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Output-only fault detection in structural engineering based on kernel PCA

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Presentation outline

1.1 Research context
1.2 Methodology
1.3 System identification method: Kernel PCA
1.4 Case study: three-span concrete bridge
1.5 Conclusions

Vibration-based structural health monitoring

– Modal characteristics depend on stiffness, mass, damping, and boundary conditions.

– SHM through continuous or repeated modal parameter estimation.







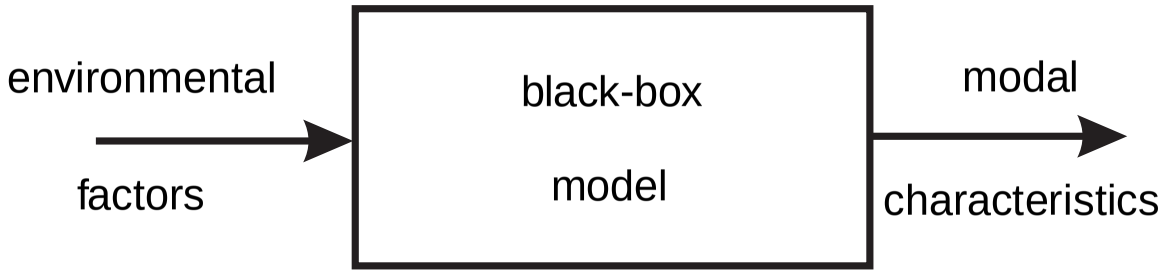




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Overview

– Modal characteristics are sensitive to environmental and operational variability.
  ↪ identify a model in undamaged condition and monitor misfit.



– Modeling options:
  → physical vs. black box.
  → input-output vs. output-only.
  → static vs. dynamic.
  → linear vs. non-linear.

– Model of the structure to be identified

$$\mathbf{\Phi}(\mathbf{y}_k) = \mathbf{H}_0 \mathbf{u}_k + \tilde{\mathbf{e}}_k.$$

Identifying a nonlinear environmental model with kernel PCA

– Model of the structure to be identified:

$$\mathbf{\Phi}(\mathbf{y}_k) = \mathbf{H}_0 \mathbf{u}_k + \tilde{\mathbf{e}}_k.$$

– Correlate the mapped *training* outputs.

$$\mathbf{\Lambda}_0 := \sum_{k=1}^{n_t} \frac{1}{n_t} \mathbf{\Phi}(\mathbf{y}_k)\mathbf{\Phi}^T(\mathbf{y}_k) = \begin{bmatrix} \mathbf{U}_1 & \mathbf{U}_2 \end{bmatrix} \begin{bmatrix} \mathbf{\Sigma}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{\Sigma}_2 \end{bmatrix} \begin{bmatrix} \mathbf{U}_1^T \\ \mathbf{U}_2^T \end{bmatrix}$$

– Assume misfit is small during training phase:

$$\mathbf{\Lambda}_0 \approx \mathbf{H}_0 \left(\sum_{k=1}^{n_t} \frac{1}{n_t} \mathbf{u}_k \mathbf{u}_k^T \right) \mathbf{H}_0^T = \mathbf{U}_1 \mathbf{\Sigma}_1 \mathbf{U}_1^T.$$

– For *all* outputs, compute the part of the misfit that is uncorrelated with the unknown environmental inputs:

$$\mathbf{e}_k = \mathbf{U}_2 \mathbf{U}_2^T \mathbf{\Phi}(\mathbf{y}_k), \qquad \forall k$$

– Remaining problems:

→ specification of the nonlinear mapping $\mathbf{\Phi}$.

→ specification of the appropriate input dimension n_u.

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Identifying a nonlinear environmental model with kernel PCA

– n_u determined as in standard PCA
  $\hookrightarrow$ explain $99\ \%$ of variability in nonlinearly mapped training data.

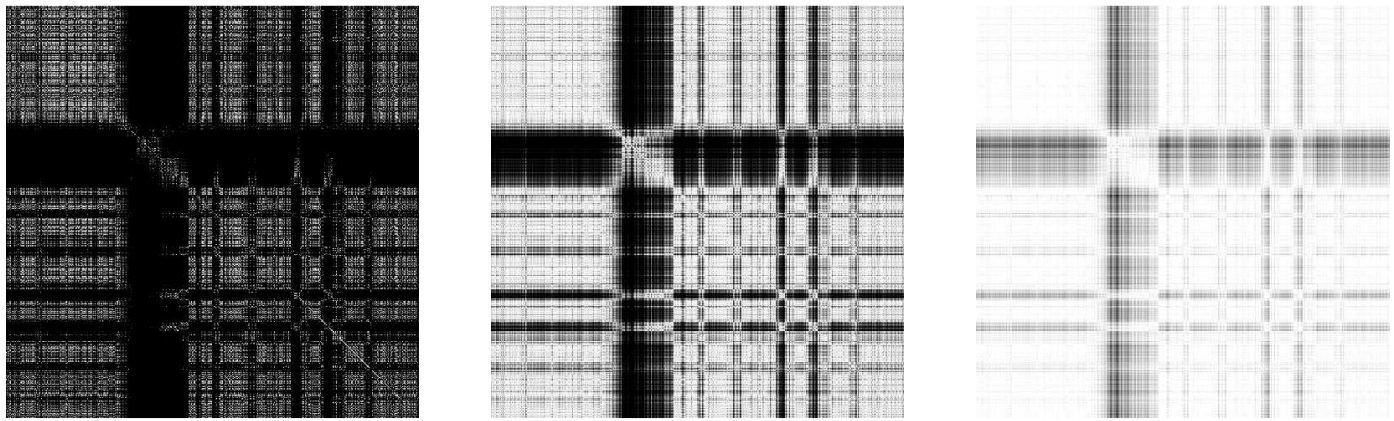
– Nonlinear mapping: kernel trick
  $\hookrightarrow$ reformulation in terms of inner products of $\mathbf{\Phi}(\mathbf{y}_k)$ only.
  $\hookrightarrow$ only the inner product kernel needs to be defined, e.g.

