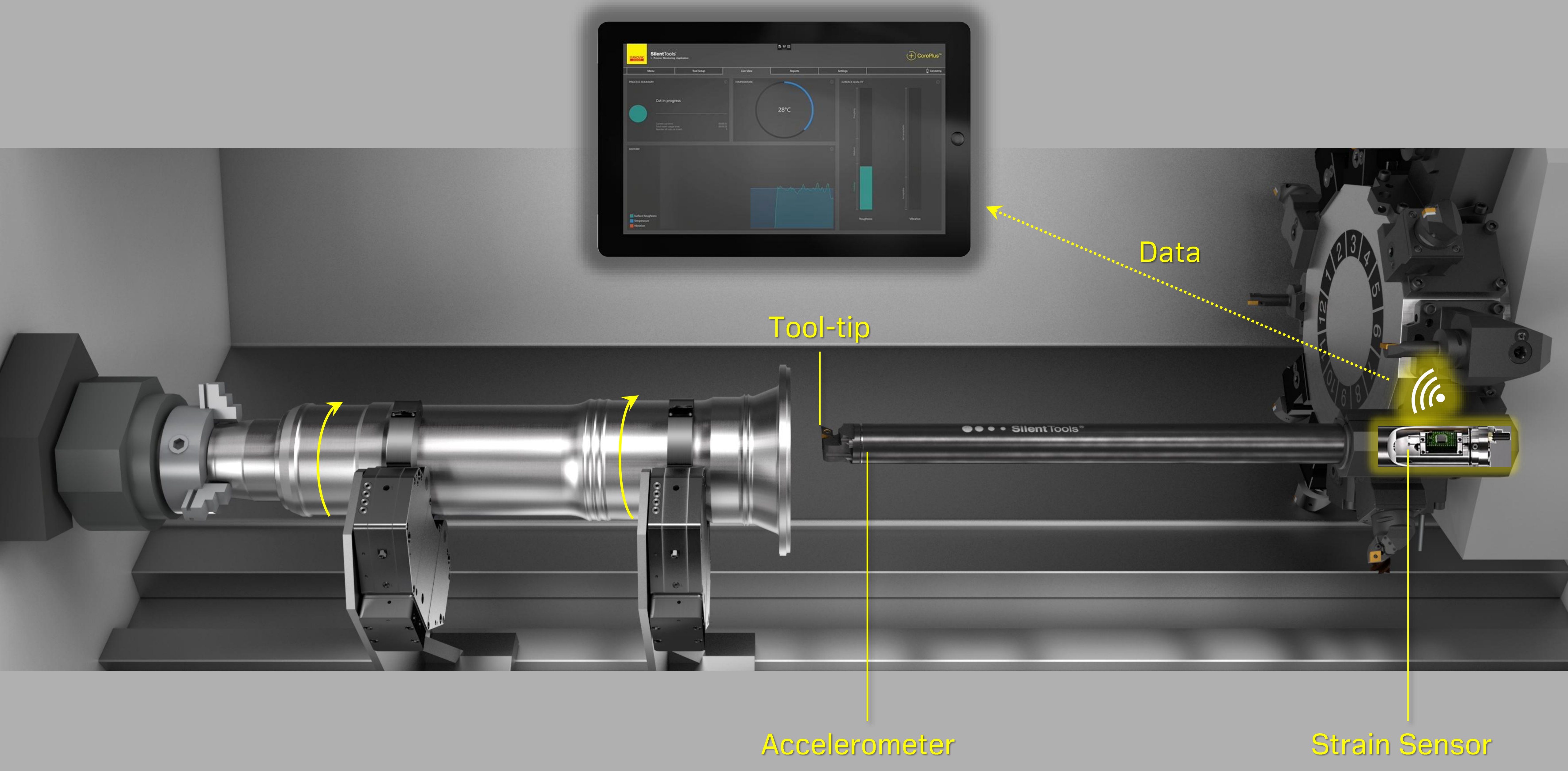




Metal Cutting Tool = Insert + Tool Head + Adaptor



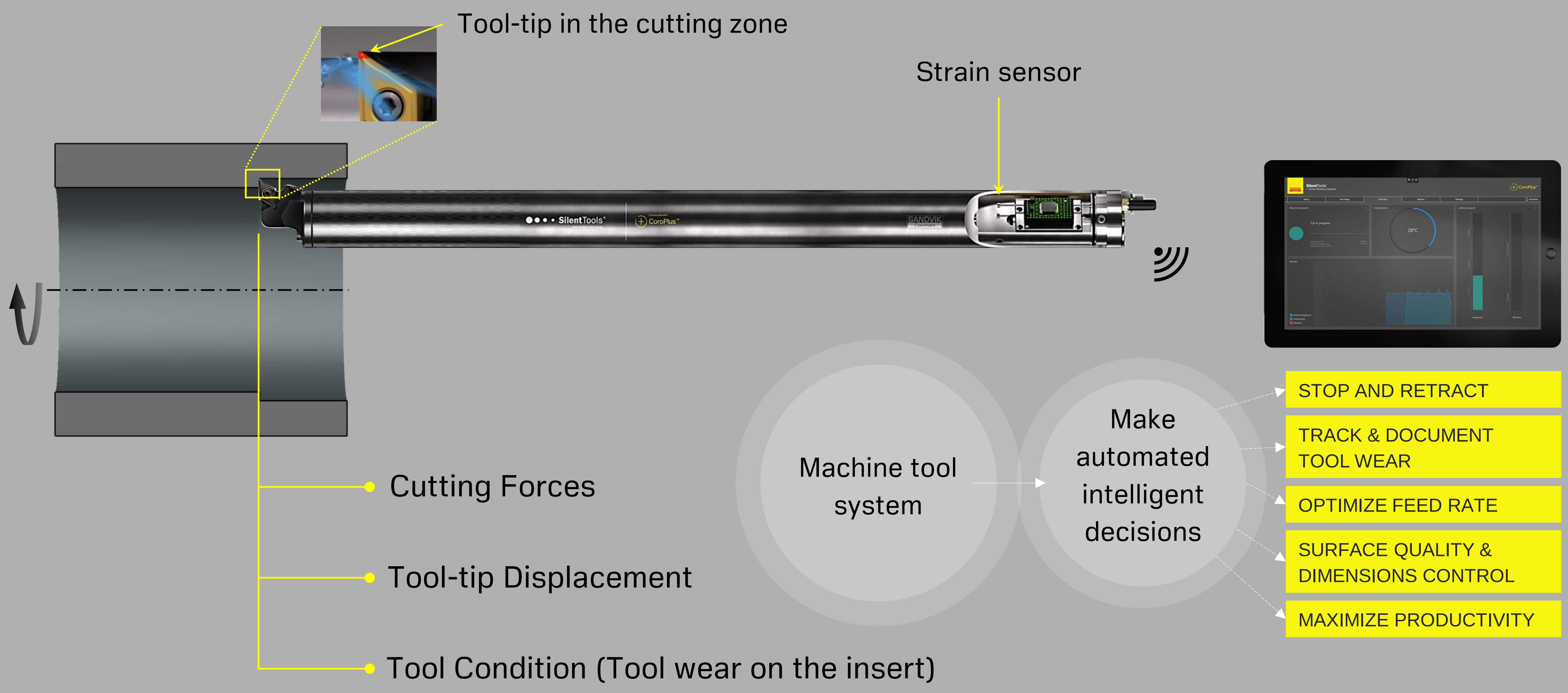
Sensor-equipped Cutting Tool



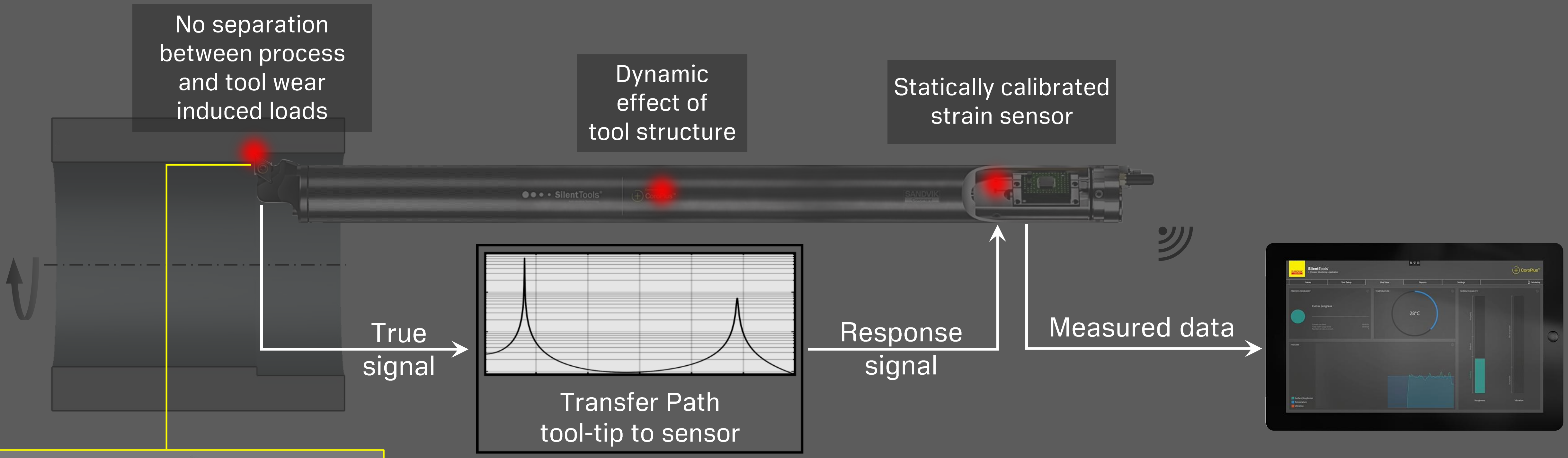
Silent Tools™

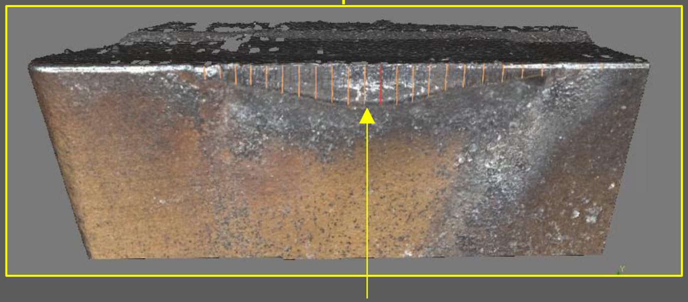
Next-gen turning adaptors

Aim and scope



Challenge





Tool wear on the relief side of insert

Challenges:

1. Lack of accurate model describing the relationship between cutting forces and tool wear.
2. Dynamic effect of the transfer path
3. Dynamic loads prediction by statically calibrated strain sensor

Research Questions

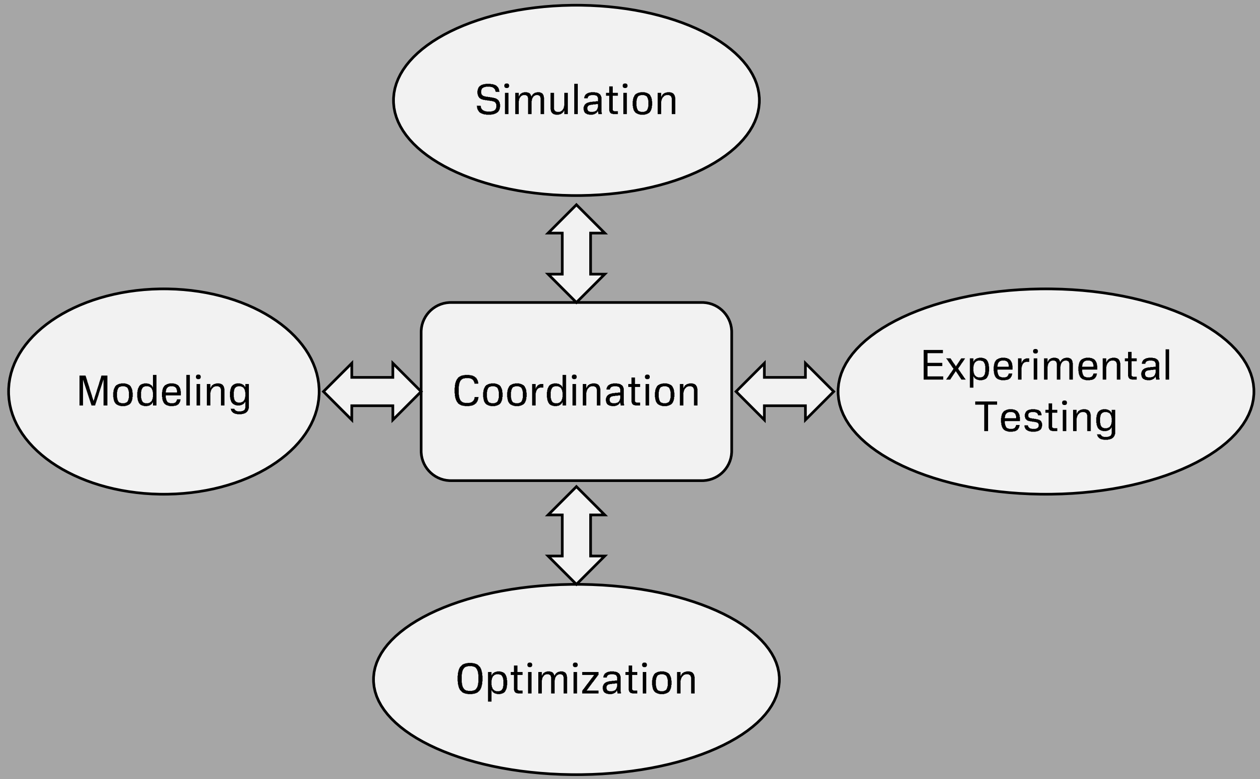
RQ 1: How can cutting force modeling enhance the interpretation of sensor data to distinguish the contributions of the cutting process and tool deterioration?

RQ 2: How can data from sensor-equipped cutting tools be used to accurately estimate dynamic loads and tool-tip deflection, while accounting for the dynamic effect of the transfer path between the tool tip and the sensor?

RQ 3: How can the integration of advanced modeling, signal processing techniques, and sensor-equipped cutting tools improve data quality, enhance measurement accuracy, and enable more precise real-time monitoring of machining conditions?

