Extracting periodic patterns in steel

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AI-ROT

- Research project funded by Academy of Finland
- Aims to improve product lines with focus on rotating components
- Investigates new methods for machine direction analysis
- Industrial partner SSAB

Steel strip production process

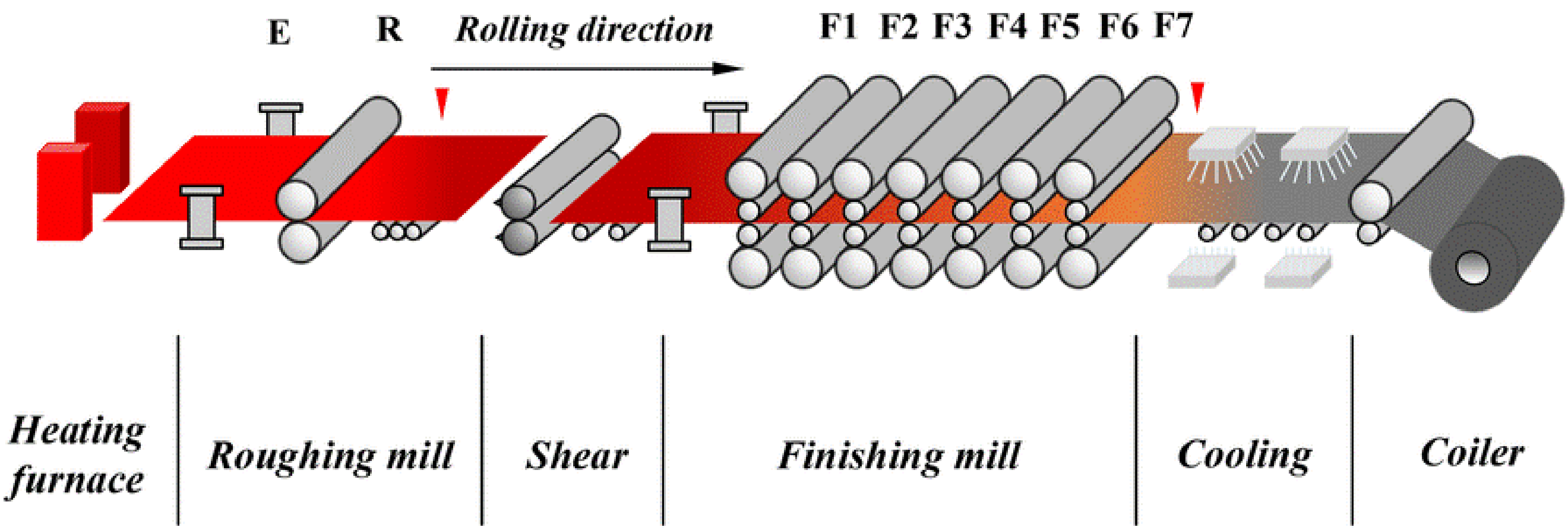
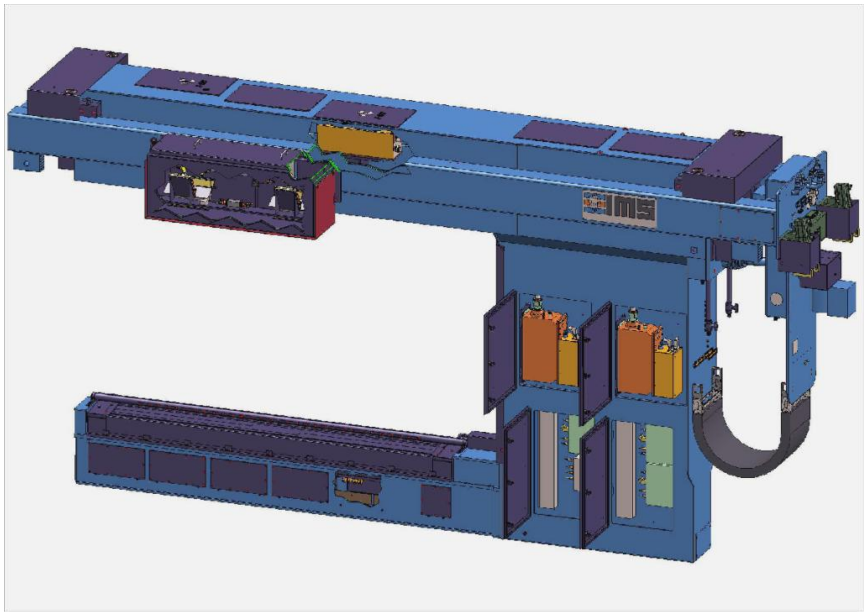