$$\mathbf{\Phi}(\mathbf{y}_i)^T \mathbf{\Phi}(\mathbf{y}_j) = \exp\left(-\frac{||\mathbf{y}_i - \mathbf{y}_j||^2}{2\sigma^2}\right)$$

  $\hookrightarrow$ identification in ∞ dimensional mapped space governed by 1 parameter σ!

– σ determined by maximizing information entropy of training data inner product matrix

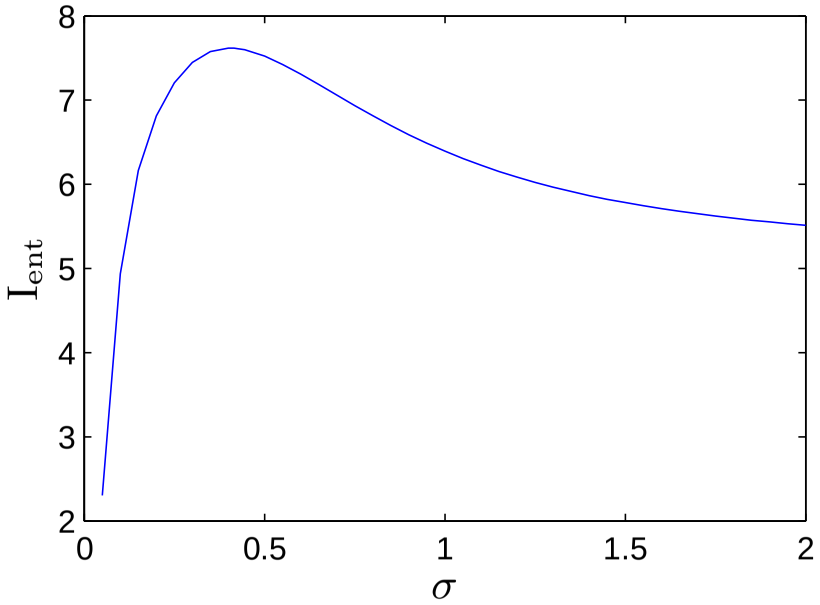
$\sigma = 0.1$ $\sigma = 0.405$ $\sigma = 1.75$



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Identifying a nonlinear environmental model with kernel PCA

– σ determined by maximizing information entropy of training data inner product matrix