Research Methodology

- Hybrid methodology—Design Research Methodology & Coordinated Approach
  - **DRM** utilized to define research problems, identify gaps, establish relevance, and set clear objectives.
  - **Coordinated Approach** provides the foundational framework to foster multi-disciplinary collaboration and align research activities toward a shared goal:



Paper I

A prediction of cutting forces using extended Kienzle-Sağlam force model incorporating tool flank wear progression

Wu, P., Liljerehn, A., Magnevall, M., & Östling, D. (2025). A prediction of cutting forces using extended Kienzle-Sağlam force model incorporating tool flank wear progression. Machining Science and Technology, 1–17. https://doi.org/10.1080/10910344.2025.2473572

Motivations:

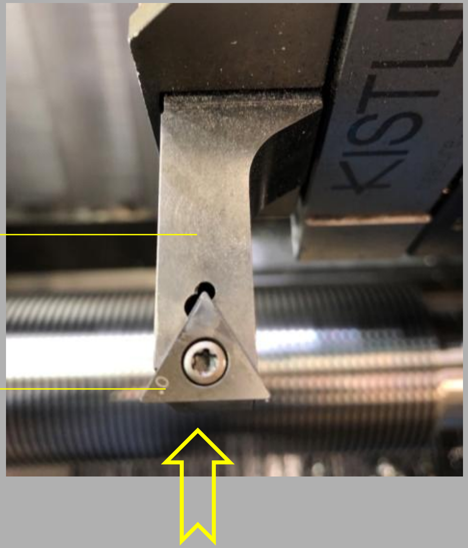
- To develop a model that accurately captures how cutting forces change as tool wear progresses during machining.

- This model will become a crucial tool for real time monitoring of tool wear based on high-quality force data collected from sensor-equipped cutting tools.

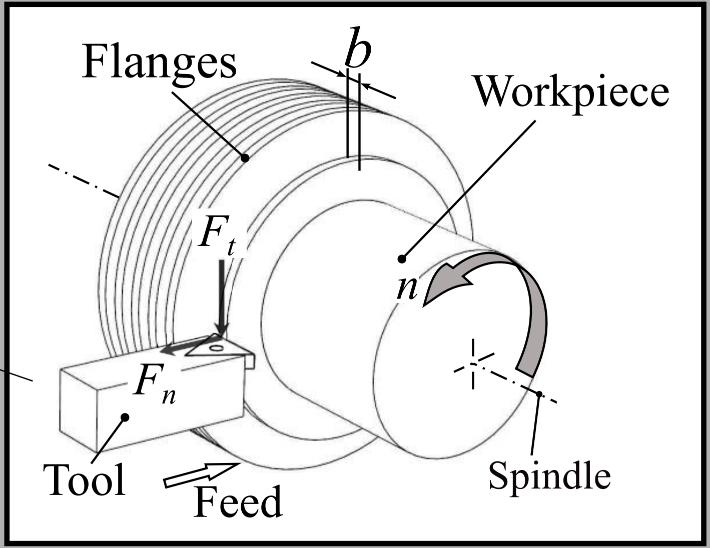
Tool Wear

Tool Holder

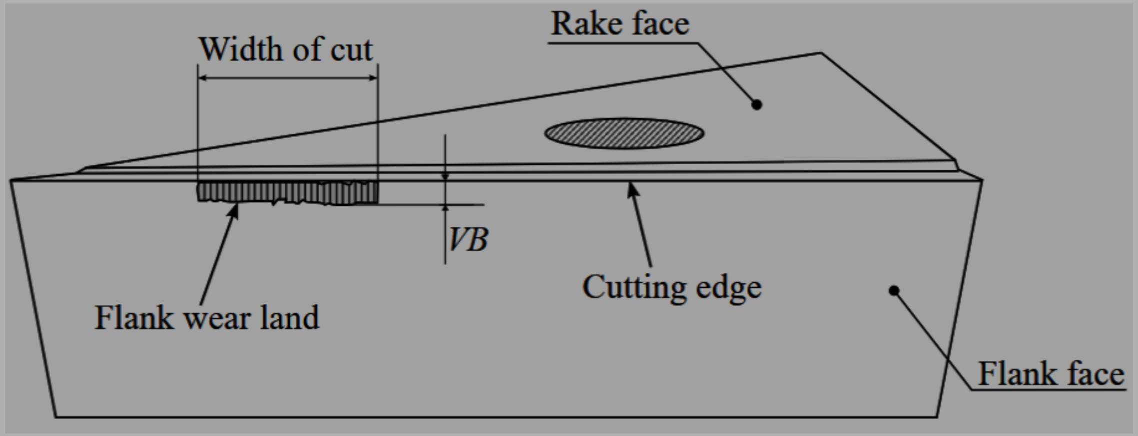
Insert

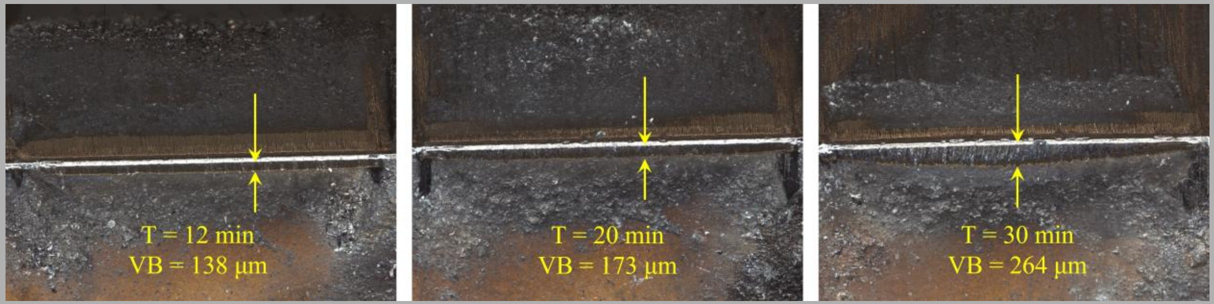


View on Flank Face of Insert



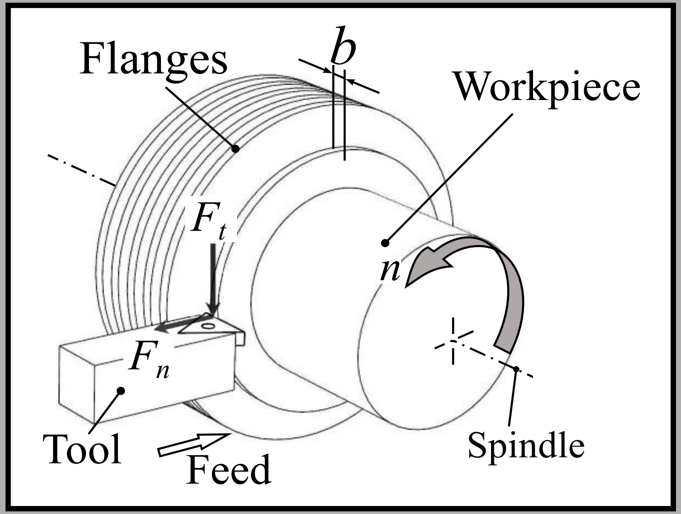
2D Orthogonal Cutting Operation



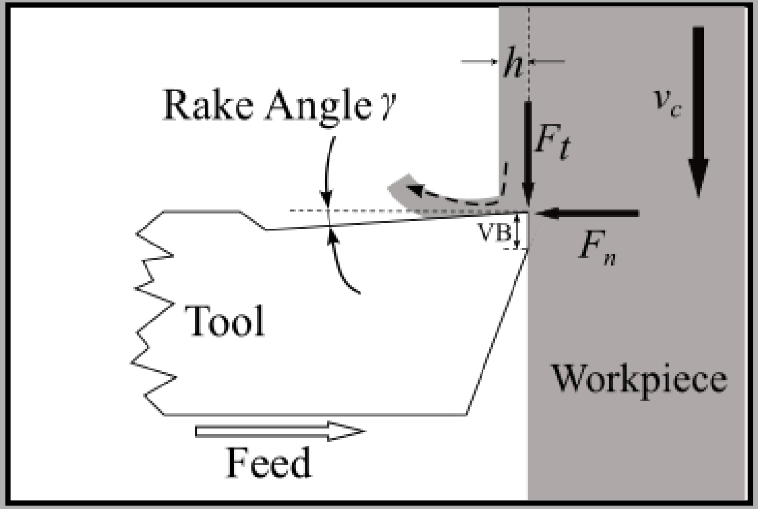


Aiming to develop $F = f(b, h, VB)$

Mechanistic Force Model



Orthogonal Cutting Operation



Cross-section view

Experimental Settings:

Operation	Orthogonal cutting
Workpiece material	34CrNiMo6+QT (300 HV)
Width of cut b	3 mm
Cutting velocity v_c	236—490 m/min
Feed rate f_n	0.05, 0.1, 0.2, 0.3 mm/rev
Rake anlge γ	-10°, 0°, 5°, 10°
Nr. of experiments	16

Kienzle-Sağlam Force Model:

Tangential force: $$F_t = b \cdot K_{t1.1} h^{1-m_t}\left(1 - \frac{\gamma}{\gamma_t}\right)$$

Normal force: $$F_n = b \cdot K_{n1.1} h^{1-m_n}\left(1 - \frac{\gamma}{\gamma_n}\right)$$

Extended Force Model:

$$F_t = b \cdot K_{t1.1} h^{1-m_t}\left(1 - \frac{\gamma}{\gamma_t}\right) \cdot (1 + c_t \cdot VB)$$

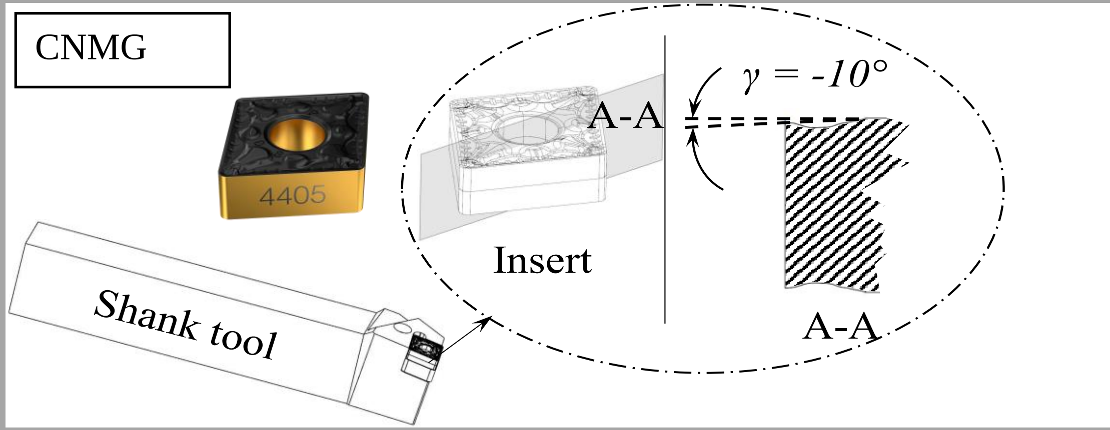
$$F_n = b \cdot K_{n1.1} h^{1-m_n}\left(1 - \frac{\gamma}{\gamma_n}\right) \cdot \left[1 + \frac{c_{n1} \cdot (VB \cdot h)^{c_{n2}}}{h}\right]$$

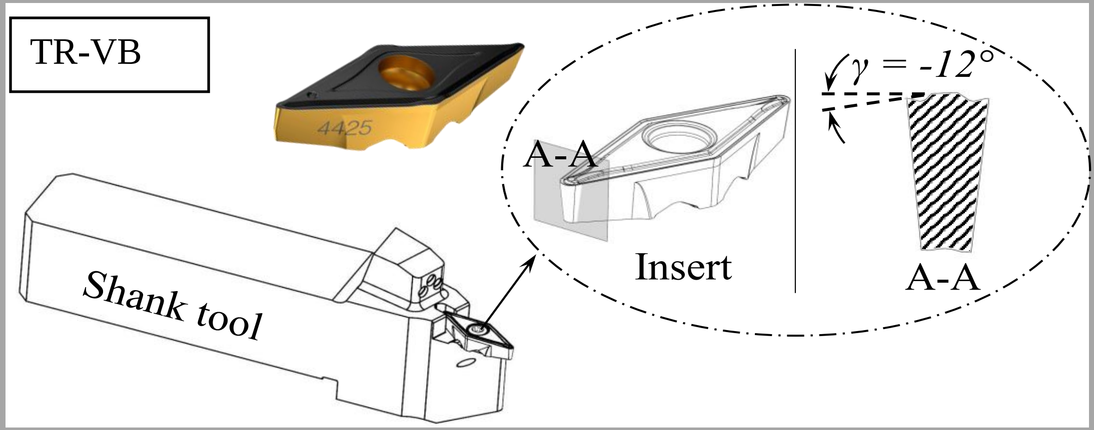
Regression Analysis
On Dataset

Validation Tests

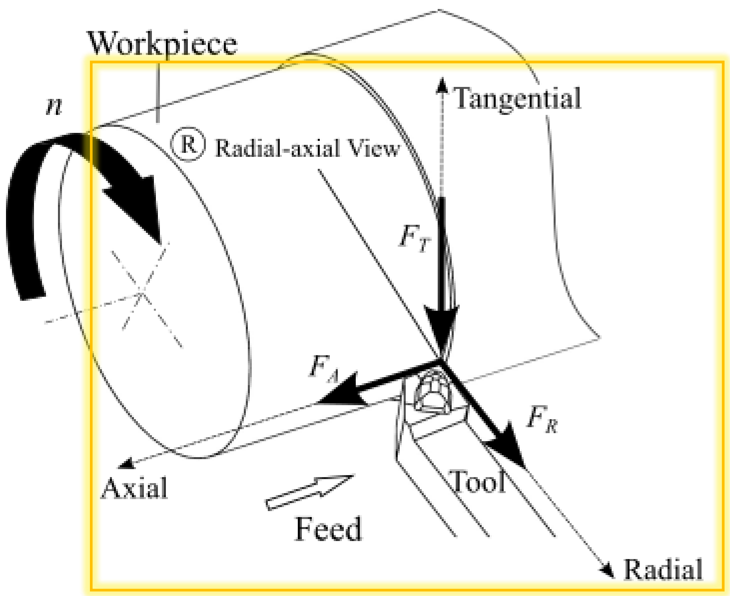
Experimental Setting:

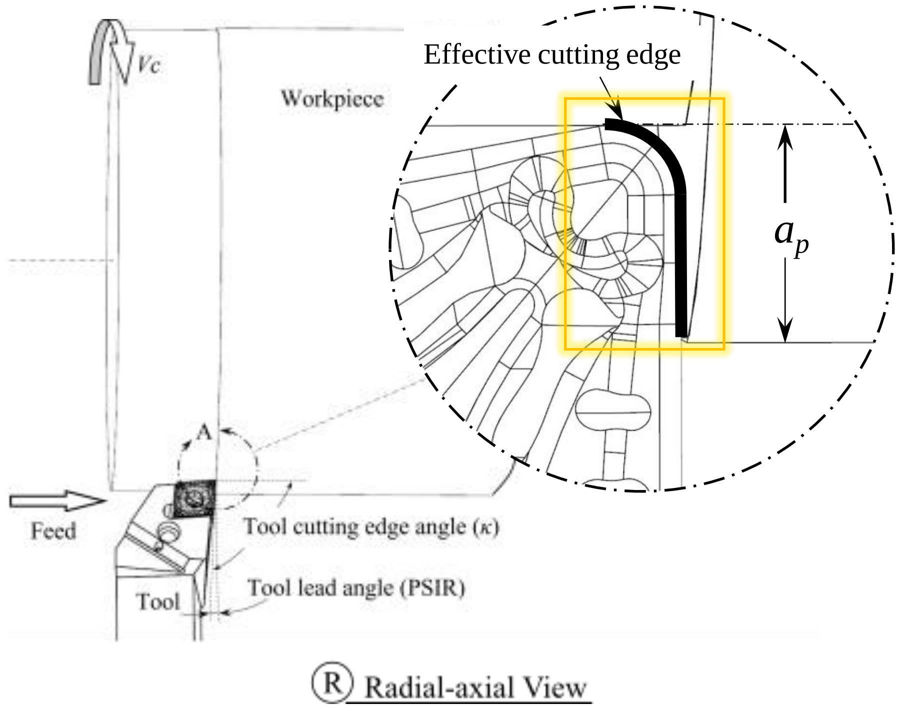
Workpiece Material	34CrNiMo6+QT (300HV)	
Feed rate f_n	0.2 mm/rev	
Cutting velocity v_c	250 m/min	
Insert	CNMG	TR-VB
Depth of cut a_p	2.5 mm	1.5 mm
Rake anlge γ	-10°	-12°
Inclination angle λ	-5°	-3°