Image: Song, L., Xu, D., Wang, X. *et al.* Application of machine learning to predict and diagnose for hot-rolled strip crown. *Int J Adv Manuf Technol* **120**, 881–890 (2022). https://doi.org/10.1007/s00170-022-08825-w

Online measurement of steel strips

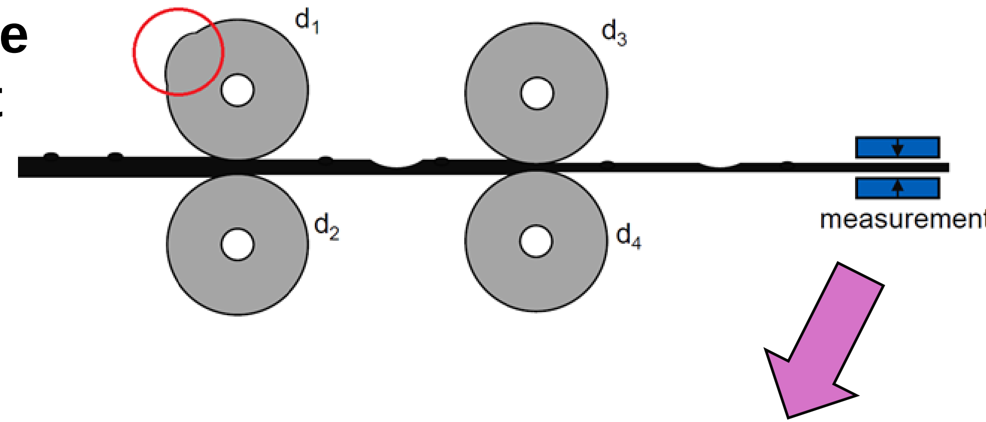


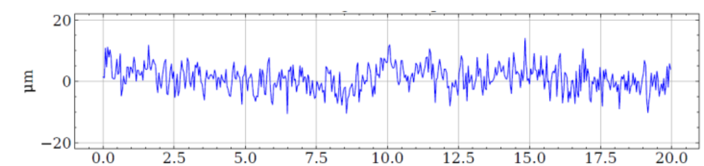
Some quality parameters:

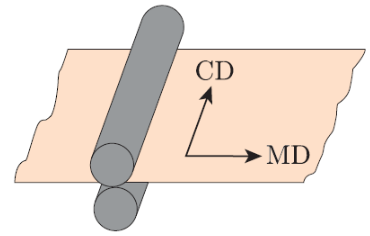
- **Centerline thickness**
- Cross profile measurement
- Crown and wedge
- Edge-drop
- Strip width
- Strip contour
- Strip temperature cross profile

Machine direction analysis

- **Rotating machine elements cause imperfections in the end product corresponding to their rotating speeds:**
  - **Roundness errors of rolls**
  - **Unbalance**
  - **Vibrations**
- **Obtain machine direction data with online system or laboratory analyzer**
- **Rotating speeds of components are known, repeating patterns can be separated**







Modeling the thickness variation from single roll with sinusoids

Stationary: $$x(n) = \sum_{l=1}^{L} A_l e^{jl\omega n}$$

Varying amplitude: $$x(n) = \sum_{l=1}^{L} A_l(n) e^{jl\omega n}$$

Varying frequency: $$x(n) = \sum_{l=1}^{L} A_l e^{jl\varphi(n)}, \quad \varphi(n) = \varphi(0) + \int_0^n \omega(\tau) d\tau$$

Proposed procedure for extracting the patterns

1. Estimate the frequency curve for each roll assuming constant amplitude-varying frequency model
2. Estimate the varying amplitudes during the rolling process using result from step 1
3. Resample and synchronize the patterns to angular domain

Frequency profile estimation with nonlinear least squares (NLS)

- The line speed in the end is known
- Assumpion that all rolls are rotating at speed proportional to the line speed
- Maximizing the NLS cost-function yields the relationship term

$$\mathbf{Z}_L(k) = \begin{bmatrix} e^{ik\varphi(0)} & e^{ik2\varphi(0)} & \cdots & e^{ikL\varphi(0)} \\ e^{ik\varphi(1)} & e^{ik2\varphi(1)} & \cdots & e^{ikL\varphi(1)} \\ \vdots & \vdots & \ddots & \vdots \\ e^{ik\varphi(N-1)} & e^{ik2\varphi(N-1)} & \cdots & e^{ikL\varphi(N-1)} \end{bmatrix}$$

$$\varphi(t) = \varphi(0) + \int_0^t \omega(\tau)d\tau$$

$$J_L(k) = \mathbf{x}^T\mathbf{Z}_L(k)[\mathbf{Z}_L^T(k)\mathbf{Z}_L(k)]^{-1}\mathbf{Z}_L(k)^T\mathbf{x}$$