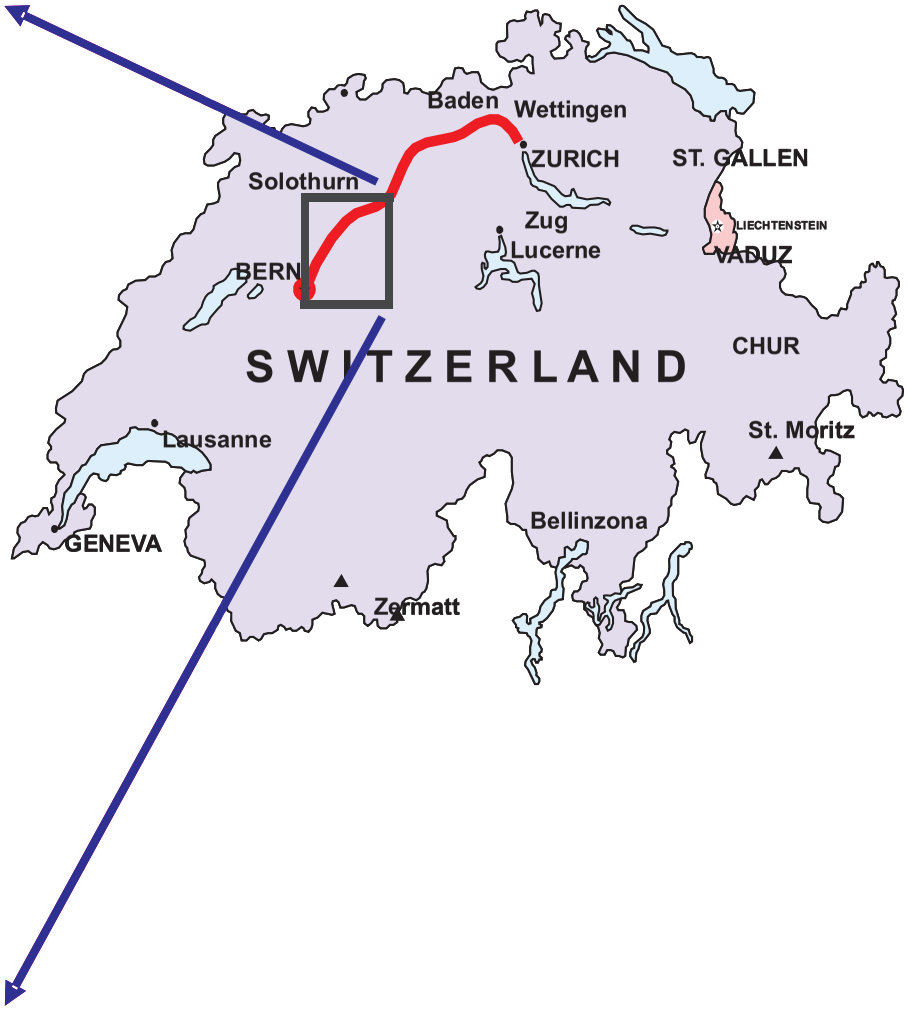


[D. Widjaja et al., Application of kernel principal component analysis for single-lead-ECG-derived respiration. *IEEE Transactions on Biomedical Engineering*, 59(4):1169-1176, 2012.]

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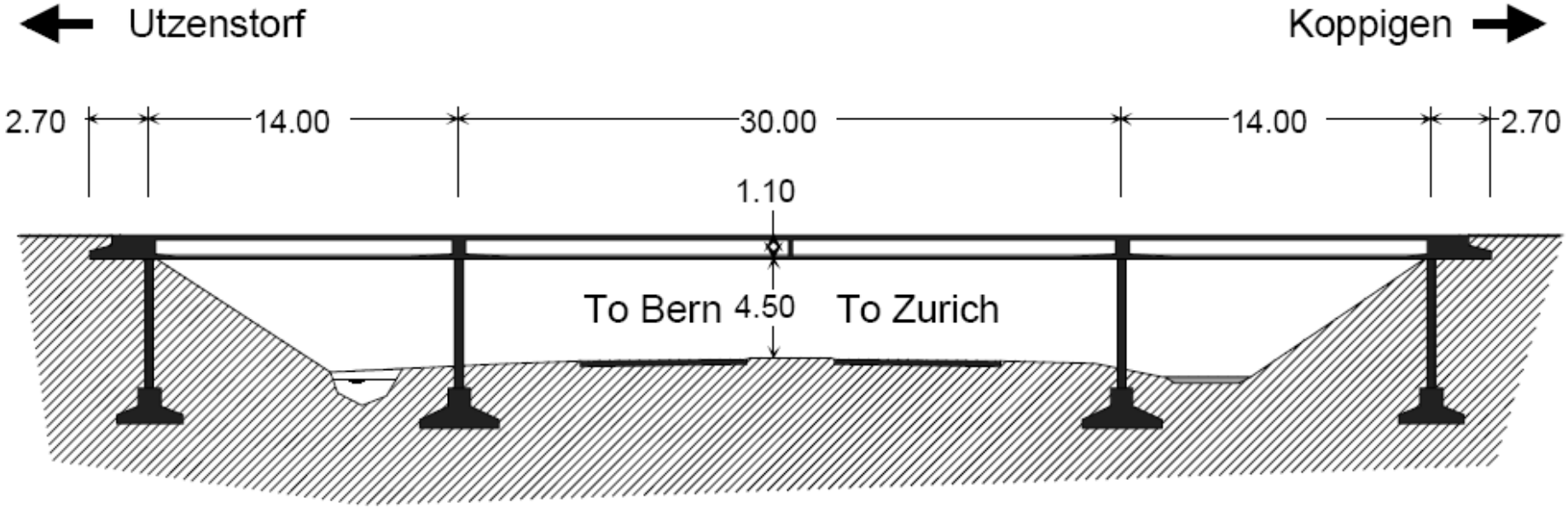
Case study: monitoring the Z24 bridge





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Case study: monitoring the Z24 bridge

