Classification and Key Feature Extraction for Equipment Health Monitoring in Plasma Etching

GMM Fachgruppe 1.2.3. – Abscheide- und Ätzverfahren

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Outline

I. Motivation
II. Classification of curve shapes
III. Key feature extraction
IV. Application examples
V. Further steps for EHF calculation
VI. Conclusion
I. Motivation

**Definition**: Equipment health factor

- Key indicator for monitoring of equipment state
- Based on process/tool, logistic and metrology data
- Utilization of historical data for training of EHF system

**Related key words**

- Equipment health monitoring
- Equipment fingerprinting
- Health index
- EHF
Goal of the EHF application is to enable…

- **Dynamic Sampling**
  Sampling rate is flexible and adjusted to the machine state.

- **Material flow of critical products**
  The production of critical products (important customers lots, urgent jobs, etc.) is planned only on machines which have a good system state.

- **Predictive Maintenance (PdM) based on condition monitoring**
  The PdM offers cost savings over time-based preventive maintenance, because maintenance actions are performed only when necessary.
Instance for EHF application

- Good machine state – EHF is high
  - Lower lot sampling rate, important lots will preferably be scheduled to run on this machine

- Machine state not ideal – EHF decreases
  - More frequent lot sampling, important lots might be scheduled to run on another tool

- “bad” machine state – EHF drops below certain limit
  - Schedule maintenance
Related work

- Utilization of sensors for simple measurement of wear
- Detection of failures based on key indicators
- Usually only implemented for specific failure classes
- No general method for detection of unknown failures

Our objective:

- Improved preprocessing method to find unknown failures
- Use of various feature extraction methods dependent on curve shape
- Generic concept transferable to other processes
Our approach for EHM

- Process variable (time series)

- Classification of curve shape:
  - Oscillating behavior
  - Piecewise-constant
  - Spike behavior
  - Smooth behavior

- Scalar key values for EHF calculation
  - Outlier

- Feature extraction method
  - e.g. regression coefficients
II. Classification

- Process variable (time series)
- Classification of curve shape:
  - Oscillating behavior
  - Piecewise-constant
  - Spike behavior
  - Smooth behavior
- Scalar key values for EHF calculation
- Feature extraction method:
  - e.g. regression coefficients
Defined variable types

- **Oscillating behavior**: trajectories with periodical variation around a central value
- **Piecewise-constant**: rectangular shaped pulses
- **Spike behavior**: most data points are close to zero with occasional peaks
- **Smooth behavior**: data with little change in their point to point value, the derivation showing only small differences in the gradient

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Oscillating behavior

![Oscillating behavior](example_image1.png)

E.g. chamber temperature

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Piecewise-constant

![Piecewise-constant](example_image2.png)

E.g. gas flows

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Spike behavior

![Spike behavior](example_image3.png)

E.g. reflected RF power

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Smooth behavior

![Smooth behavior](example_image4.png)

E.g. ESC temperature values
Classification through cubic Support Vector Machine

- Create a training data set containing assignment of variable types
- Cubic support vector machine (SVM) was used
- As predictors were chosen:
  - Kurtosis
  - Crest factor
  - Mean difference of normalized derivation
  - Standard deviation of normalized time series
  - Standard deviation of normalized derivation
  - Logical factor for invariant time series (1 for invariant behavior and 0 for other behavior)
III. Feature Extraction

- Process variable (time series)
- Classification of curve shape
  - Oscillating behavior
  - Piecewise-constant behavior
  - Spike behavior
  - Smooth behavior
- Scalar key values for EHF calculation
- Feature extraction method
  - e.g., regression coefficients
Types of feature extraction

- **Simple key features**
  - Mean, median, standard deviation and range

- **Structural features**
  - Descriptive statistics of trajectories

- **Dynamic time warping**
  - Euclidean-distance-based similarity measurement technique

