Identification of Eigenmodes in Vibration Data

Christine Preisach, Krisztian Buza, Lars Schmidt-Thieme

Information Systems and Machine Learning Lab (ISMLL)

University of Hildesheim

Germany

Wye Houn Leong and Mark Walters

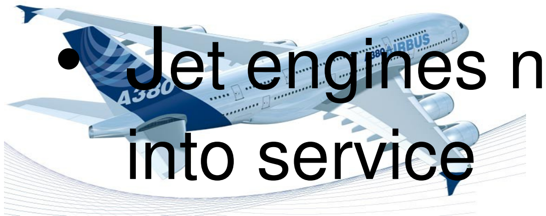
Rolls-Royce

UK

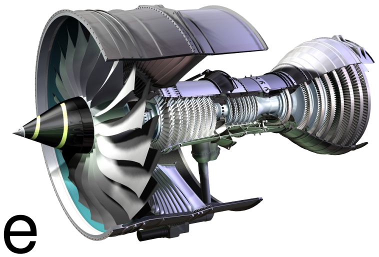
Outline

- Motivation
- Problem Description
- Eigenmode Identification with iterative Hough Transform using background knowledge
- Evaluation
- Conclusion

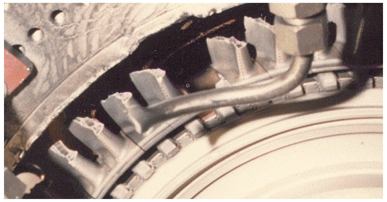
Motivation



- Jet engines need to be certified before going into service
- Components in jet engines are exposed to vibrations caused by unsteady forces (relative motions of rotating and non-rotating parts)



- These can cause high cycle fatigue (damage)



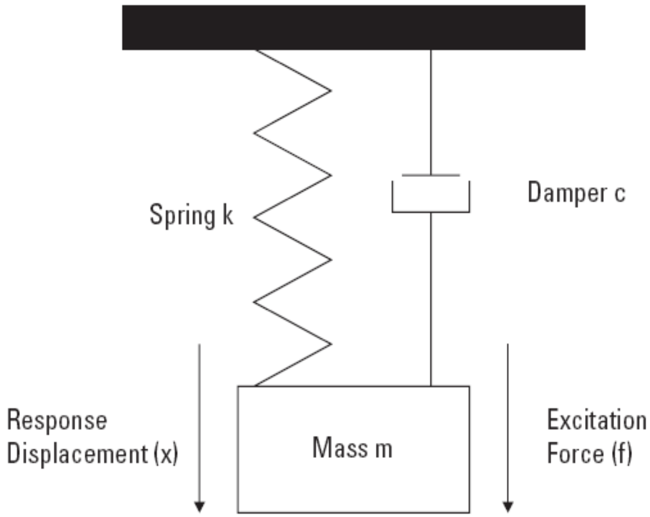
- Manual analysis of vibration data, i.e. detection of high stresses

→ **Support engineers in vibration analysis with Machine Learning**

Problem Description

- Vibration
  - Mechanical oscillation as a response of a system to an internal or external stimulus

$$m\ddot{x} + c\dot{x} + kx = f$$



Problem Description

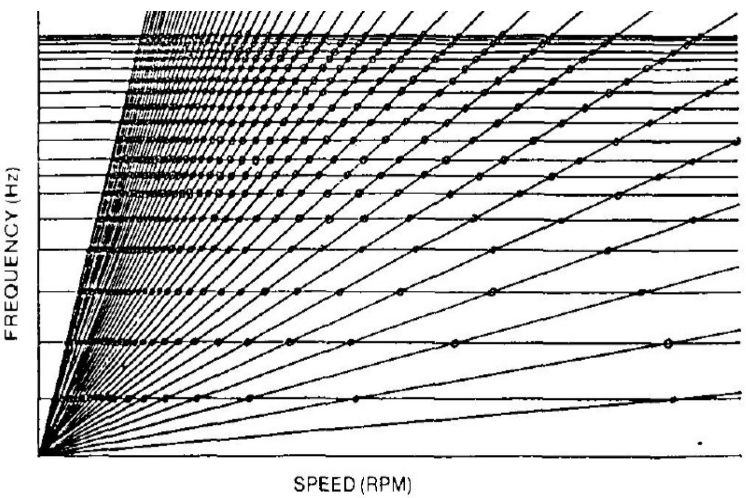
- Natural frequencies
  - Every component has a series of natural frequencies and associated modeshapes
  - These natural frequencies are called **Eigenmodes**
- Excitation frequencies/orders
  - Time-periodic excitation is caused by rotational motion, i.e. excitation frequency corresponds to a multiple of the rotation frequency