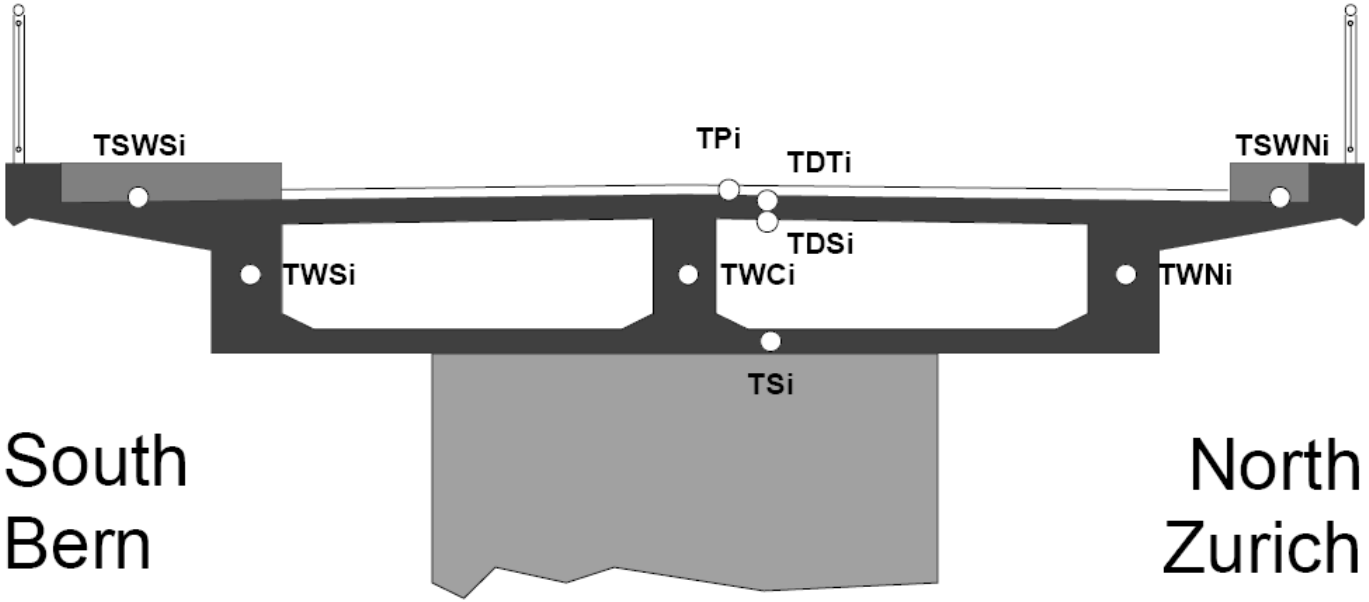


- 3-span prestressed concrete highway bridge, built in 1963.
- Demolished in 1998 due to the construction of a railroad next to the highway.
- Long-term ambient vibration monitoring test.
- Progressive damage test with 17 scenarios.
- Aim: investigate the influence of realistic damage on modal parameters.

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Case study: monitoring the Z24 bridge

Z24 bridge: Monitoring system



- 5 sensors for atmospheric conditions, 1 sample/hour:
  air temperature, air humidity, rain, wind speed, wind direction.
- 36 temperature sensors, 1 sample/hour.
- 7 static deformation sensors, 1 sample/hour.
- 16 accelerometers, $100\ \mathrm{Hz}$, 11 min/hour.

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Z24 bridge: Overview of PDT scenarios

1. Reference measurement (healthy structure).
2. Installation of lowering system.

3-6. Lowering of pier with 20, 40, 80, and $95\mathrm{mm}$ (settlement, erosion).

7. Tilt of pier (settlement, erosion).









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8. Reference measurement (lifting bridge to initial position).

9-10. Spalling of concrete over 12 and $24\mathrm{m}^2$ (vehicle impact, corrosion).

11. Landslide (erosion).





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Z24 bridge: Overview of PDT scenarios

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7. Tilt of pier (settlement, erosion).
8. Reference measurement (lifting bridge to initial position).
9-10. Spalling of concrete over 12 and $24\mathrm{m}^2$ (vehicle impact, corrosion).
11. Landslide (erosion).
12. Failure of concrete hinge (corrosion).
13-14. Failure of anchor heads (corrosion, overstress).
15-17. Rupture of tendons (corrosion).

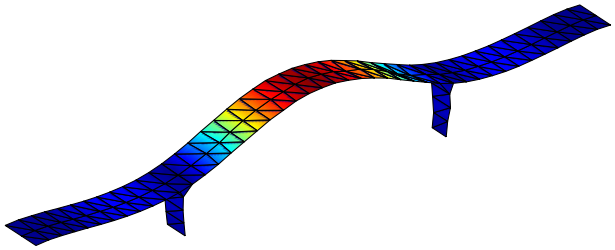




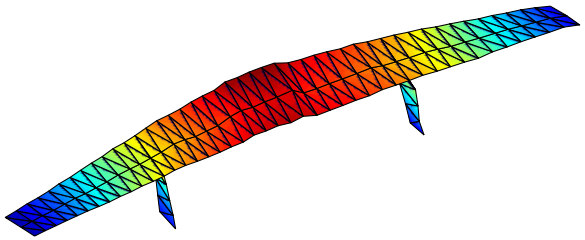
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Z24 bridge: operational modal analysis