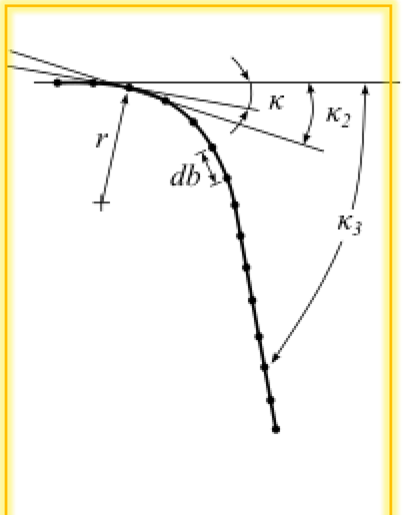


Transformation Model— 2D Mechanics to 3D

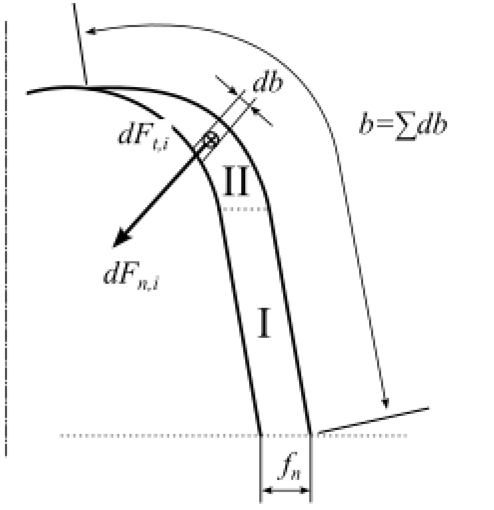




Cutting edge of the insert that acutally cuts the workpiece



Discretized cutting edge



Cutting edge after one revolution f_n

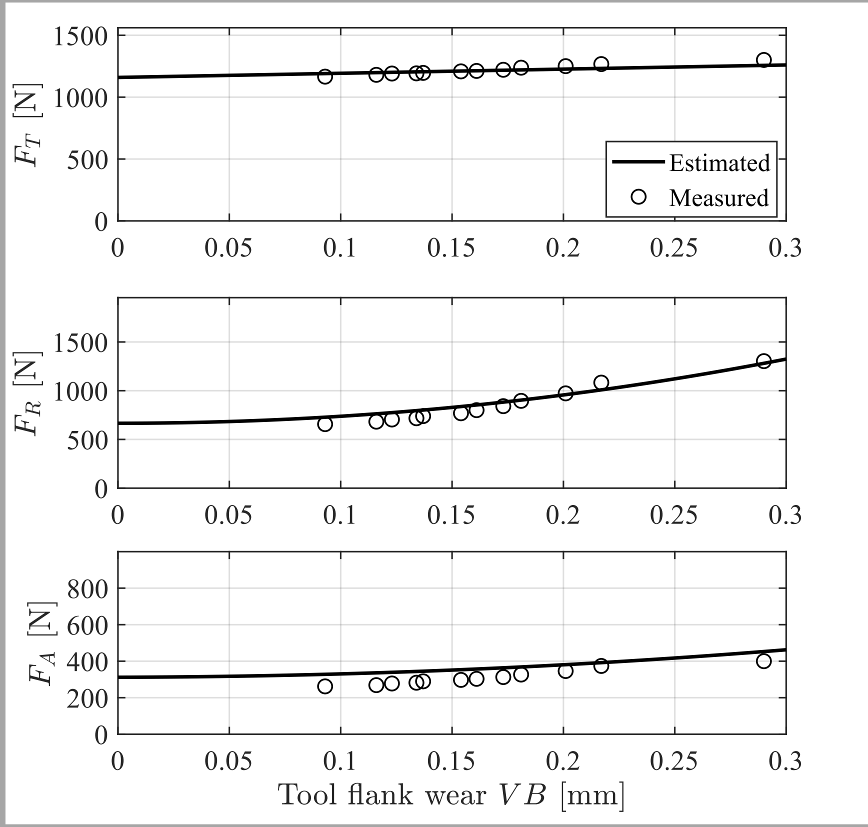
$$\Delta \boldsymbol{h}_i = f_n \sin \kappa_i \tag{1}$$

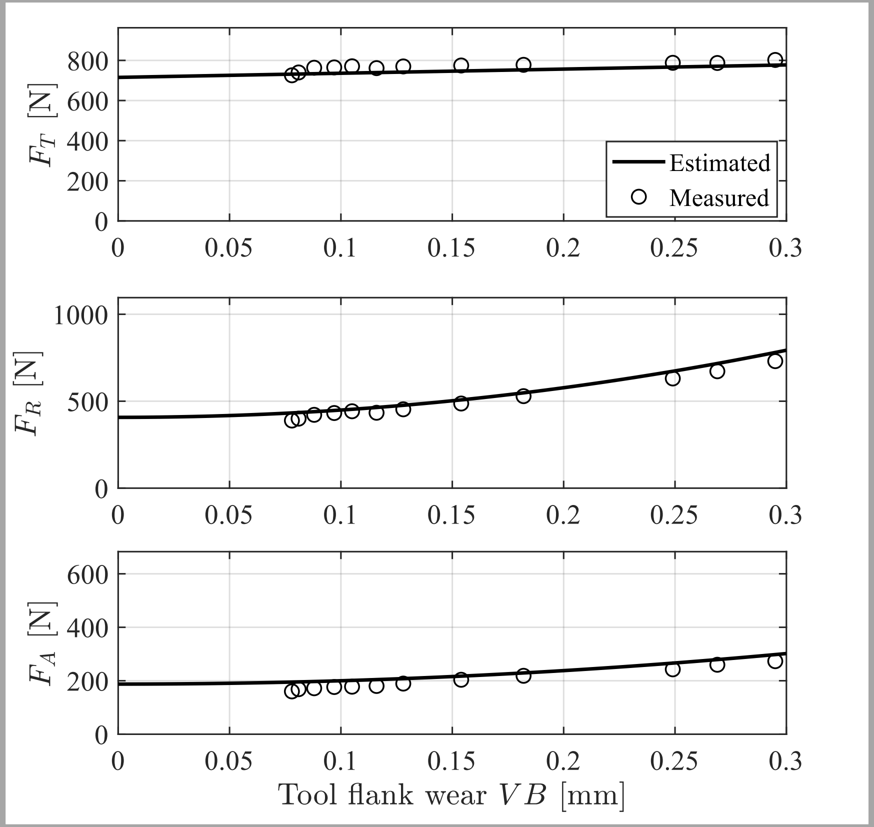
$$\begin{cases} d\boldsymbol{F}_{t,i} = db \cdot K_{t1.1} \Delta \boldsymbol{h}_i^{\,1-m_t} \left(1 - \frac{\gamma}{\gamma_t}\right) \cdot \left(1 + c_{t1} \cdot VB\right) \\ d\boldsymbol{F}_{n,i} = db \cdot K_{n1.1} \Delta \boldsymbol{h}_i^{\,1-m_n} \left(1 - \frac{\gamma}{\gamma_n}\right) \cdot \left[1 + \frac{c_{n1} \cdot (VB \cdot \Delta \boldsymbol{h}_i)^{c_{n2}}}{\Delta \boldsymbol{h}_i}\right] \end{cases} \tag{2}$$

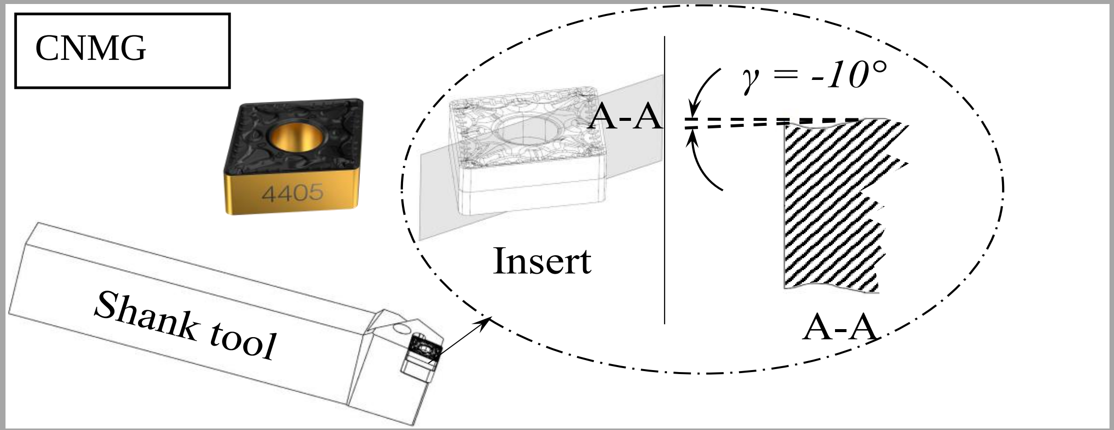
$$\begin{bmatrix} d\boldsymbol{F}_{T,i} \\ d\boldsymbol{F}_{R,i} \\ d\boldsymbol{F}_{A,i} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \sin\lambda & \cos\kappa_i & 0 \\ 0 & \sin\kappa_i & 0 \end{bmatrix} \begin{bmatrix} d\boldsymbol{F}_{t,i} \\ d\boldsymbol{F}_{n,i} \\ 0 \end{bmatrix} \tag{3}$$

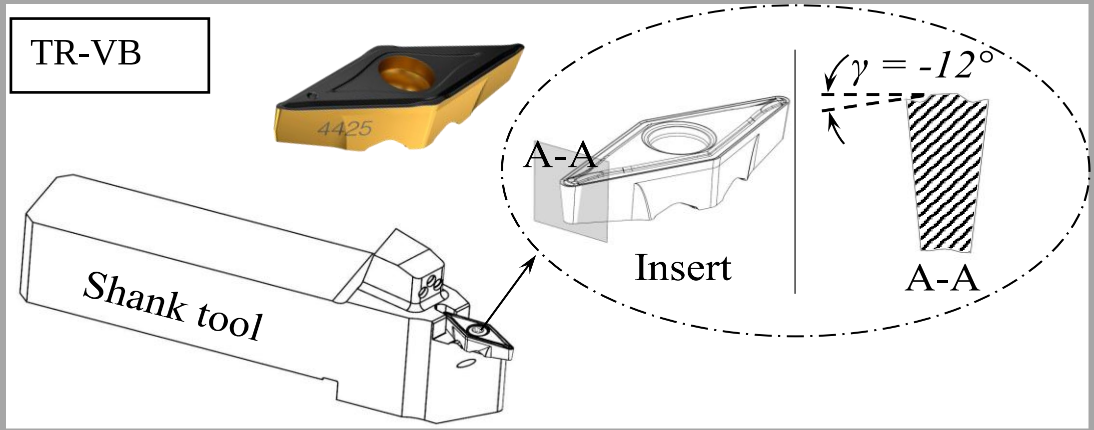
$$\boldsymbol{F}_q = \sum_{i=1}^{N} d\boldsymbol{F}_{q,i}, \; q = T, R, A \tag{4}$$

Validation Test Results









Paper II

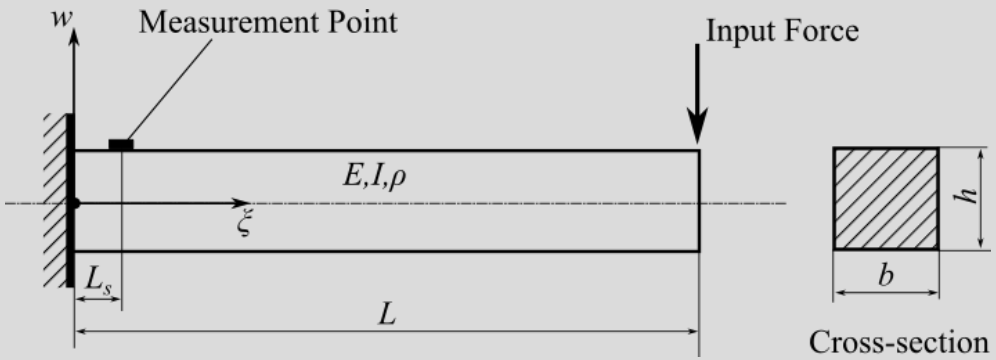
Cutting force estimation in metal cutting tools: a study on a sensor-equipped cantilever beam

P. Wu, M. Magnevall, A. Liljerehn, and D. Östling, 'Cutting force estimation in metal cutting tools: a study on a sensor-equipped cantilever beam', in Proceedings of ISMA 2024 - International Conference on Noise and Vibration Engineering and USD 2024 - International Conference on Uncertainty in Structural Dynamics, 2024, pp. 1445–1456.