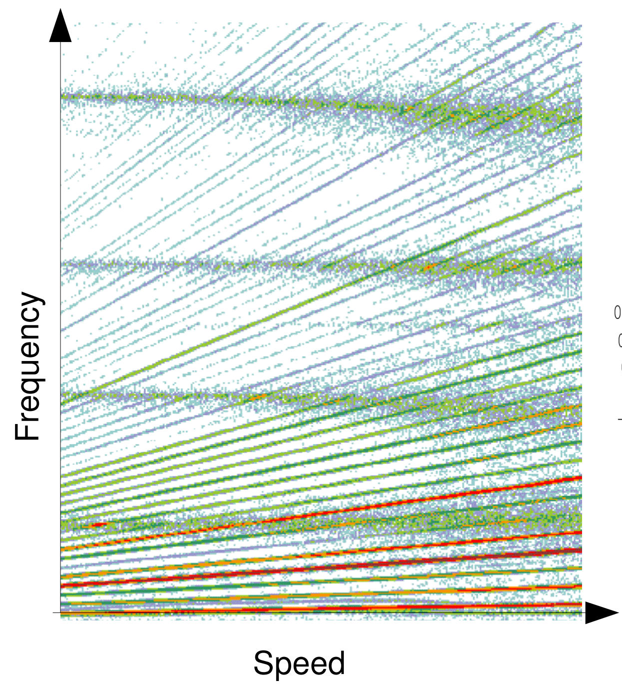
Problem Description

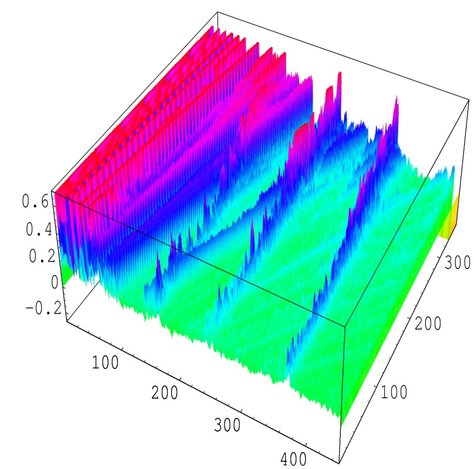
- Resonance
  - If the component is excited at the same frequency as the natural frequency, then it will resonate with a response many times greater than if excited at a non-natural frequency
  - High stresses (response with high amplitude) lead to high cycle fatigue (damage)

Problem Description

- Campbell Diagram





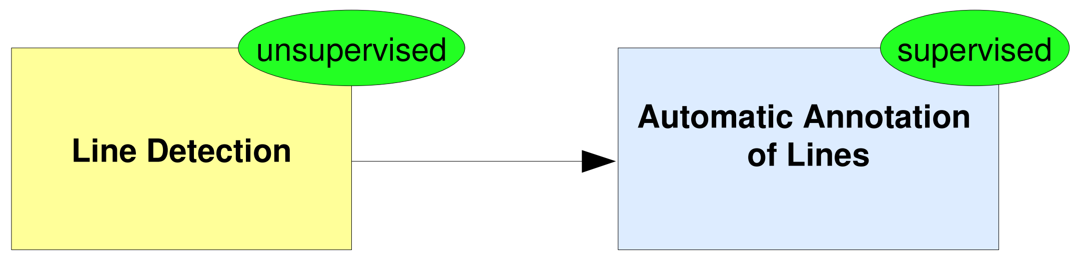


Problem Description

- Vibration Analysis
  - Lab measurements on blades (e.g. capture modeshape, eigenfrequencies)
  - Predict Eigenmodes from FEM
  - Test engine under running conditions
  - Analyze vibration and lab data
    - **Identify Eigenmodes**
    - Peak stress value extraction
    - Endurance calculation