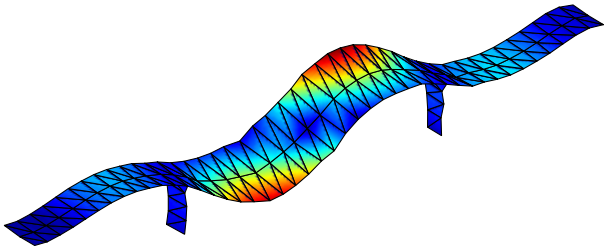
mode 1 - 3.86Hz - 0.8%



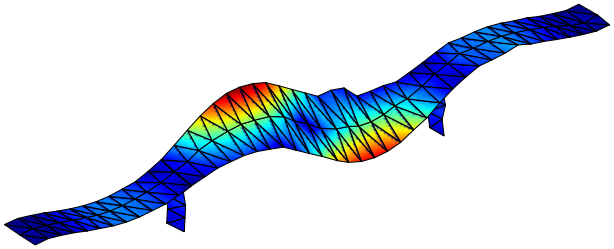
mode 2 - 4.90Hz - 1.4%



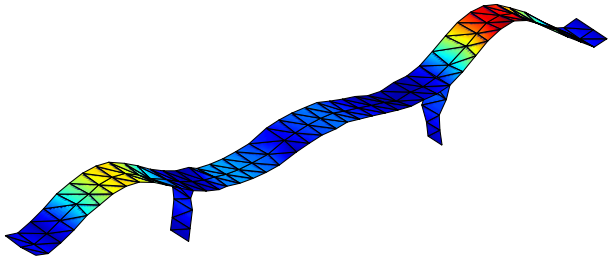
mode 3 - 9.76Hz - 1.4%



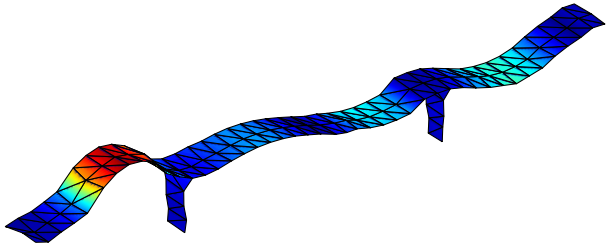
mode 4 - 10.30Hz - 1.3%



mode 5 - 12.41Hz - 2.8%