Motivations:

- To enhance the data quality and reliability, we need a model to capture the dynamic properities of transfer path between tool tip and sensor location
- A model-based approach is needed to efficiently and accurately estimate input forces using measured strain response data

Classical modal concept on a beam



Property	Value	
Beam Length, L	152.35	mm
Width, b	12.25	mm
Height, h	12.25	mm
Young's modulus E	206	GPa
Density, ρ	7850	kg/m^3
Sensor location, L_s	4.55	mm

1. Euler-Bernoulli Beam theory:

$$EI\left[\frac{\partial^4 w(\xi,t)}{\partial \xi^4}\right] + m_\rho \frac{\partial^2 w(\xi,t)}{\partial \xi^2} + c\frac{\partial w(\xi,t)}{\partial \xi} = f(\xi,t) \qquad (1)$$

2. Transversal deflection mode shapes $\phi_r(\xi)$ and undamped natural frequencies ω_r

3. Determine modal mass based on mode shape scaling:

$$m_r = \int_0^L m_\rho \cdot |\phi_r(\xi)|^2 \qquad (2)$$

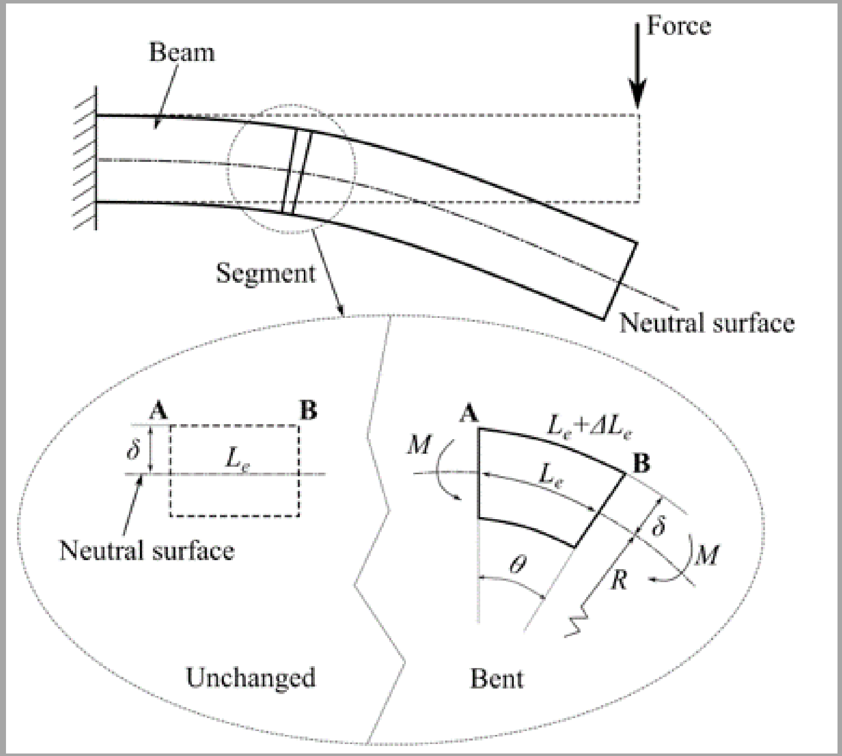
4. Deflection-force transfer function (modal superposition):

$$H_{pq}(s) = \sum_{r=1}^{N} \frac{\mathbb{R}_{pqr}}{s-\lambda_r} + \frac{\mathbb{R}^*_{pqr}}{s-\lambda^*_r} \qquad (3)$$

$$Residues:\ \mathbb{R}_{pqr}, \mathbb{R}^*_{pqr} = \mp j\frac{\phi_{pr}\phi_{qr}}{2\omega_{dr} m_r} \qquad (4)$$

$$Poles:\ \lambda_r, \lambda^*_r = -\zeta_r\omega_r \pm j\omega_r\sqrt{1-\zeta_r^2} = -\zeta_r\omega_r \pm j\omega_{dr} \qquad (5)$$

Modeling strain-force transfer function



5. The relationship between transversal deflection and strain

$$\theta = \frac{L_e}{R} = \frac{L_e + \Delta L_e}{R + \delta} \quad \rightarrow \quad \frac{\delta}{R} = \frac{\Delta L_e}{L_e} = \varepsilon \qquad (6)$$

$$Curvature: \frac{1}{R} \approx \frac{d^2 w}{d\xi^2} \qquad (7)$$

$$\varepsilon = -\delta \cdot \frac{d^2 w}{d\xi^2} \qquad (8)$$

6. Deflection and strain mode shapes:

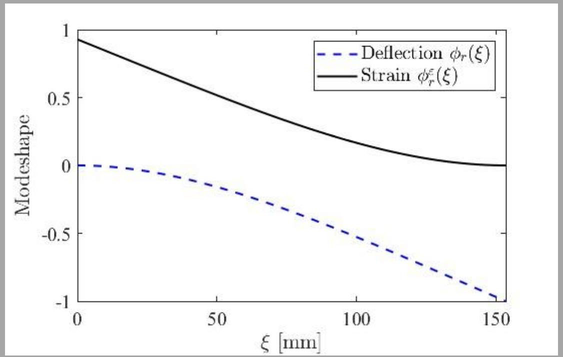
$$\phi_r(\xi) = C_1 \cos(\beta_r \xi) + C_2 \sin(\beta_r \xi) + C_3 \cosh(\beta_r \xi) + C_4 \sinh(\beta_r \xi) \qquad (9)$$

$$\phi_r^{\varepsilon}(\xi) = \delta {\beta_r}^2 [C_1 \cos(\beta_r \xi) + C_2 \sin(\beta_r \xi) - C_3 \cosh(\beta_r \xi) - C_4 \sinh(\beta_r \xi)] \qquad (10)$$

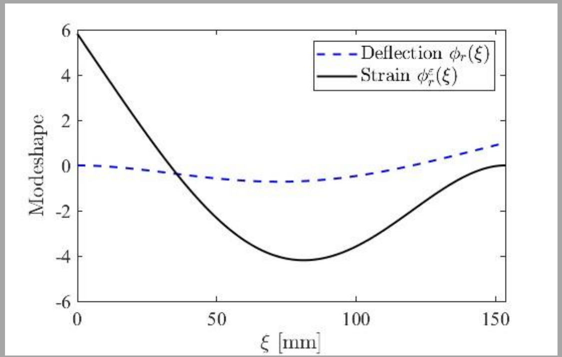
7. Strain-force transfer function (superposition model):

$$H_{pq}^{\varepsilon}(s) = \sum_{r=1}^{N} \frac{\mathbb{R}_{pqr}^{\varepsilon}}{s - \lambda_r} + \frac{\mathbb{R}_{pqr}^{\varepsilon *}}{s - \lambda_r^*} \qquad (11)$$

$$Residues: \mathbb{R}_{pqr}^{\varepsilon}, \mathbb{R}_{pqr}^{\varepsilon *} = \mp j \frac{\phi_{pr}^{\varepsilon}(\xi_p) \cdot \phi_{qr}(\xi_q)}{2\omega_{dr} m_r} \qquad (12)$$



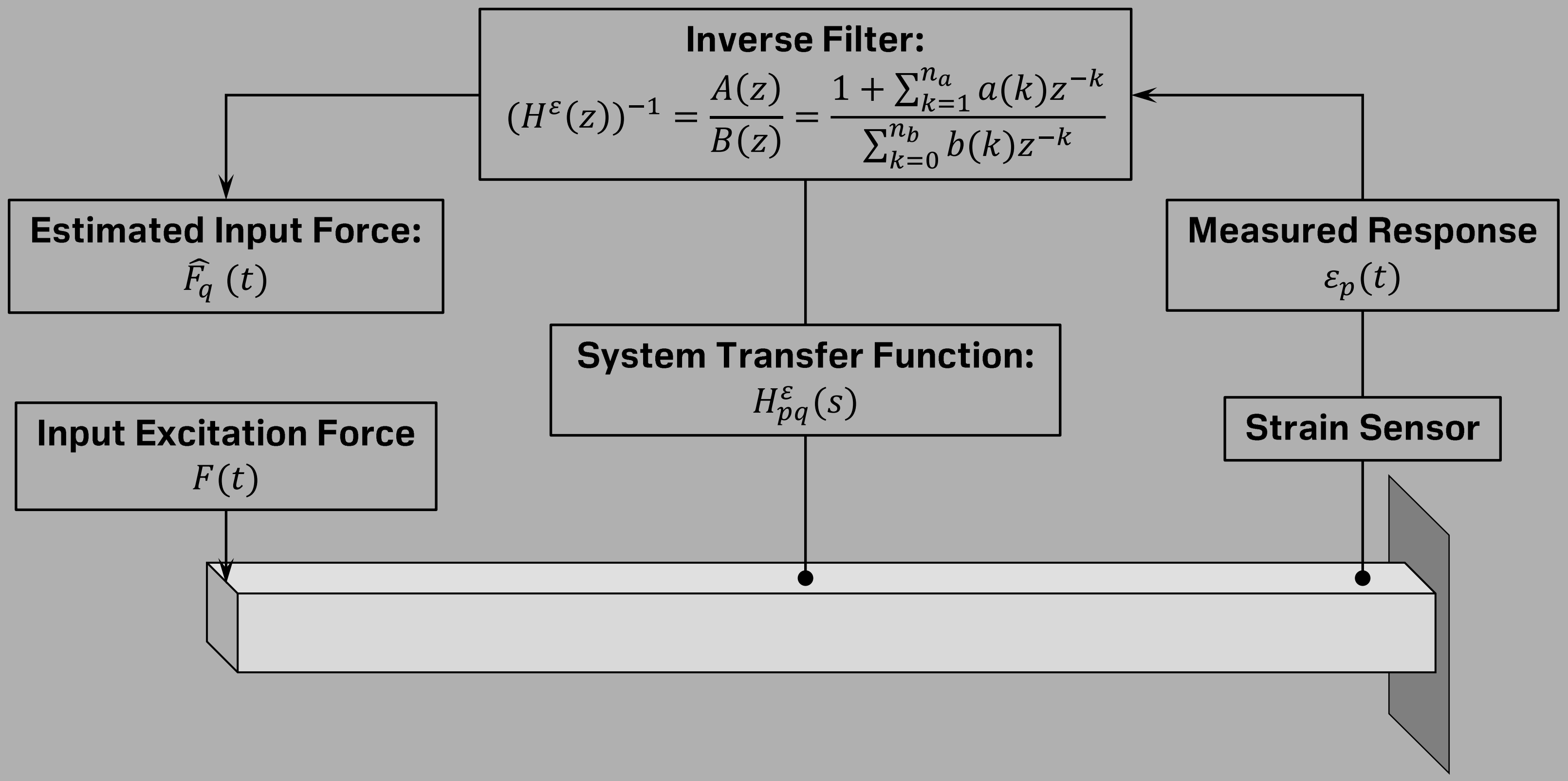
Mode 1



Mode 2

Experimental Validation:
Analytical Model vs. Measurement Results

Model-based approach for input force estimation



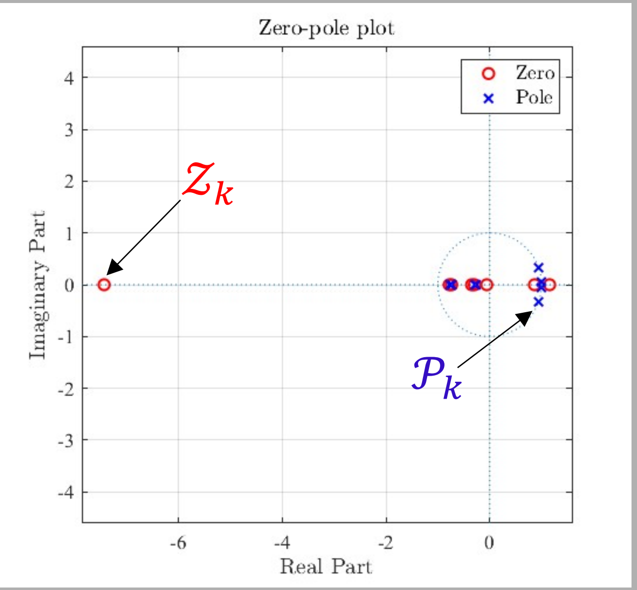
- To enable efficient computation using sampled strain data, the transfer function is identified as a digital filter by:

$$H^{\varepsilon}(z) = \frac{B(z)}{A(z)} = \frac{\sum_{k=0}^{n_b} b(k)z^{-k}}{1+\sum_{k=1}^{n_a} a(k)z^{-k}} = b(0)\,\frac{\prod_{k=1}^{n_b}(1-\mathcal{Z}_k z^{-1})}{\prod_{k=1}^{n_a}(1-\mathcal{P}_k z^{-1})}$$

Inverse filtering

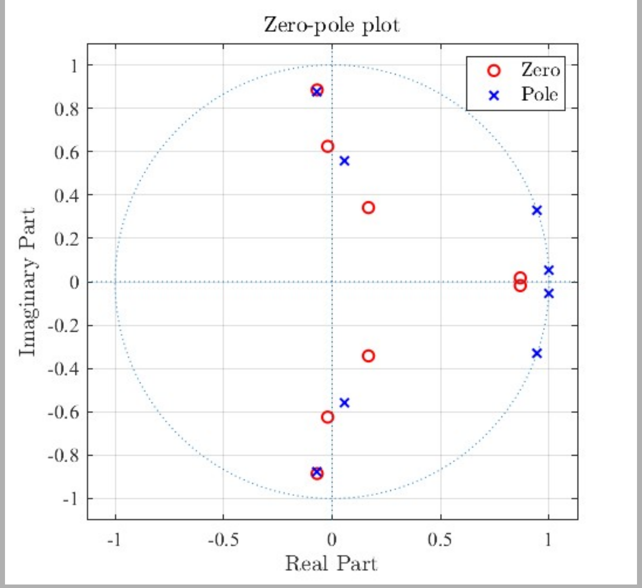
Digital transfer function $H^{\varepsilon}_{ori}(z)$:

$$H^{\varepsilon}_{ori}(z) = b(0)\frac{\prod_{k=1}^{n_b}(1-\mathcal{Z}_k z^{-1})}{\prod_{k=1}^{n_a}(1-\mathcal{P}_k z^{-1})}$$



Resulting the inverse filter unstable

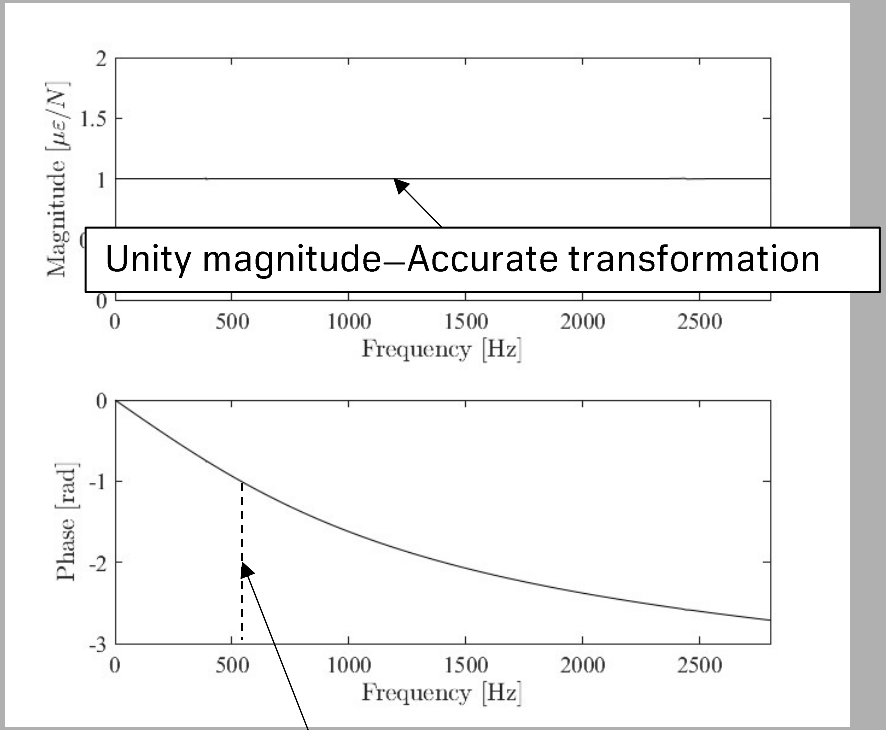
Convert Digital TF into minimum phase TF $H^{\varepsilon}_{min}(z)$



The inverse filter is stabilized

Frequency-response analysis on $H^{\varepsilon}_{com}(z)$

$$H^{\varepsilon}_{com}(z) = H^{\varepsilon}_{ori}(z) \cdot (H^{\varepsilon}_{min}(z))^{-1}$$



Aprox. linear phase until 650Hz, low-pass filter with a cutoff at 650Hz is applied to the inverse-filtered signals.