Problem Description

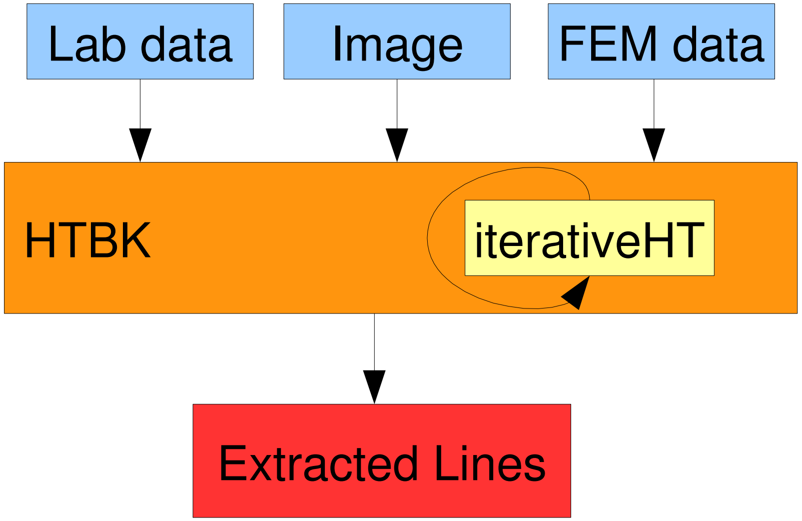
- Given:
  - Images I containing set of lines
  - Background knowledge
    - Lab data L_{lab}
    - FEM data L_{fem}



- Aim:
  - Detect lines $\hat{L}$ with high accuracy
  - Assign mode numbers to detected lines and reach at least quality of Lab and FE model

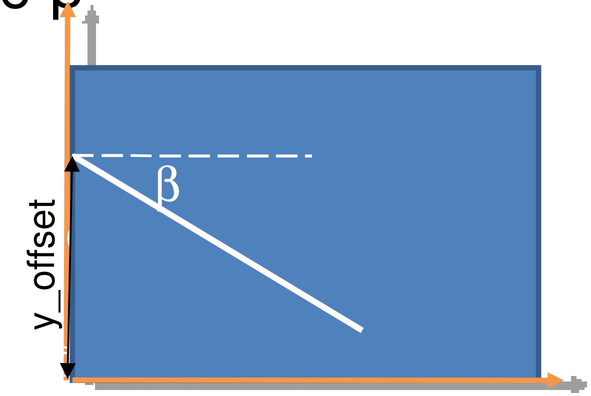
Identification of Eigenmodes

- Identification of Eigenmodes
  - Using Iterative Hough Transform
    - Incorporating background knowledge



Hough Transform

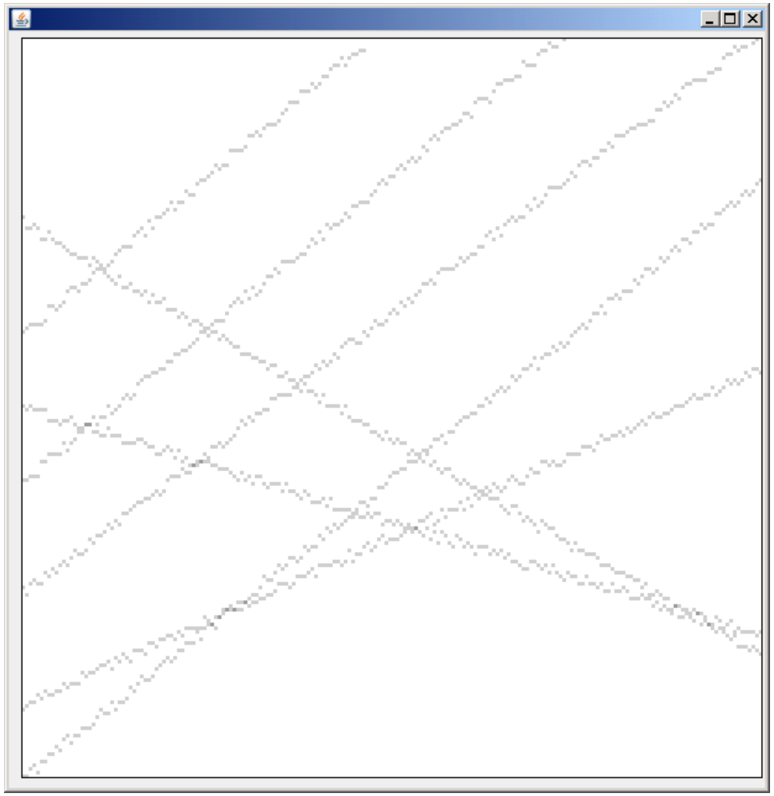
- Feature extraction technique used in image analysis [Hough1962,Duda1972]
- Applied for recognition of lines or other parameterizable shapes
- A line can be described by its *y-offset* and slope β
- Each pixel can belong to several lines