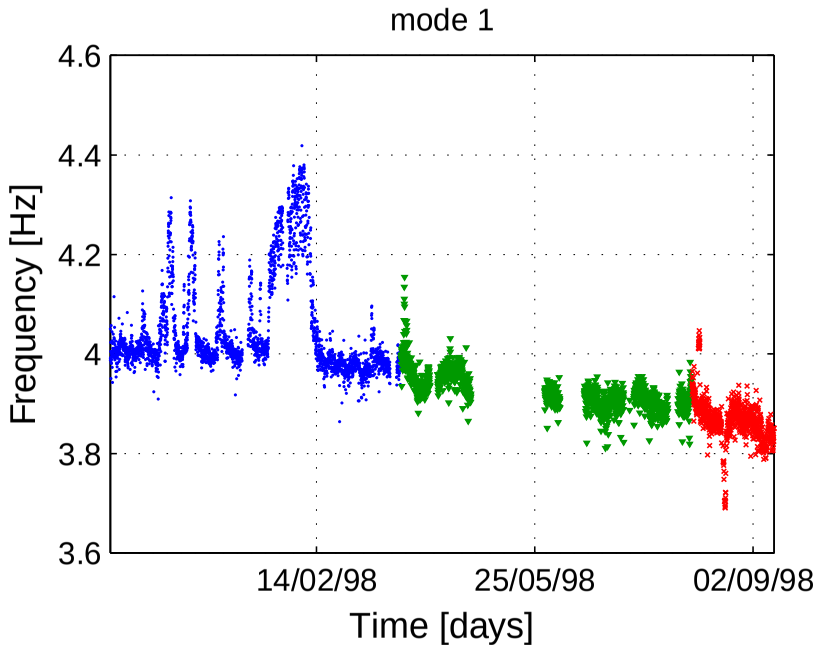


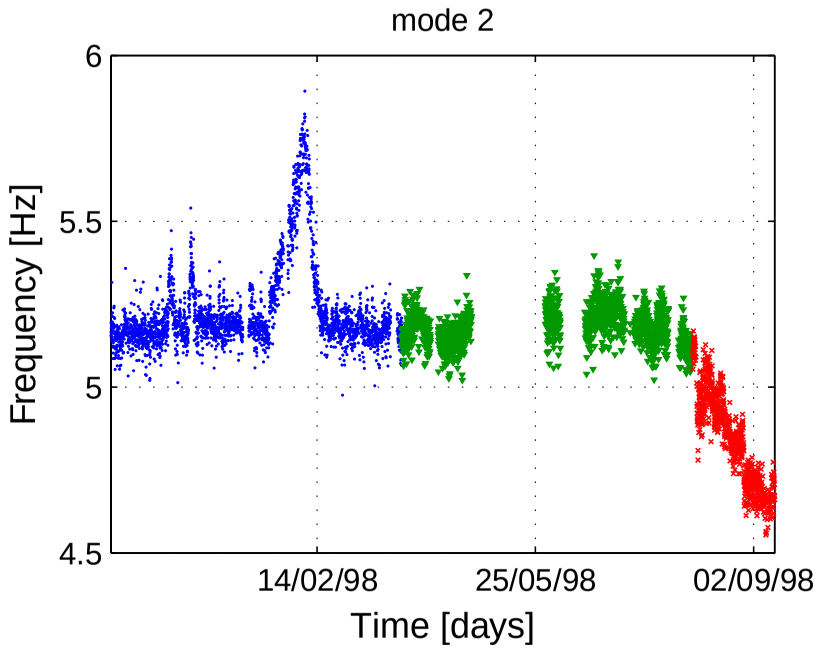
mode 6 - 13.25Hz - 3.2%

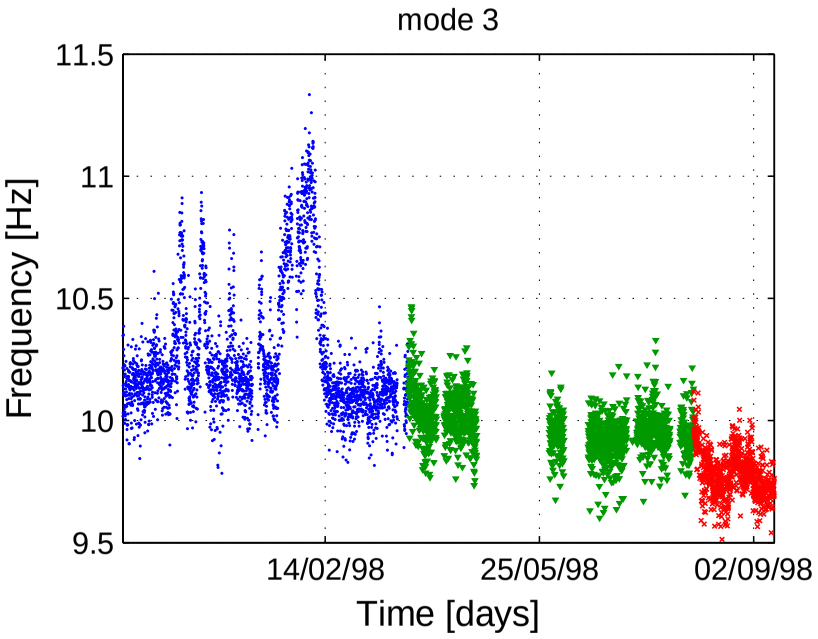


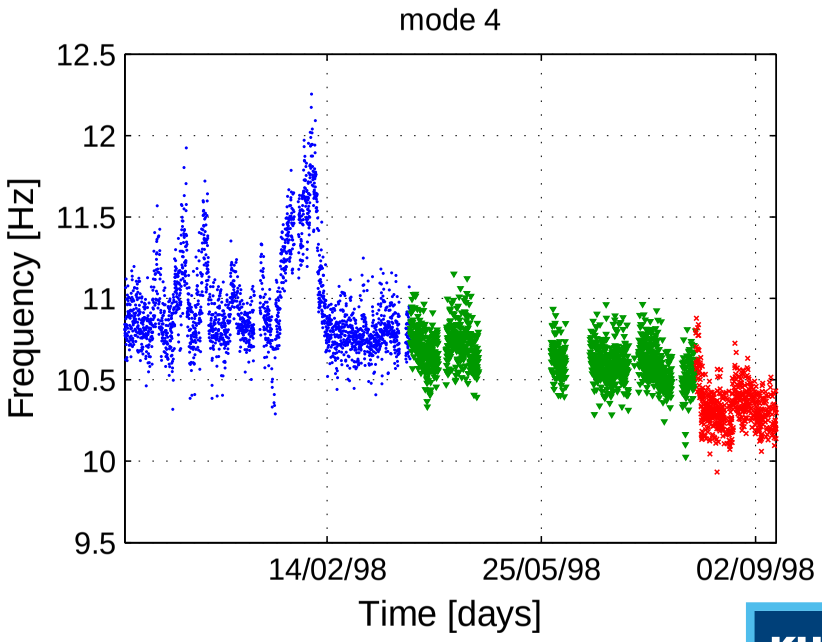
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Z24 bridge: evolution of natural frequencies