Experimental Validation Results: Estimated input forces vs. Measurement

Paper III

Cutting force estimation in sensor equipped metal cutting tools using strain-force transfer function

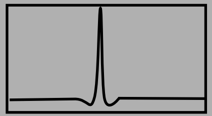
P. Wu, A. Liljerehn, M. Magnevall, D. Östling, Cutting force estimation in sensor-equipped metal cutting tools using strain-force transfer function. Presented at IMAC-XLIII, Conference on Structural Dynamics, Orlando, USA, 2025

Motivations:

- Need to evaluate the developed approach using a physical sensor-equipped cutting tool.
- Need to investigate if the analytical model can be calibrated to the tool configuration using only measured strain response
- Need to evaluate if both the impulse input force and tool-tip displacement can be accurately estimated from the measured strain data

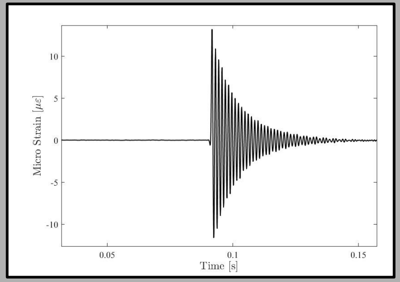
Analytical model

F (unknown)

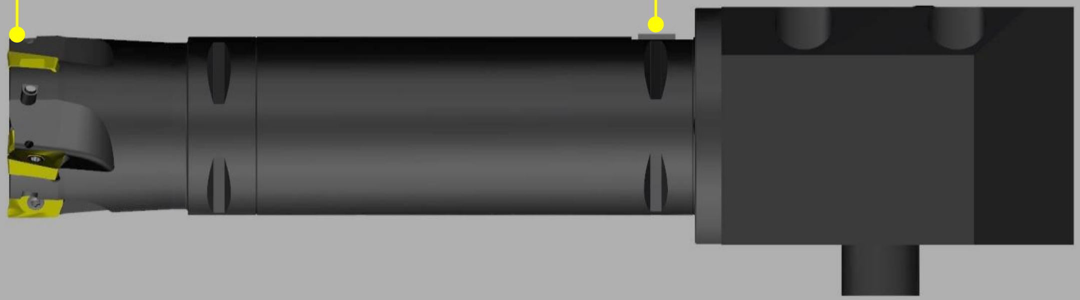


Excitation at q-point

ε_p (Measured)



Strain Sensor at p-point



Excitation Force
F (unknown)

↓

Strain Response
ε_p (measured)

↓

Modal Parameter Identification
ω_{m1}, ζ_1

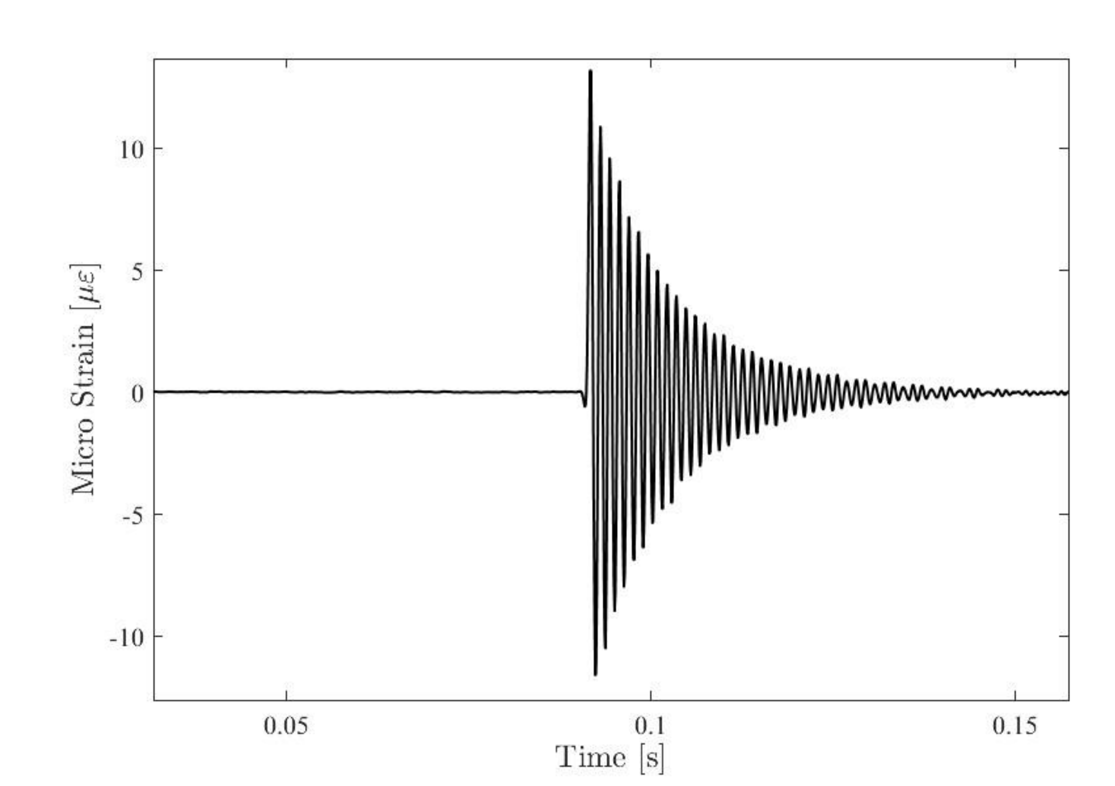
↓

Adapting Analytical Model

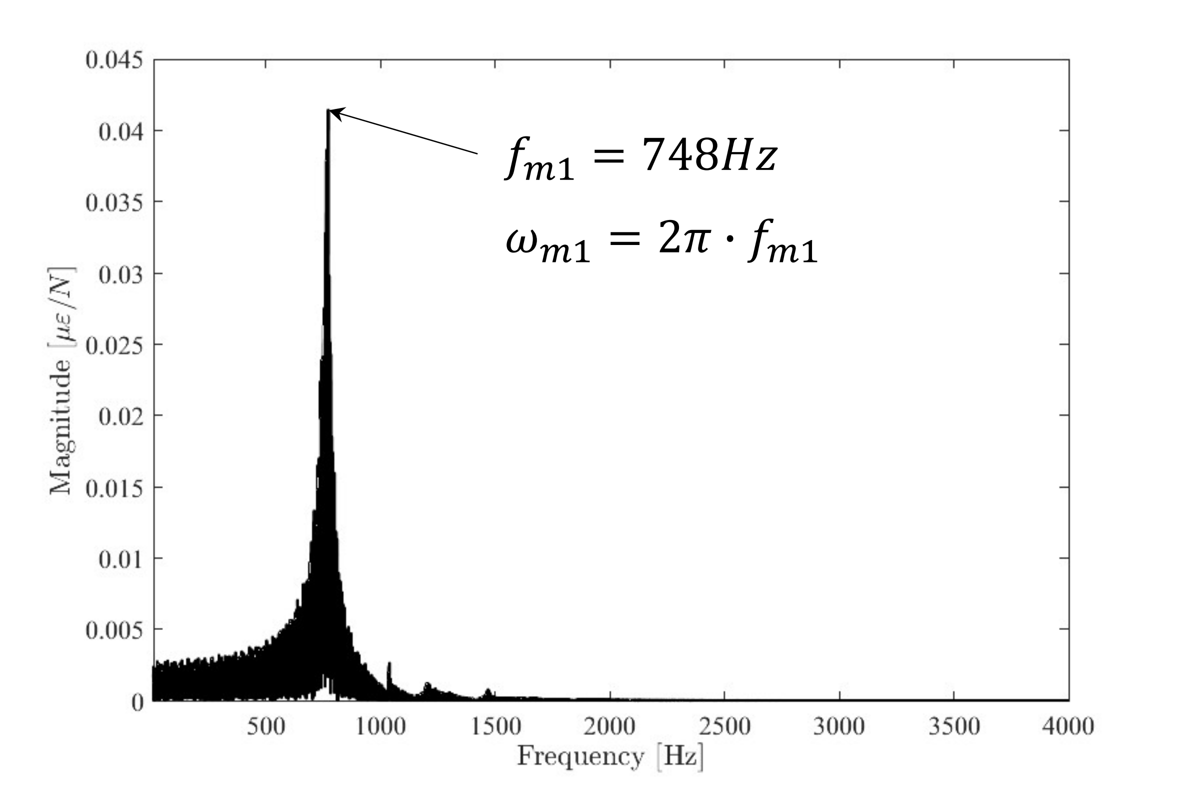
$$\omega_r' = \frac{\omega_{m1}}{(\beta_1 L)^2} \cdot (\beta_r L)^2$$

Calibration Stage
(Paper II)

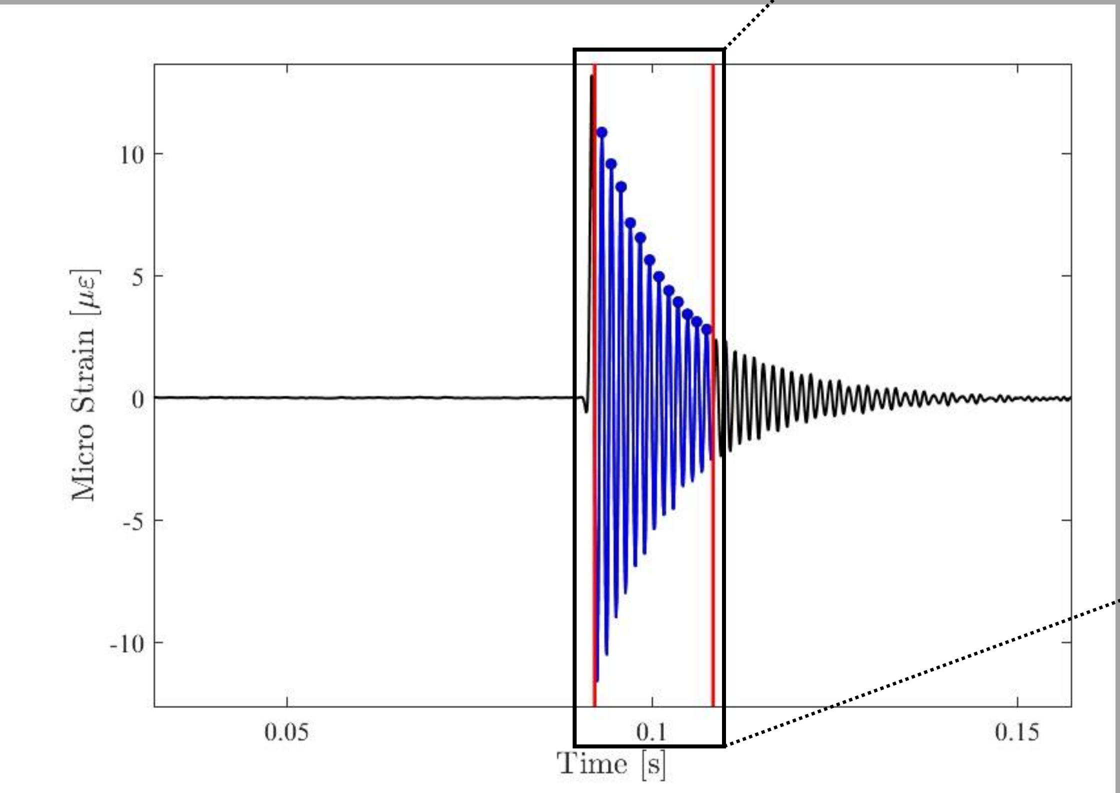
First Natural Frequency - ω_{m1}

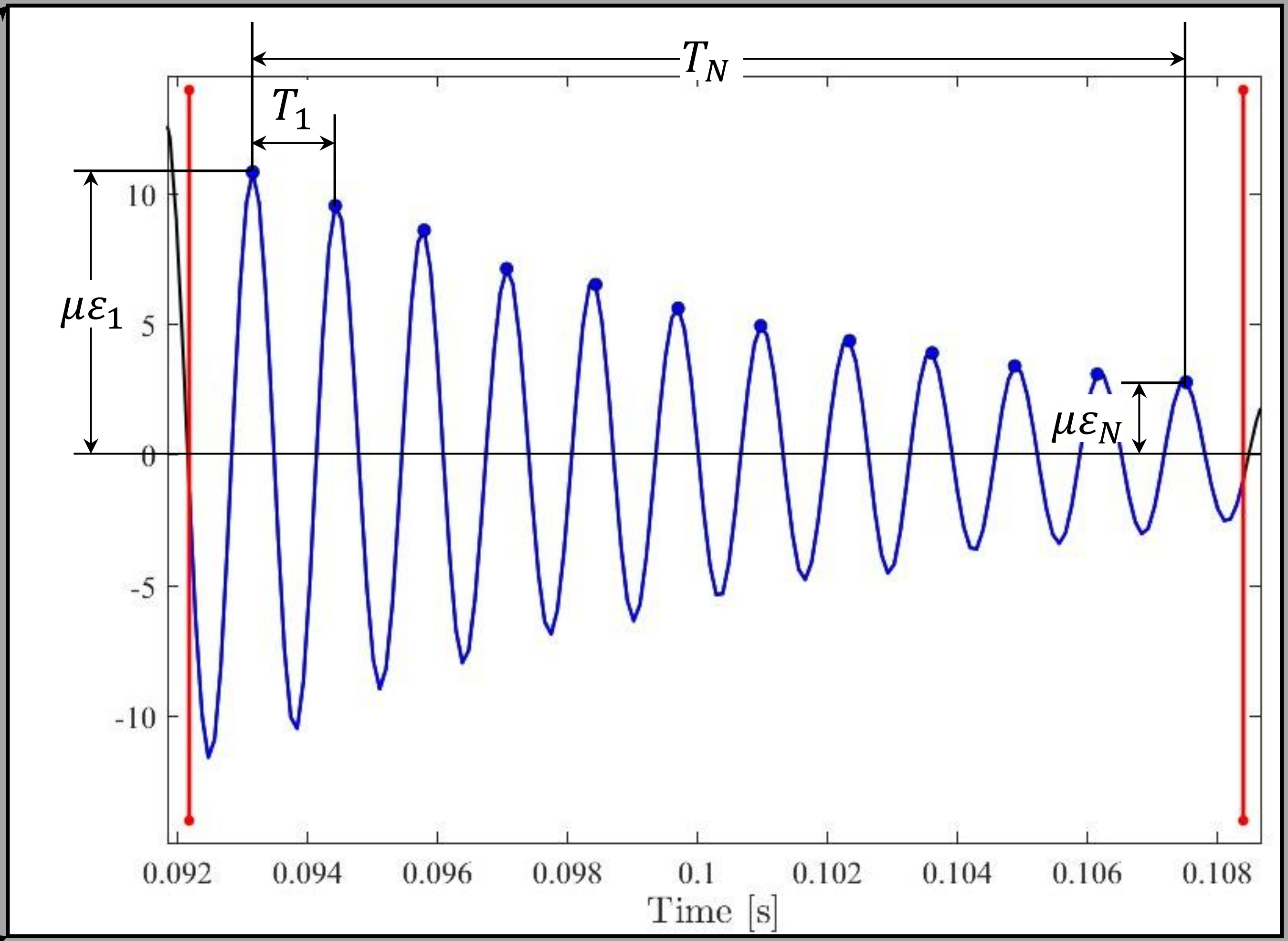


FFT



Damping Ratio - ζ_1





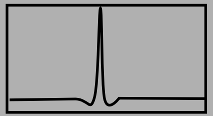
Logarithmic decrement approach:

$$\zeta_1(\delta_N, N) = \frac{\delta_N/(2\pi N)}{\sqrt{1 + (\delta_N/(2\pi N))^2}} = 0.0094$$

where, $\delta_N = \ln\left(\frac{\mu\varepsilon_1}{\mu\varepsilon_N}\right), \; N = \frac{T_N}{T_1}$