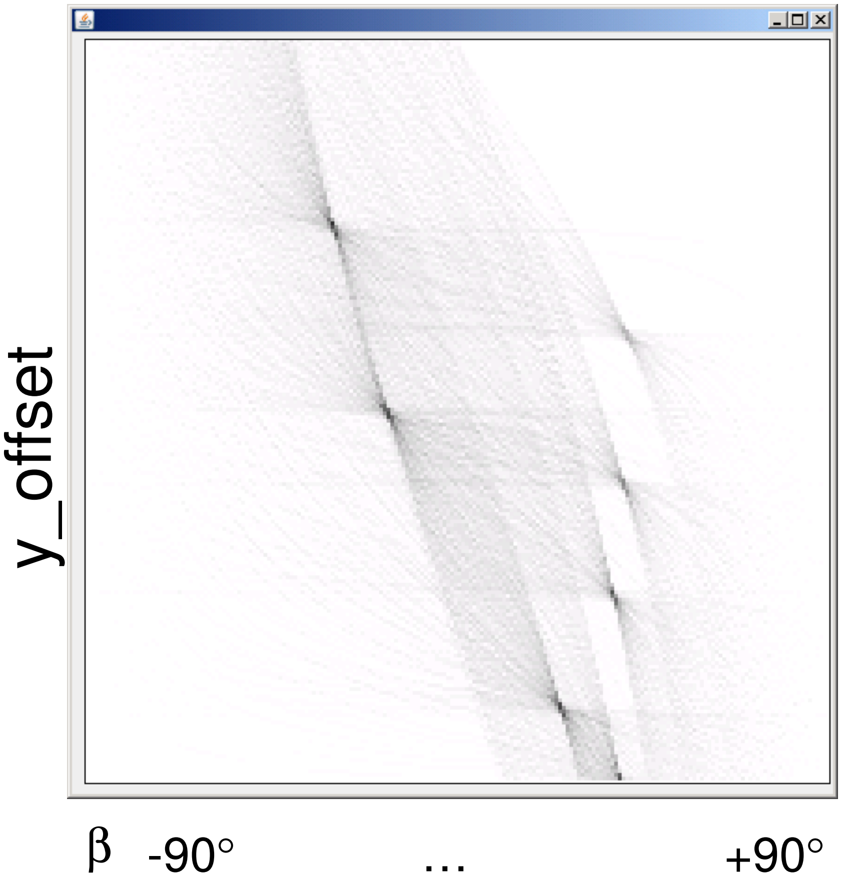


$\mathrm{HT}(i, \beta_{\min}, \beta_{\max})$:
foreach (x, y) $\in i$ do
  for $\beta = \beta_{\min} \ldots \beta_{\max}$ do
    $y_o = y - x * \tan(\beta)$
    $H[\beta][y_o] := H[\beta][y_o] + \mathrm{colval}(x, y)$
    $H[\beta][y_{o+1}] := H[\beta][y_{o+1}] + \lambda \cdot \mathrm{colval}(x, y)$
    $H[\beta][y_{o-1}] := H[\beta][y_{o-1}] + \lambda \cdot \mathrm{colval}(x, y)$
  od
od
return H