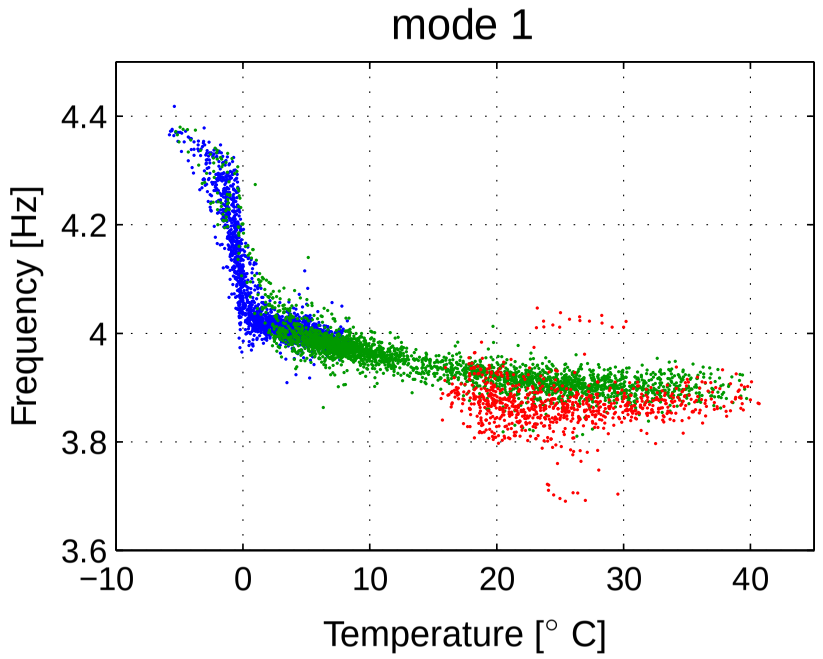


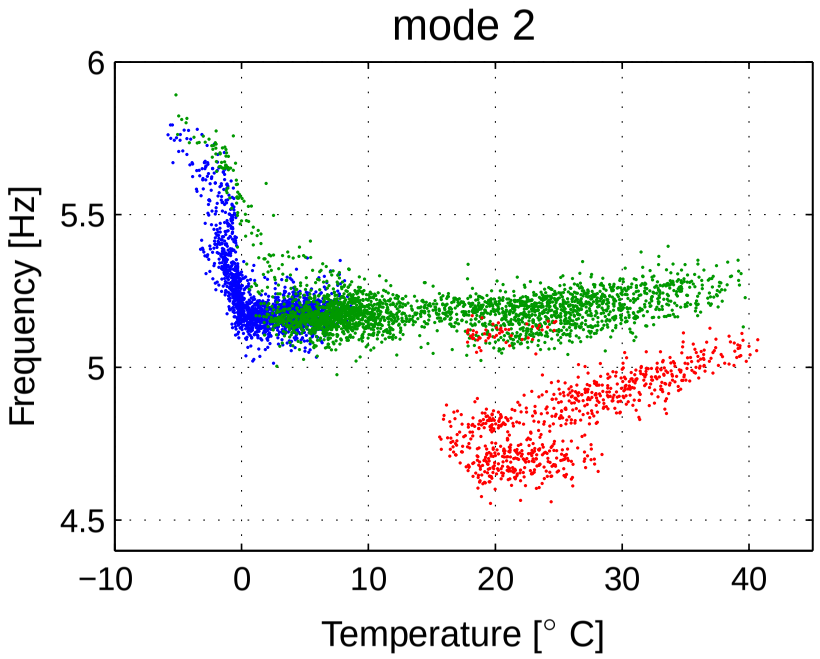


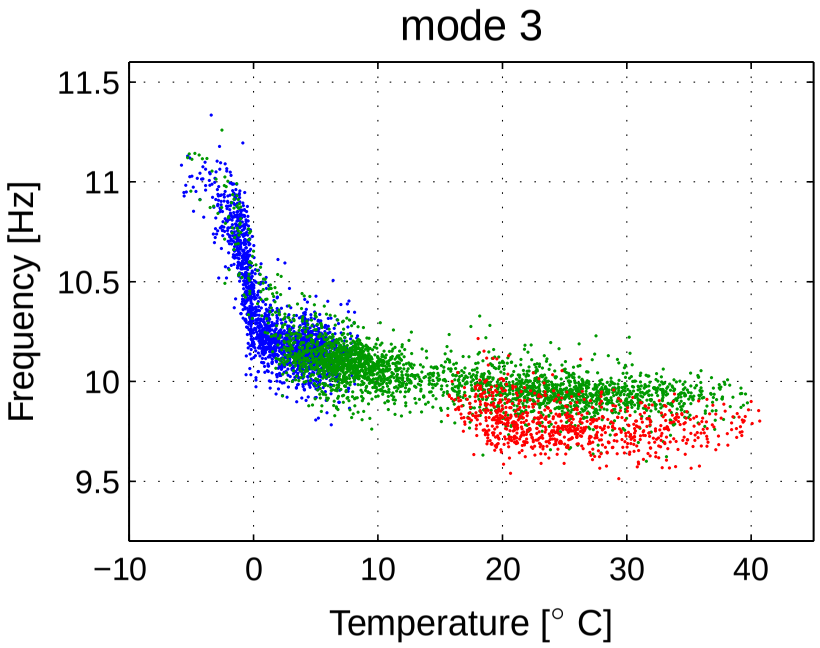


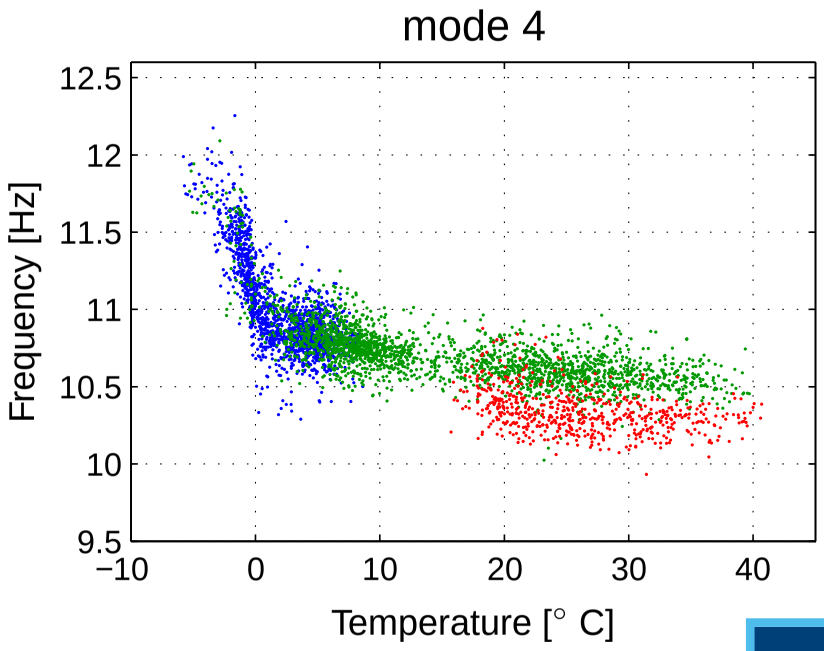