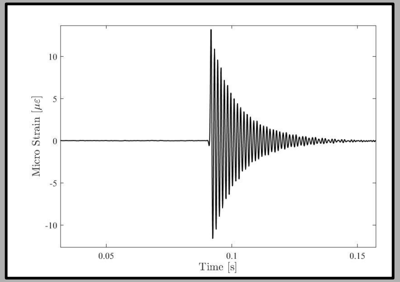
Analytical Model

F (unknown)

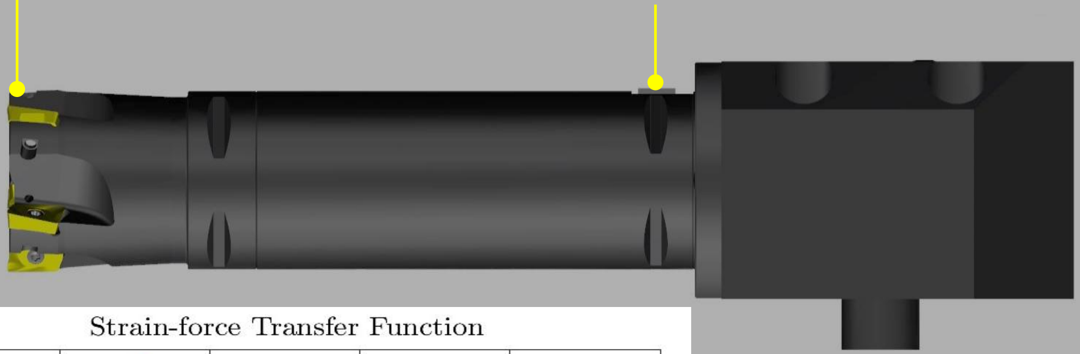


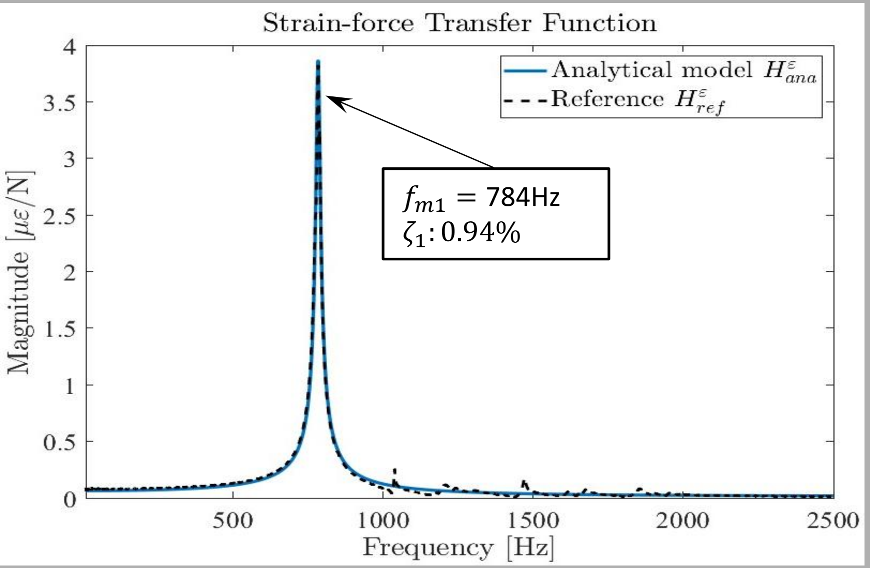
Excitation at q-point

ε_p (Measured)



Strain Sensor at p-point





Calibration Stage

Excitation Force
F (unknown)

↓

Strain Response
ε_p (measured)

↓

Modal Parameter Identification
ω_{m1}, ζ_1

↓

Adapting Analytical Model

$$\omega_r' = \frac{\omega_{m1}}{(\beta_1 L)^2} \cdot (\beta_r L)^2$$

↓

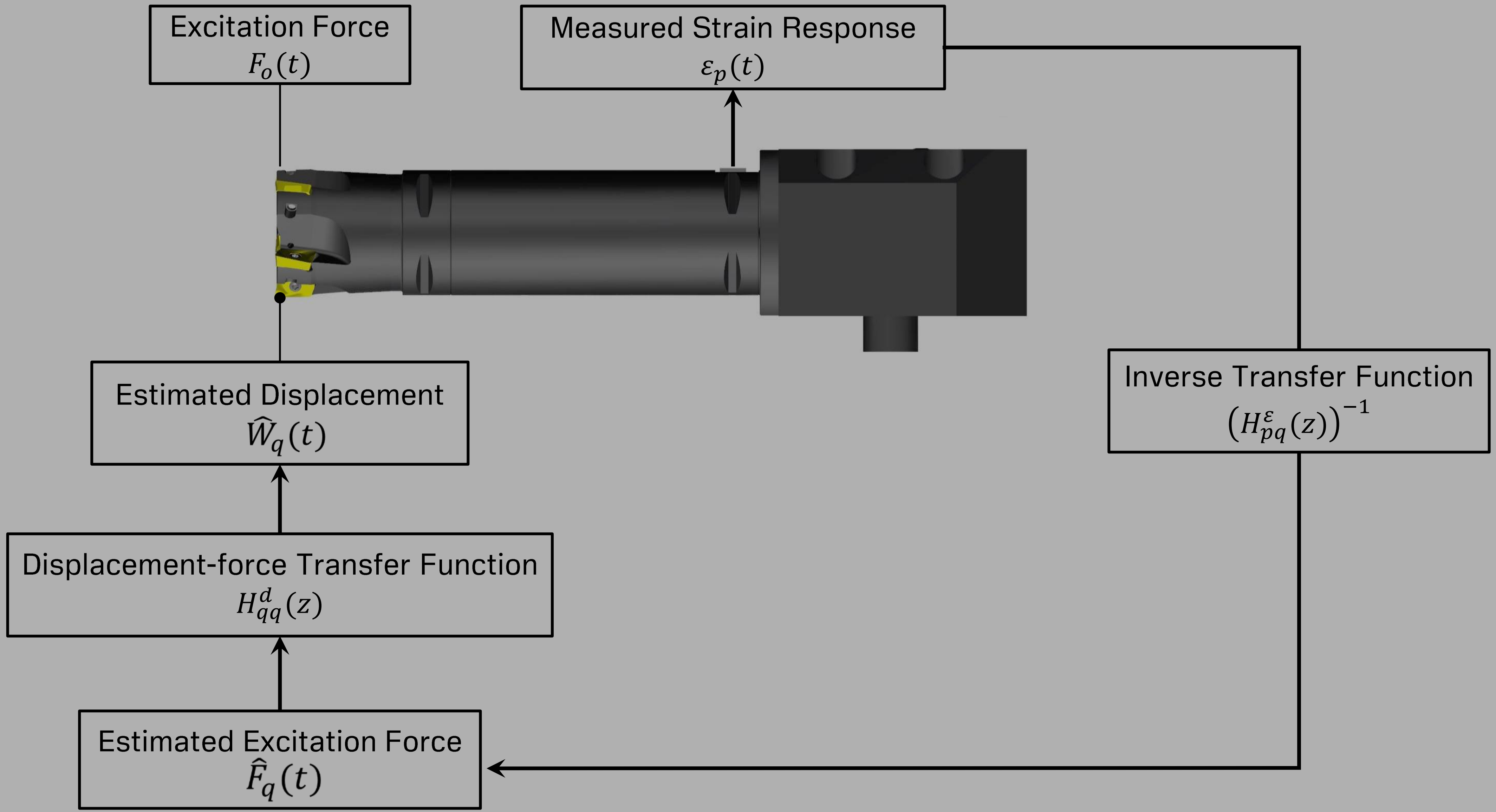
Strain-force Transfer Function
$H^{\varepsilon}_{pq}(s)$

↓

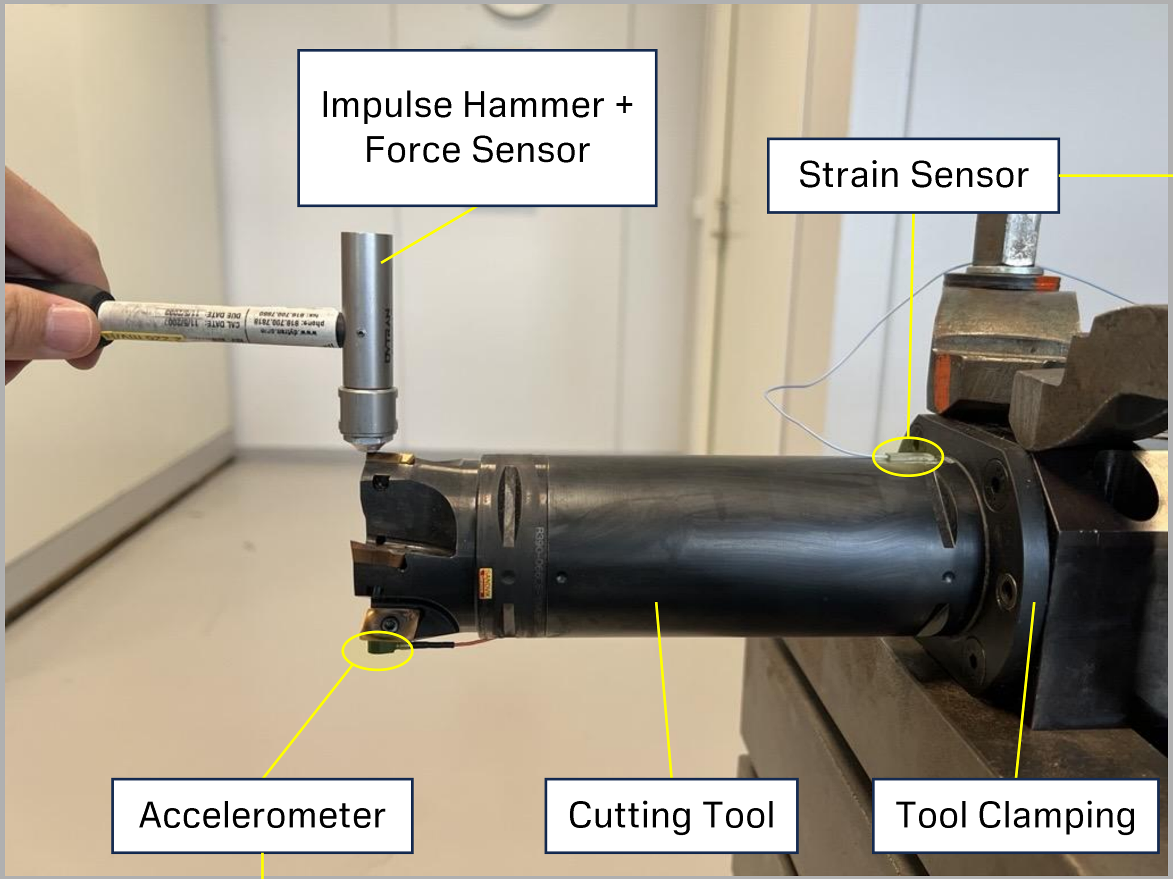
Inverse Transfer Function (filter)
$\left(H^{\varepsilon}_{pq}(z)\right)^{-1}$