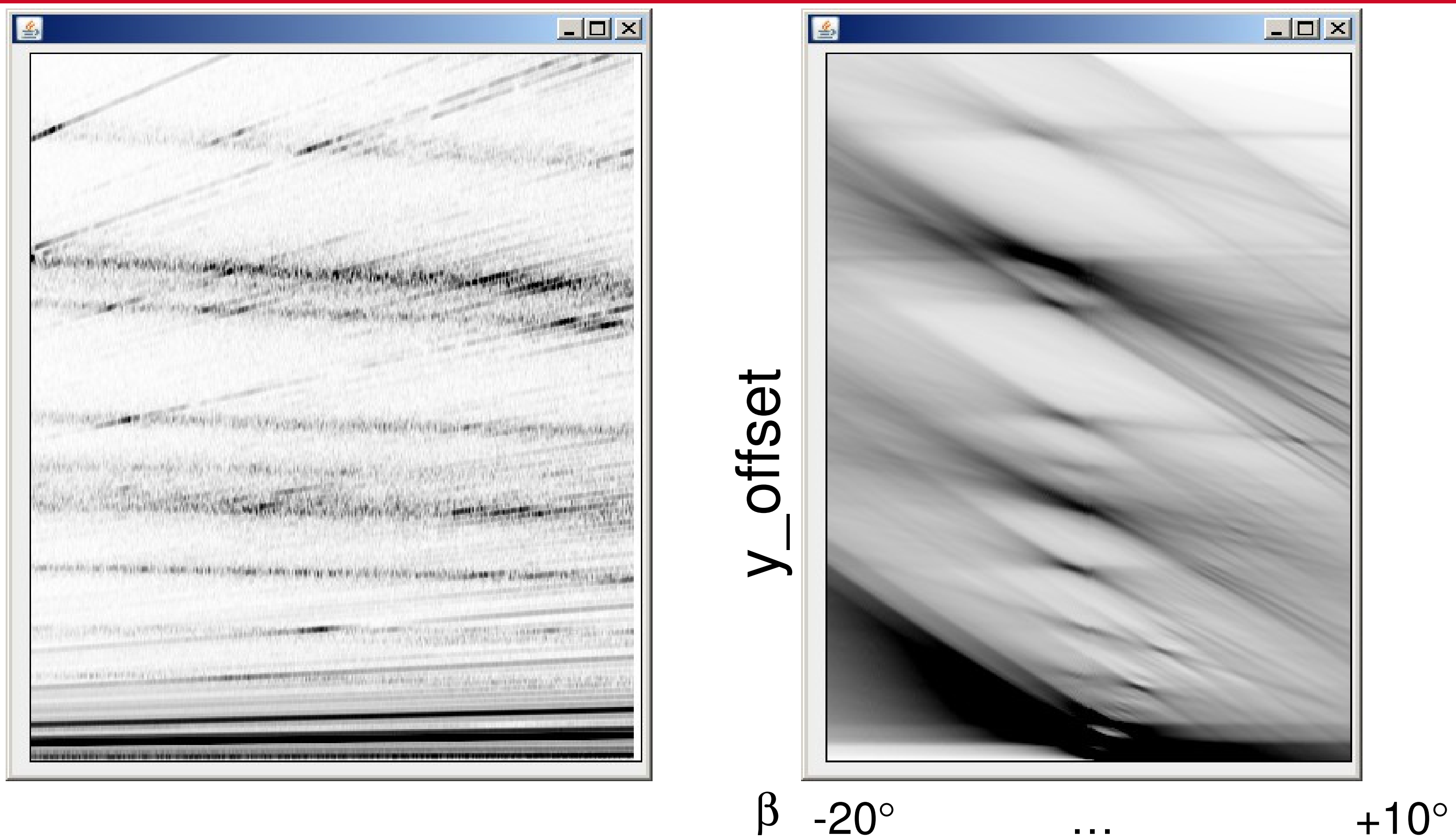
- The counters with highest values correspond to lines in the image