$$\hat{k} = \arg\max_k J_L(k)$$

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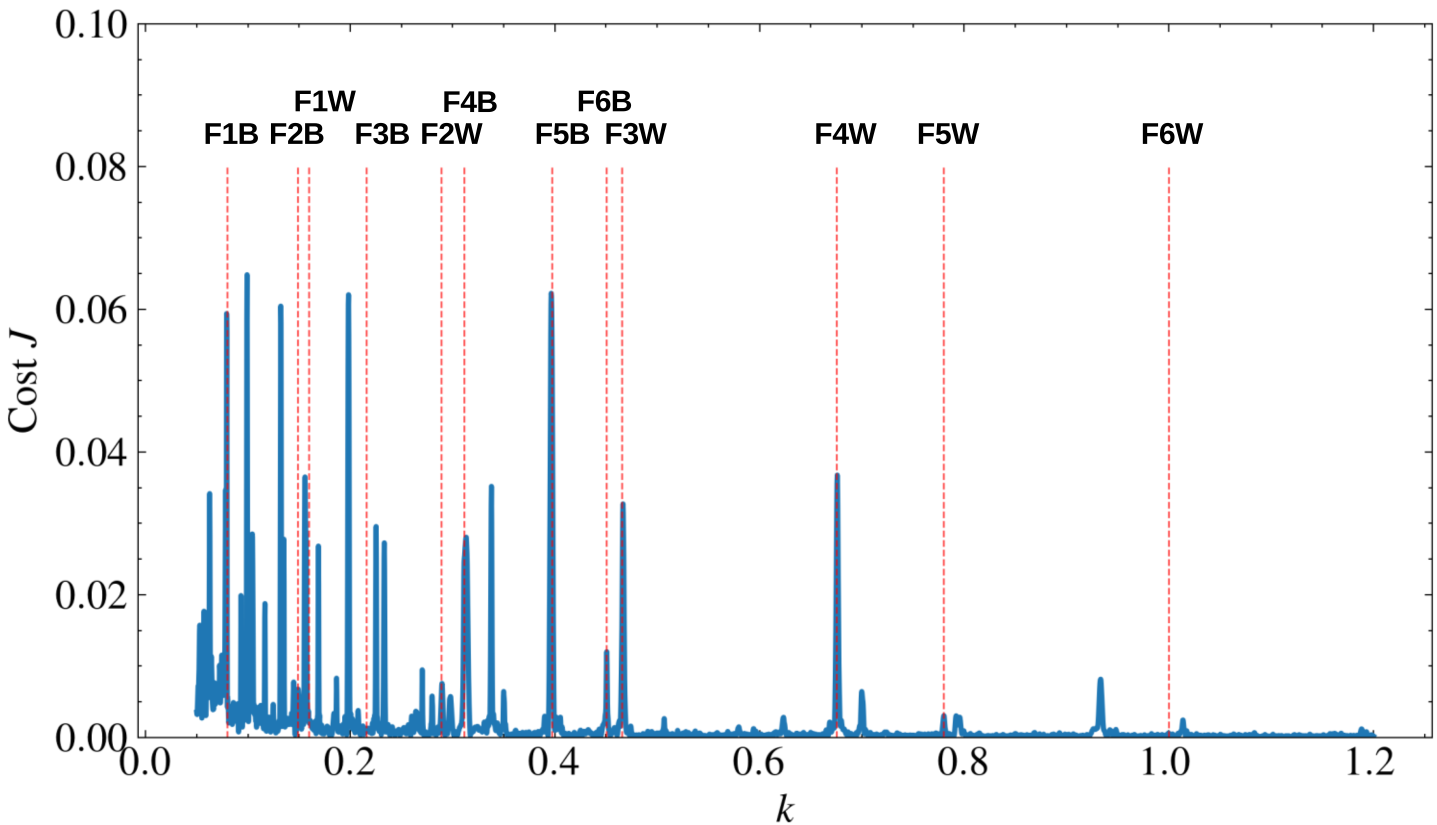
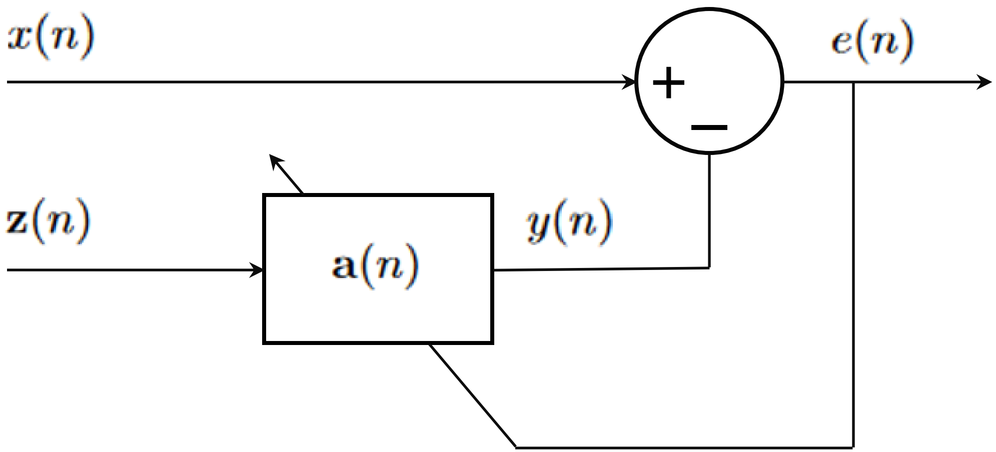
NLS spectrum for one strip