Displacement-force Transfer Function
$H^{d}_{qq}(s)$

Method for estimating force and displacement



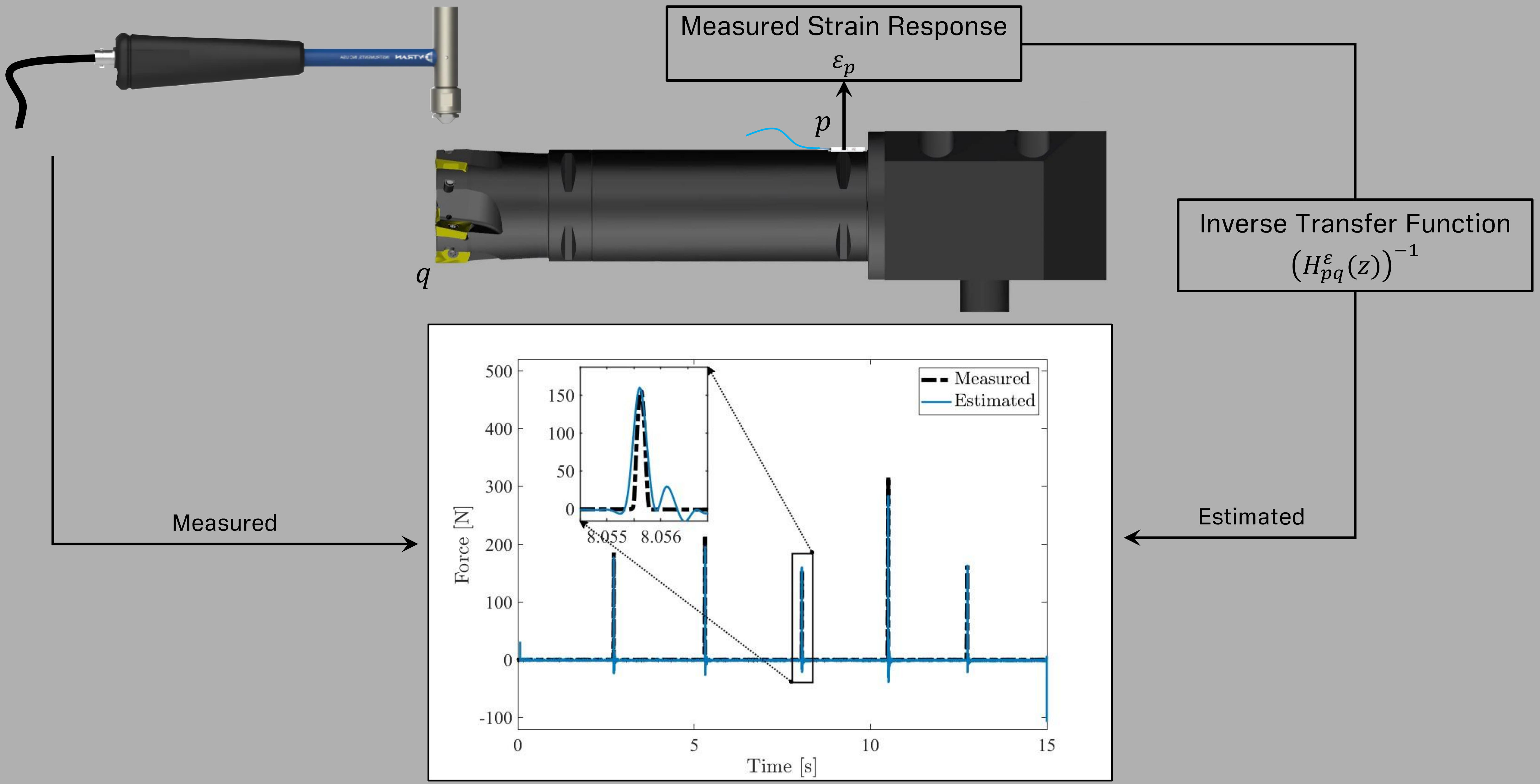
Experimental setup



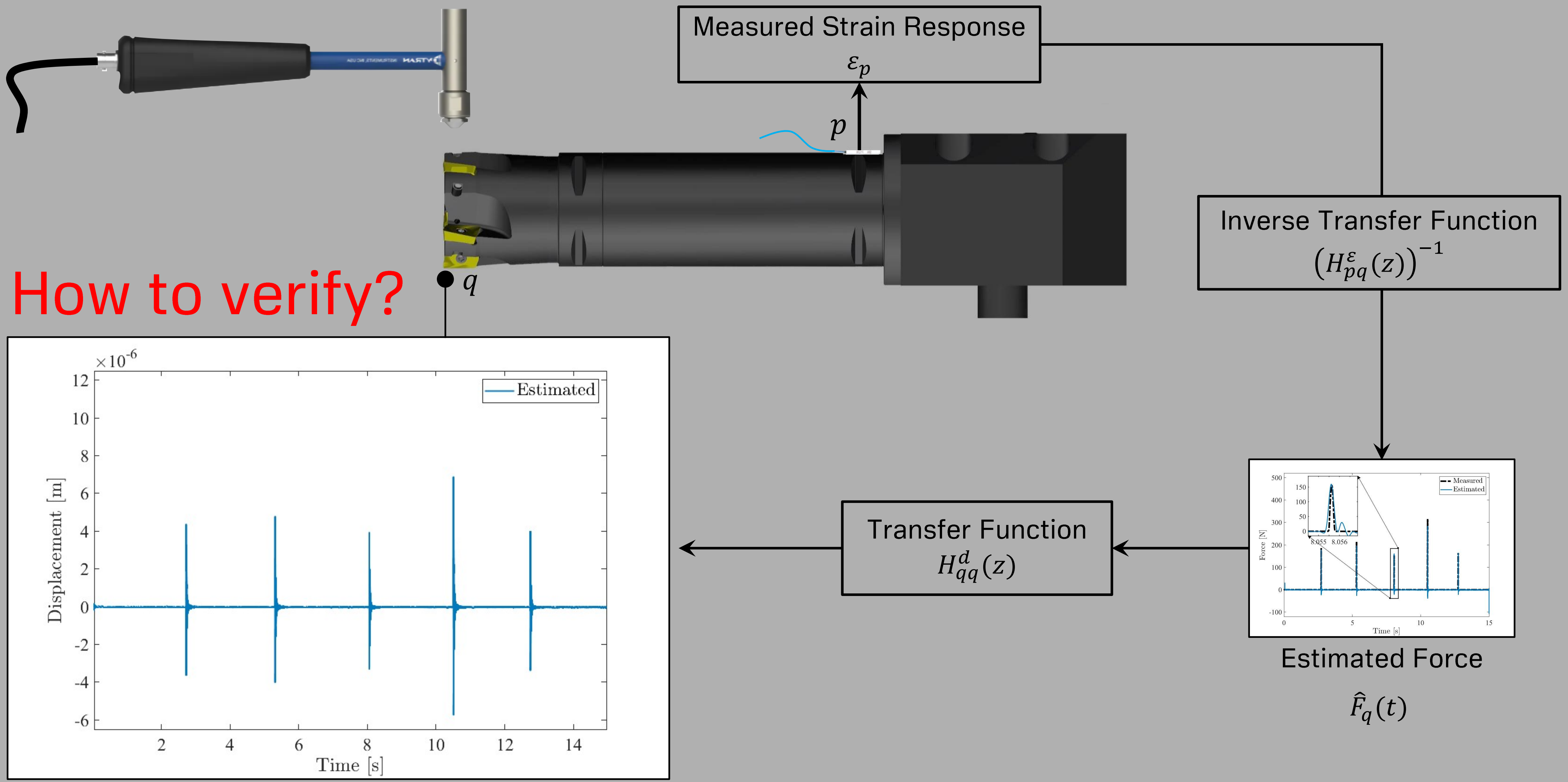
https://www.pcb.com/sensors-for-test-measurement/strain-sensors/reusable-icp

https://news.thomasnet.com/fullstory/miniature-accelerometer-weighs-0-2-g-820051

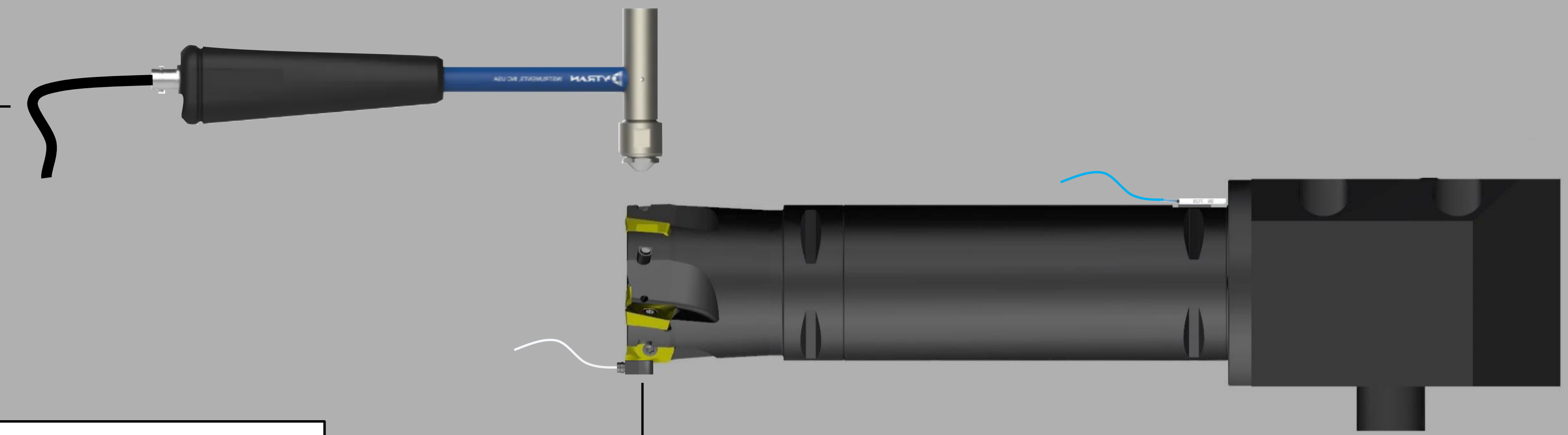
Estimating Input Force via Inverse TF



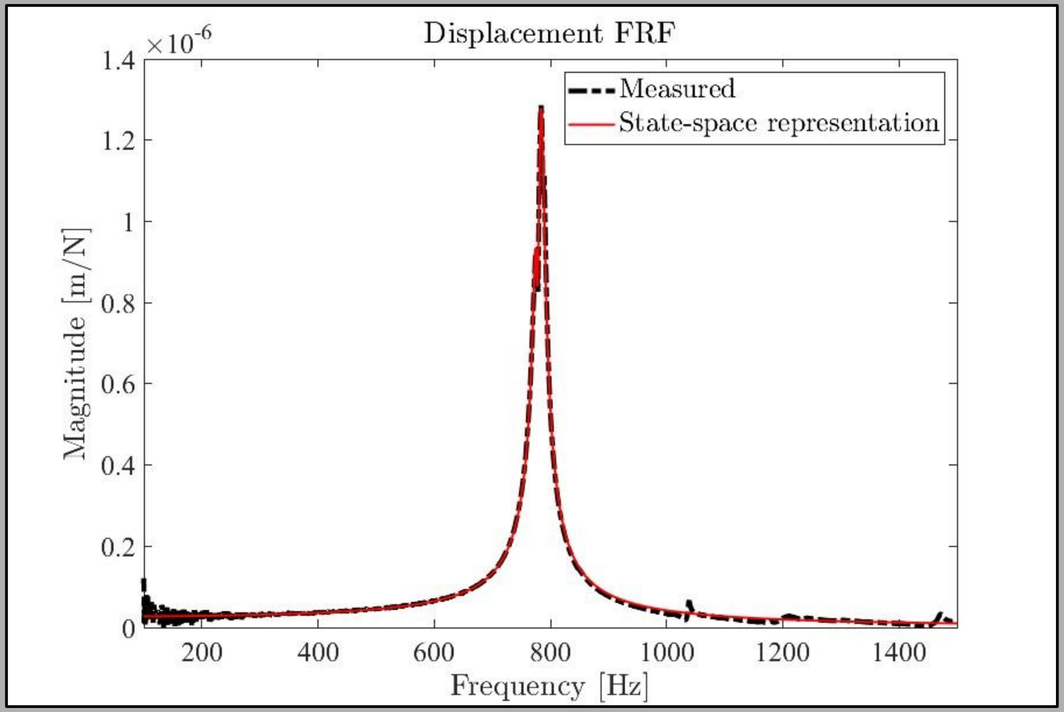
Estimating tool-tip displacement



Validate displacement estimation

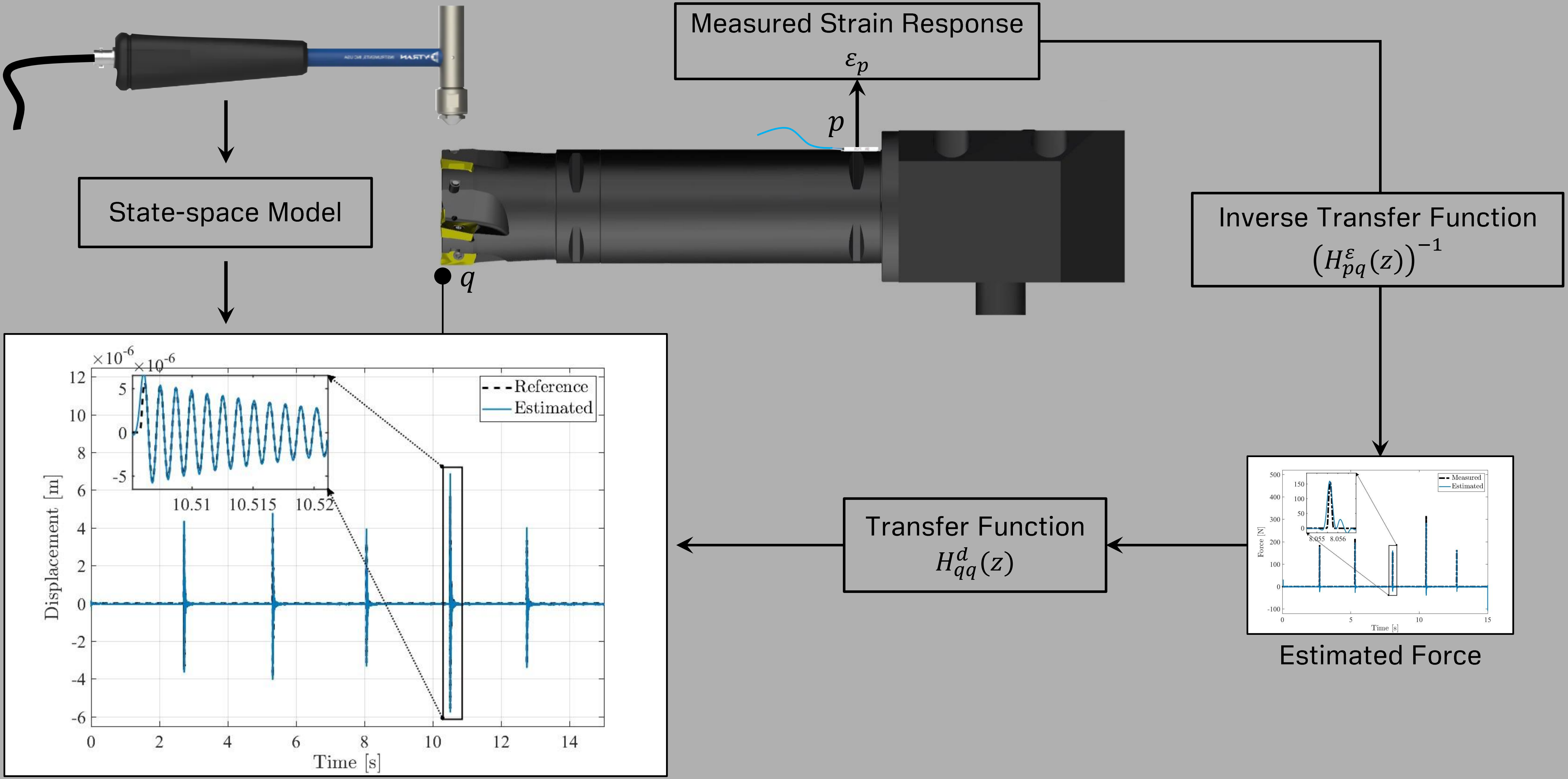


Accelerometer



Using measured FRF to fit State-space model by MATLAB's System Identification Toolbox

Result of Estimating tool-tip displacement



Discussion

Publications	RQ 1	RQ 2	RQ 3
Paper I			
Paper II			
Paper III			

Fully addressed

Partially addressed

RQ 1: How can cutting force modeling enhance the interpretation of sensor data to distinguish the contributions of the cutting process and tool deterioration?

RQ 2: How can data from sensor-equipped cutting tools be used to accurately estimate dynamic loads and tool-tip deflection, while accounting for the dynamic effect of the transfer path between the tool tip and the sensor?

RQ 3: How can the integration of advanced modeling, signal processing techniques, and sensor-equipped cutting tools improve data quality, enhance measurement accuracy, and enable more precise real-time monitoring of machining conditions?

Conclusion

✓ Developed a cutting force model that includes tool wear
→ Enabling accurate force prediction and wear monitoring

✓ Proposed a strain-force transfer model
→ Combined with inverse filtering to correct for dynamic distortion

✓ Validated all models through controlled lab tests
→ Demonstrated strong agreement with experimental results

✓ Proved the concept of integrating modeling, sensing, and filtering
→ Sets foundation for future sensor-equipped tool applications

Future Work

- Extend models and methods
  → Include more degrees of freedom

- Test under real machining conditions
  → Use sensor-equipped prototype tools
  → Compare with high-grade reference sensors

- Enhance data quality from the prototype tool
  → Apply proper signal processing techniques
  → Meet accuracy needs for estimation and real-time monitoring

Thank you!