Hough Transform





Hough Transform with background knowledge

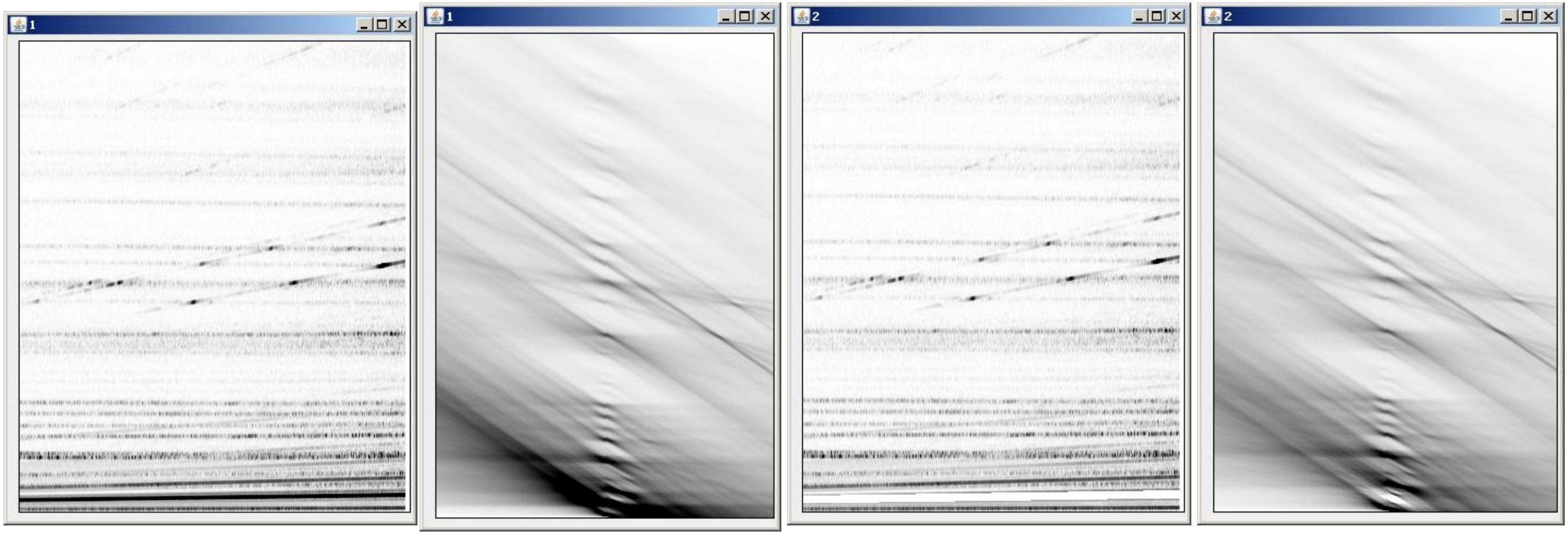


- EO lines could be confused with Eigenmodes
- Lines blurred and very close to each other

Hough Transform with background knowledge

$\text{iterativeHT}(i, K, w, \theta, \beta_{\min}, \beta_{\max})$:
$\hat{L} := \emptyset$
for $k =: 0 \ldots K$ do
$H = \text{HT}(i, \beta_{\min}, \beta_{\max})$
$\hat{\ell} = \text{argmax}_{(y_o,\beta)} H[\beta][y_o]$
if $\text{offset}(\hat{\ell}) > \theta$
$\hat{L} := \hat{L} \cup \{\hat{\ell}\}$
delete $\hat{\ell}$ from image i with width w
fi
od
return $\hat{L}$

Hough Transform with background knowledge



- Greedy forward line selection
- Removing strongest line from the original image

Hogh Transform with background knowledge

$\mathrm{HTBK}(I, L^{\mathrm{lab}}, L^{\mathrm{fem}}, K, d, \beta_{\mathrm{min}}, \beta_{\mathrm{max}})$:

$\hat{L} := \emptyset$

foreach i $\in$ I do

$\quad \hat{w} := \mathrm{estimateLineWidth}(L^{\mathrm{lab}_i}, L^{\mathrm{fem}_i})$

$\quad \hat{\theta} := \mathrm{estimateTheta}(L^{\mathrm{lab}_i}, L^{\mathrm{fem}_i})$

$\quad \hat{L}^i = \mathrm{iterativeHT}(i, K, \hat{w}, \hat{\theta}, \beta_{\mathrm{min}}, \beta_{\mathrm{max}})$

$\quad \hat{L} := \hat{L} \cup \hat{L}^i$

od

return $\hat{L}$

Hough Transform with Background Knowledge

$\text{estimateLineWidth}(L^{\text{lab}}, L^{\text{fem}})$:

$\hat{w}^{\text{lab}_{\min}} := \text{argmin}_{l^{\text{lab}} \in L^{\text{lab}}} \text{dist}(L^{\text{lab}})$

$\hat{w}^{\text{fem}_{\min}} := \text{argmin}_{l^{\text{fem}} \in L^{\text{fem}}} \text{dist}(L^{\text{fem}})$

$\hat{w} = \frac{3}{4} \cdot (\hat{w}^{\text{lab}_{\min}} + \hat{w}^{\text{fem}_{\min}})$

return $\hat{w}$

$\text{estimateTheta}(L^{\text{lab}}, L^{\text{fem}})$:

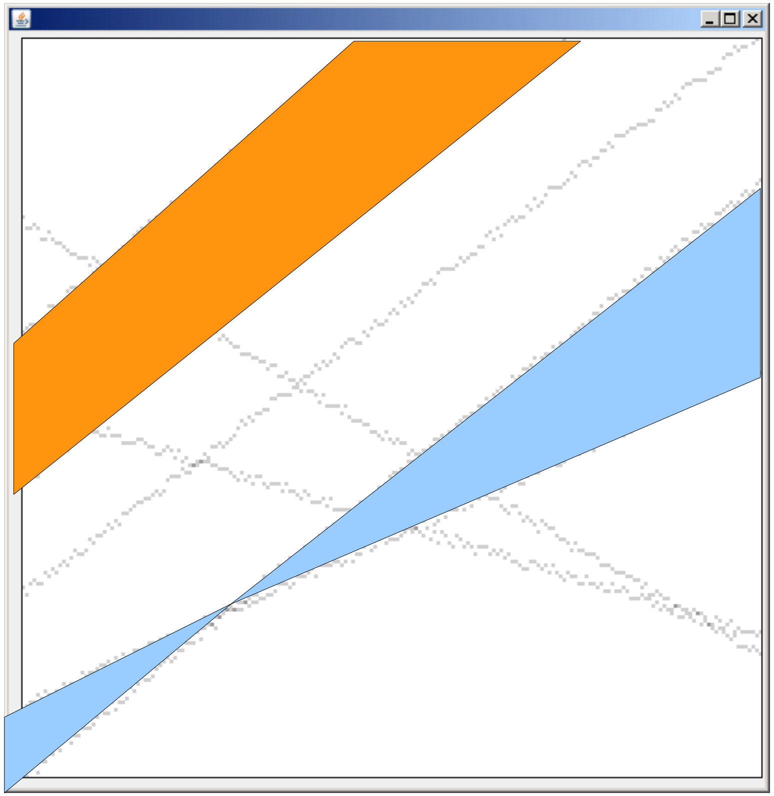
$\hat{\theta}^{\text{lab}_{\min}} := \text{argmin}_{l^{\text{lab}} \in L^{\text{lab}}} \text{offset}(L^{\text{lab}})$

$\hat{\theta}^{\text{fem}_{\min}} := \text{argmin}_{l^{\text{fem}} \in L^{\text{fem}}} \text{offset}(L^{\text{fem}})$

$\hat{\theta} = \frac{\text{avg}(\hat{\theta}^{\text{lab}_{\min}}, \hat{\theta}^{\text{fem}_{\min}})}{2}$

return $\hat{\theta}$

Evaluation Measure



$$RMSE = \sqrt{\frac{\sum_{i=1}^{|L|} \left| area(l_i - \hat{l}_i) \right|^2}{|L|}}$$

- Root Mean Squared Error of area between lines (annotated line and detected line)

Matching

- Assign Eigenmodes (mode number) to detected lines by matching
  - Priority matching
    - Match in the order of detection (line with highest Hough value first)
  - Greedy Best Fit
    - Match to lines where the between-line area is minimal
  - Local Search
    - Swap assignments if this minimizes the RMSE