- **Frequency and time-frequency analysis**
  - Analysis in frequency domain instead time domain

- **Statistical analytical methods**
  - e.g. regression coefficients or residual analysis
Issues with preprocessing using simple key features

- Over-/undershooting controllers and length of a signal can have big impact on simple key values
- Potential impact of limited data sampling frequency on true transient behavior
- Measurements from etch processes are non-stationary due to:
  - Aging of the etcher after cleaning cycles as residue accumulates on the inside of the chamber
  - Difference in the incoming materials due to changes in upstream processes
  - Drift in process-monitoring sensors themselves
Example for simple key features

Correlation matrix:

<table>
<thead>
<tr>
<th></th>
<th>w1</th>
<th>w2</th>
<th>w3</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>w2</td>
<td>0.7871</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>w3</td>
<td>0.6831</td>
<td>0.9802</td>
<td>1</td>
</tr>
</tbody>
</table>

Sequence (3 succeeding wafers, same recipe)

Mean: 3884.7 \leftrightarrow 4207.8 \leftrightarrow 4106.9
Std: 6620.2 \leftrightarrow 8104.8 \leftrightarrow 7681.4
Range: 60769 \leftrightarrow 67255 \leftrightarrow 74902
## Potential feature extraction methods

<table>
<thead>
<tr>
<th>Oscillating behavior</th>
<th>Piecewise-constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Frequency analysis</td>
<td>• Structural features</td>
</tr>
<tr>
<td>• Time-frequency analysis</td>
<td>• Integration</td>
</tr>
<tr>
<td>• Coefficients from time series modeling</td>
<td>• Regression coefficients</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spike behavior</th>
<th>Smooth behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Peak detection</td>
<td>• Regression coefficients</td>
</tr>
<tr>
<td>• Structural features</td>
<td>• Residual analysis</td>
</tr>
<tr>
<td>• Integral value of peak</td>
<td>• Coefficients from time series modeling</td>
</tr>
</tbody>
</table>
Extracted features

**Oscillating behavior**
- Periodicity
- Trend
- Simple key features

**Piecewise-constant**
- Number of pulses
- Amount of Under-/Overshoots
- Maximum Overshoot
- Surface area of pulse

**Spike behavior**
- Number of peaks
- Peak width
- Surface area of peak
- Distance of peaks

**Smooth behavior**
- Wavelet-based correlation coefficient
- RMS of residuals
- Surface area
IV. Application example 1

**Temperature chiller**

\[ signal = \text{range} \times \sin(\text{periodicity} \times x) + \text{mean} \]

<table>
<thead>
<tr>
<th>Curve</th>
<th>Mean</th>
<th>Periodicity</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>9.4508</td>
<td>15.4763</td>
<td>1.9</td>
</tr>
<tr>
<td>Orange</td>
<td>9.4511</td>
<td>6.2733</td>
<td>0.1329</td>
</tr>
</tbody>
</table>
IV. Application example 2 (1/3)

Gas flow

Time [s]

[sccm]
IV. Application example 2 (2/3)  
Comparison of two gas flows

Desired trajectory

Faulty trajectory
IV. Application example 2 (3/3)

SPC-Chart: Surface Area

- Key feature values
- Outlier

Surface area

Wafer

+3σ
+2σ
-2σ
-3σ

\( \overline{x} \)
V. Further steps for EHF calculation

- Feature selection
  - Which features are important for EHF?
  - How to select them automatically?

- EHF Calculation
  - How to combine the relevant key features to a scalar value to express the system state?
VI. Conclusion

- A general method for detection of unknown failures was developed
- Generic concept transferable to other processes
- Application of various feature extraction methods dependent on curve shape
- Extracted key features can be used for EHF calculation or other technologies to improve models, e.g. PCA
- Desired benefit of EHF
  - Lower production costs
  - To support Predictive Maintenance
  - Maintaining high yield
Acknowledgment

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Thank you for listening!