Publications

Licentiate Thesis (Kappa):

Wu, P. (2025). Enhanced Measurement and Prediction in Sensor-Equipped Metal Cutting Tools : A Model Based Approach for Force Estimation and Tool Wear Monitoring (Licentiate dissertation, Blekinge Tekniska Högskola). Retrieved from https://urn.kb.se/resolve?urn=urn:nbn:se:bth-27624

Paper I:

Wu, P., Liljerehn, A., Magnevall, M., & Östling, D. (2025). A prediction of cutting forces using extended Kienzle-Sağlam force model incorporating tool flank wear progression. Machining Science and Technology, 1–17. https://doi.org/10.1080/10910344.2025.2473572

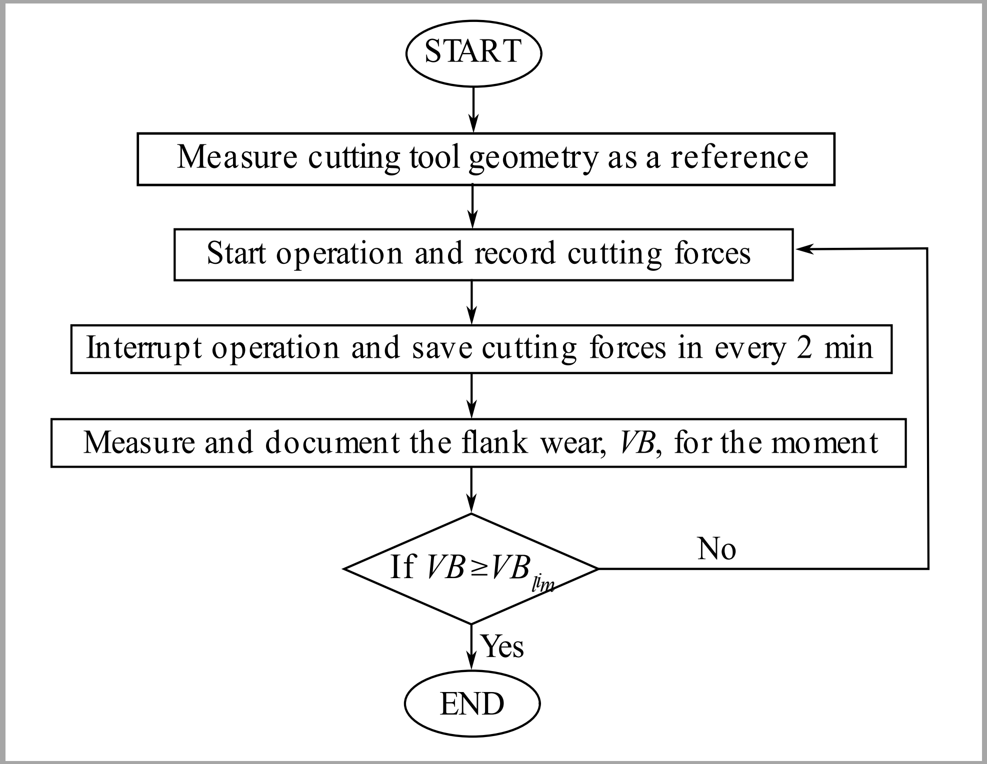
Paper II:

P. Wu, M. Magnevall, A. Liljerehn, and D. Östling, 'Cutting force estimation in metal cutting tools: a study on a sensor-equipped cantilever beam', in Proceedings of ISMA 2024 - International Conference on Noise and Vibration Engineering and USD 2024 - International Conference on Uncertainty in Structural Dynamics, 2024, pp. 1445–1456.

Paper III:

P. Wu, A. Liljerehn, M. Magnevall, D. Östling, Cutting force estimation in sensor-equipped metal cutting tools using strain-force transfer function. Presented at IMAC-XLIII, Conference on Structural Dynamics, Orlando, USA, 2025

Dataset Generation



Experimental Data for Force Model

$$\begin{bmatrix} F_t(1,1,n) & F_t(1,2,n) & F_t(1,3,n) & F_t(1,4,n) \\ F_t(2,1,n) & F_t(2,2,n) & F_t(2,3,n) & F_t(2,4,n) \\ F_t(3,1,n) & F_t(3,2,n) & F_t(3,3,n) & F_t(3,4,n) \\ F_t(4,1,n) & F_t(4,2,n) & F_t(4,3,n) & F_t(4,4,n) \end{bmatrix}$$

VB

$$\begin{bmatrix} F_t(1,1,\dots) & F_t(1,2,\dots) & F_t(1,3,\dots) & F_t(1,4,\dots) \\ F_t(2,1,\dots) & F_t(2,2,\dots) & F_t(2,3,\dots) & F_t(2,4,\dots) \\ F_t(3,1,\dots) & F_t(3,2,\dots) & F_t(3,3,\dots) & F_t(3,4,\dots) \\ F_t(4,1,\dots) & F_t(4,2,\dots) & F_t(4,3,\dots) & F_t(4,4,\dots) \end{bmatrix}$$

$$\begin{bmatrix} F_t(1,1,2) & F_t(1,2,2) & F_t(1,3,2) & F_t(1,4,2) \\ & & & (2,4,2) \\ & & & (3,4,2) \\ & & & (4,4,2) \end{bmatrix}$$

$$\begin{bmatrix} F_t(1,1,1) & F_t(1,2,1) & F_t(1,3,1) & F_t(1,4,1) \\ F_t(2,1,1) & F_t(2,2,1) & F_t(2,3,1) & F_t(2,4,1) \\ F_t(3,1,1) & F_t(3,2,1) & F_t(3,3,1) & F_t(3,4,1) \\ F_t(4,1,1) & F_t(4,2,1) & F_t(4,3,1) & F_t(4,4,1) \end{bmatrix}$$

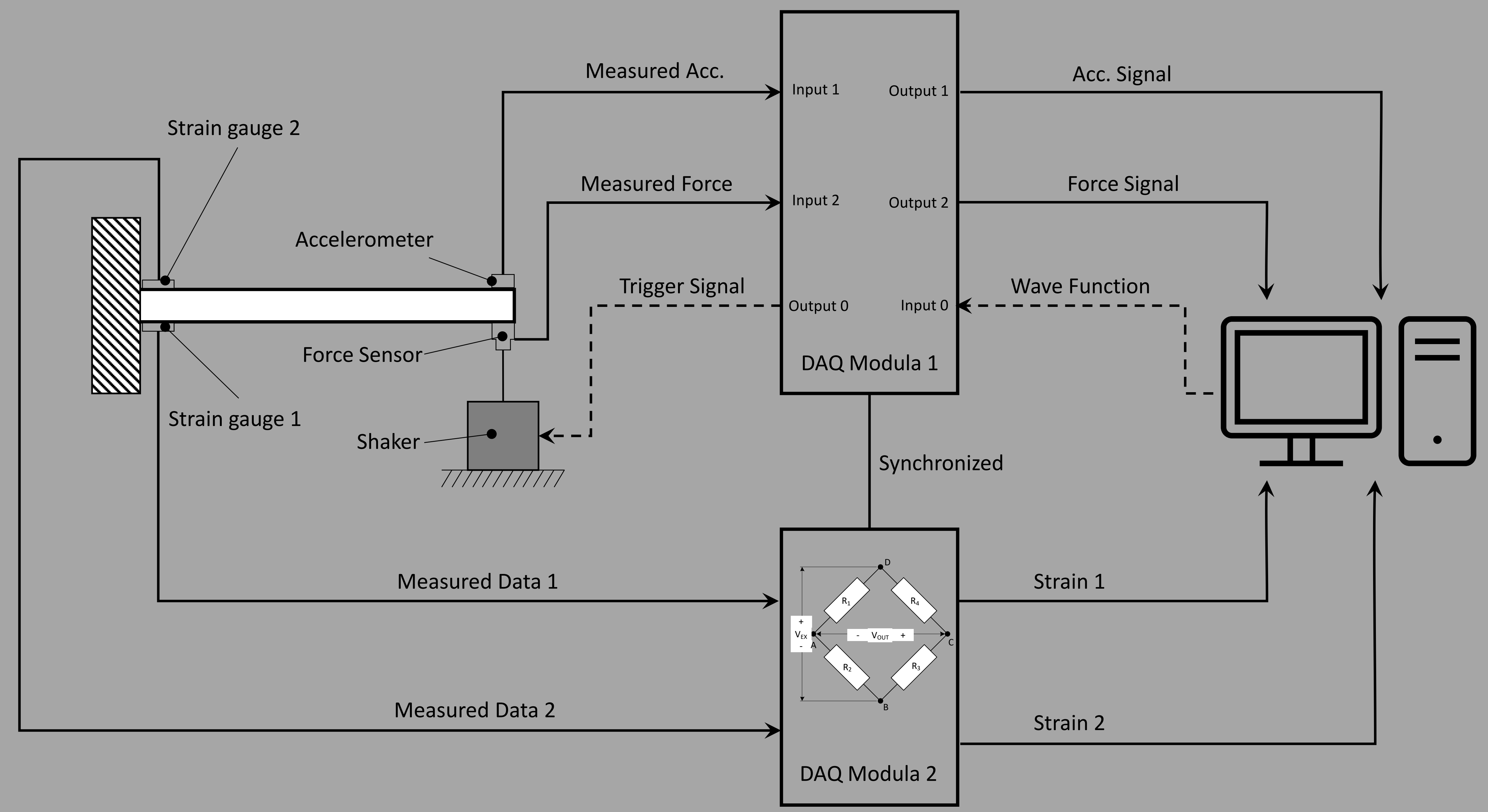
$\{\gamma\}$

$\{f_n\}$

$$\{\gamma\}_i = \{-10°, 0°, 5°, 10°\}$$

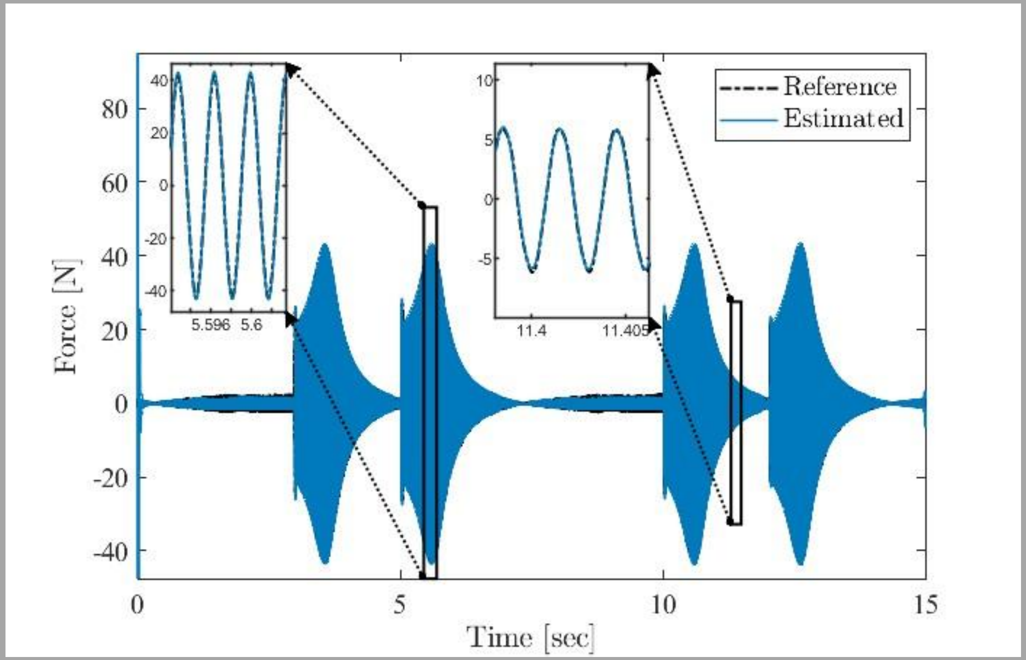
$$\{f_n\}_j = \{0.05, 0.1, 0.2, 0.3\} \text{ [mm/rev]}$$

$$\{VB\}_{ij} = \{0, VB_1, VB_2, \dots, VB_n\}$$

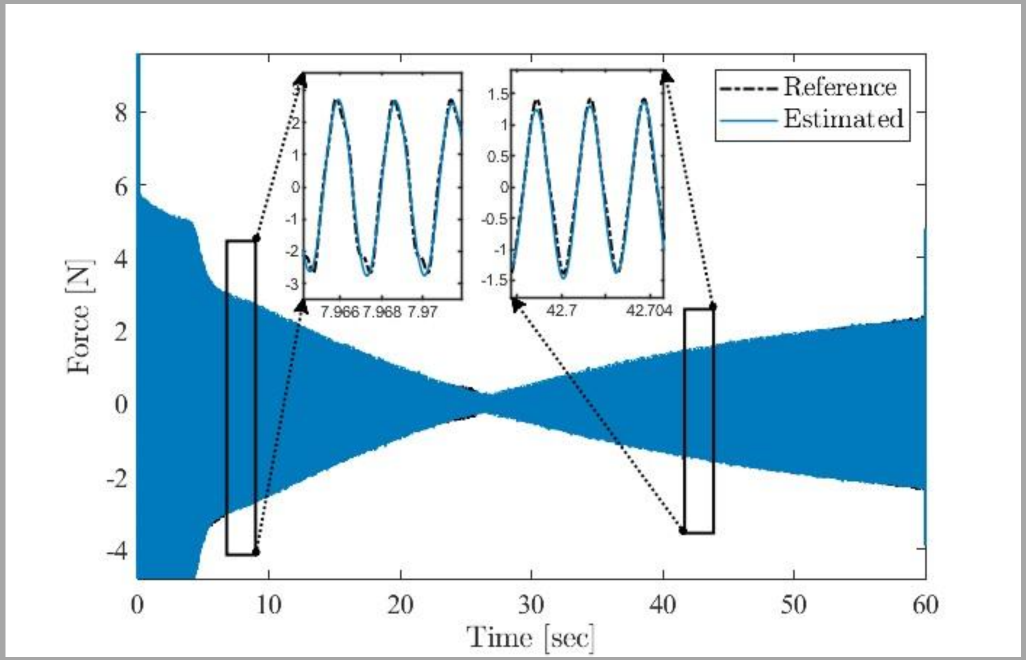


Measured Acc.
Input 1
Output 1
Acc. Signal
Strain gauge 2
Measured Force
Input 2
Output 2
Force Signal
Accelerometer
Trigger Signal
Output 0
Input 0
Wave Function
Force Sensor
DAQ Modula 1
Strain gauge 1
Shaker
Synchronized
D
R1
R4
Measured Data 1
Strain 1
VEX
VOUT
A
C
R2
R3
B
Measured Data 2
Strain 2
DAQ Modula 2

Estimating the input force via the inverse strain-force transfer function



Quick sine sweeps ×4 (250 to 550Hz)



Slow sine sweep (350 to 450Hz)