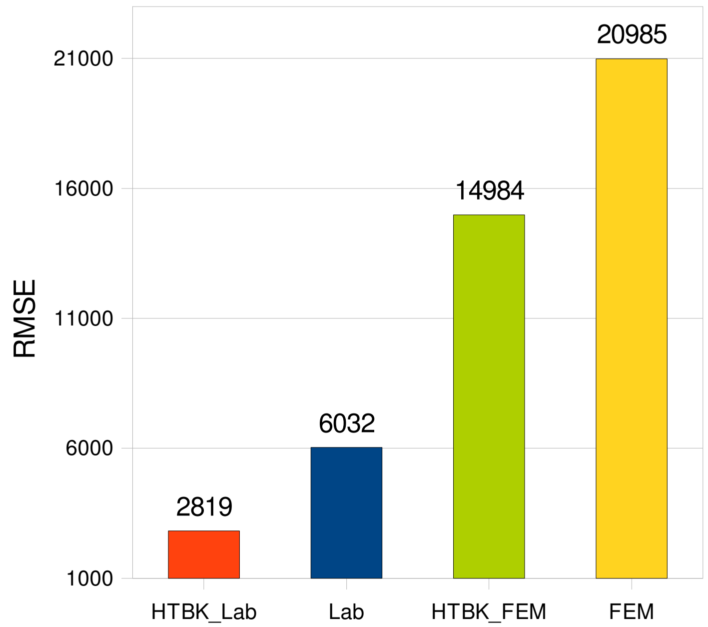
Evaluation

- Data
  - Real-life dataset from aerospace domain
  - 201 images (Campbell diagrams) from 14 vibration tests from 1 engine
  - 571 FEM lines
  - 271 lab lines

Evaluation

- Experiment Setting:
  - 3 Experiments
    - Evaluation of quality of detected lines
    - Evaluation of Mode number assignment by matching to the FEM
    - Evaluation of Mode number assignment by matching to the lab data
  - New lines are not considered in the evaluation

Evaluation Line Detection Quality

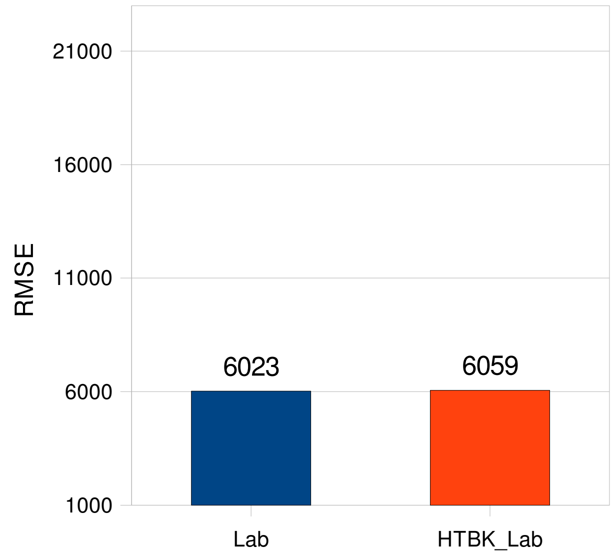


- Matching against annotation (only evaluation of line detection quality)
- Detecting lines with HTBK is very accurate
- K=30 lines extracted in each Campbell diagram

Evaluation – Matching against FEM

- Scenario: only FEM data
- 417 lines predicted
- Results achieved with Priority Matching, if no line was detected near a FEM line this has been added to the result
- Applying HT and matching the detected lines to FEM model improves results of FEM

Evaluation – Matching against Lab data



- Lab model has already very good quality but lab experiments are expensive and not done for all components
- Recall is lower than for the FEM (247 lines)
- Results achieved with Greedy Best Fit Matching, if no line was detected near a lab line it has been added to the result.
- Applying HT and matching against the lab model does not improve the lab model

Conclusion

- Introduced Iterative HT with background knowledge
  - Iterative HT allows to detected blurred lines
  - Background knowledge helps to distinguish between Eigenmodes and EO
- High detection accuracy
- FEM predictions can be improved by iterative hough transform with background knowledge
- In future work
  - Incorporate more background knowledge (e.g. sensitivity of sensors for specific Eigenmodes)
  - Use more sophisticated supervised machine learning mehtods for Eigenmode classification (assignment of mode numbers)

Thank you

Questions ?

www.ismll.uni-hildesheim.de

Christine Preisach

preisach@ismll.uni-hildesheim.de