Each red line represents either work or backup roll in the finishing mill



Amplitude estimation with LMS adaptive algorithm



Design vector: $\mathbf{z}(n) = [e^{i\hat{k}\varphi(n)}\ e^{-i\hat{k}\varphi(n)}\ e^{i2\hat{k}\varphi(n)}\ e^{-i2\hat{k}\varphi(n)} \ldots e^{iL\hat{k}\varphi(n)}\ e^{-iL\hat{k}\varphi(n)}]$

Estimated roll pattern: $y(n) = \mathbf{a}(n)^{\mathrm{H}}\mathbf{z}(n)$

Error signal: $e(n) = x(n) - y(n)$

Update amplitudes and phases: $\mathbf{a}(n+1) = \mathbf{a}(n) + \mu e(n)\mathbf{z}(n)$

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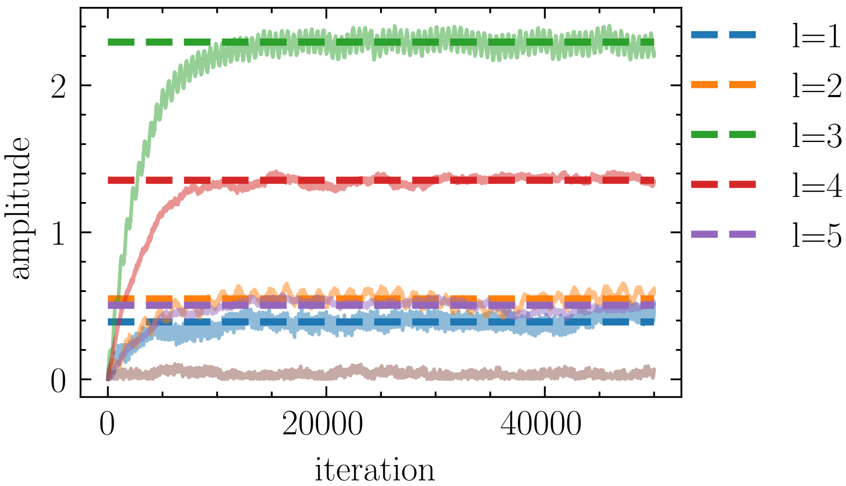
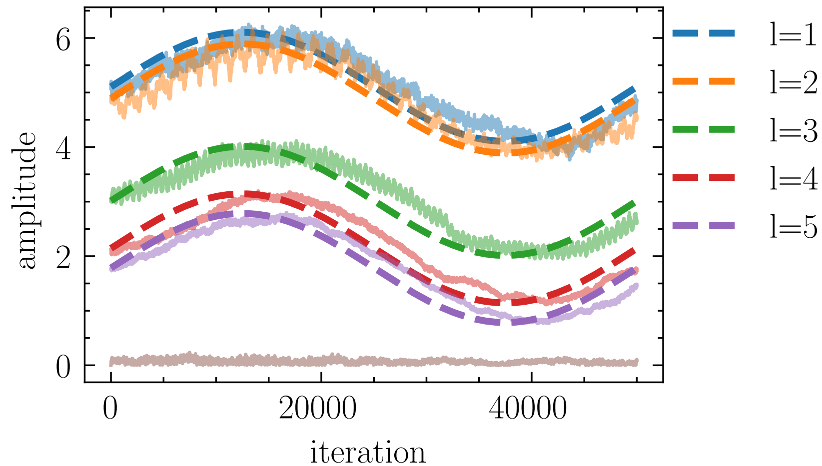
Amplitude estimation for simulated signal





Conclusion and future research

- NLS can be used to refine the estimated frequency profile
- Estimating the amplitudes and phases of the rolls using the LMS algorithm
- Extracting average patterns for the rolls using real data
- Quantifying the contributions of each roll to propose scheme for intelligent service scheduling based on development of individual roll patterns

Thank You

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