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Z24 bridge: temperature influence



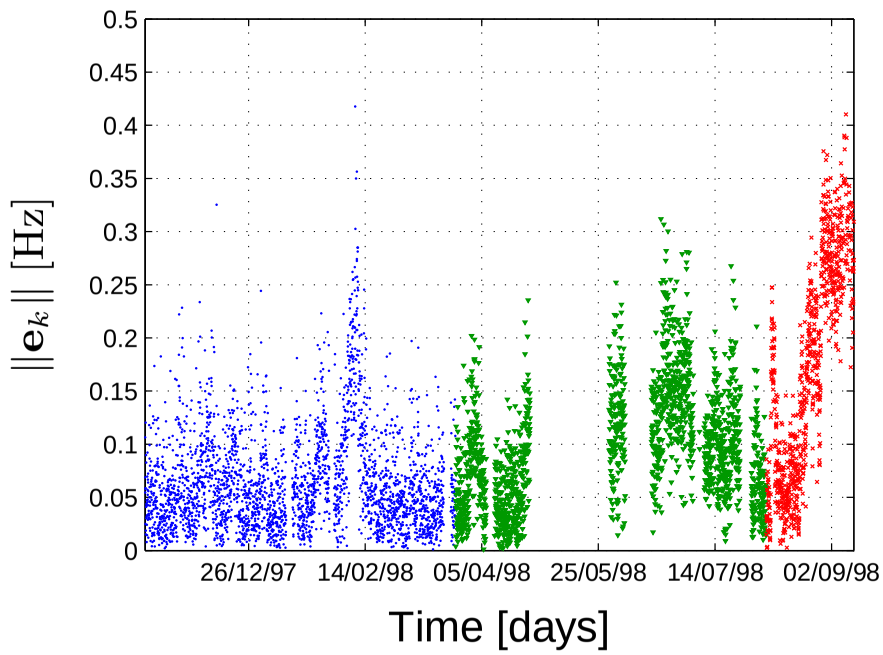


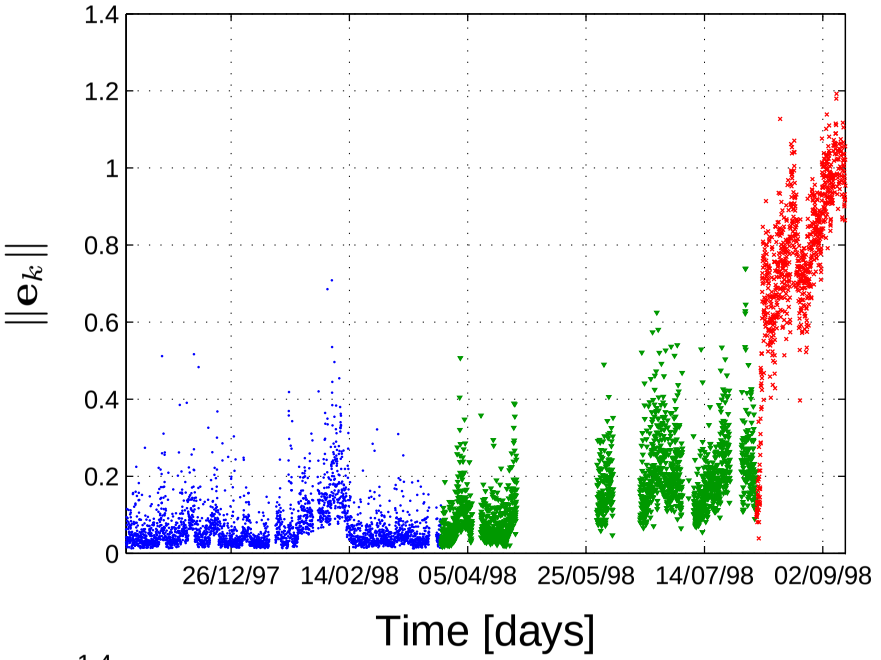


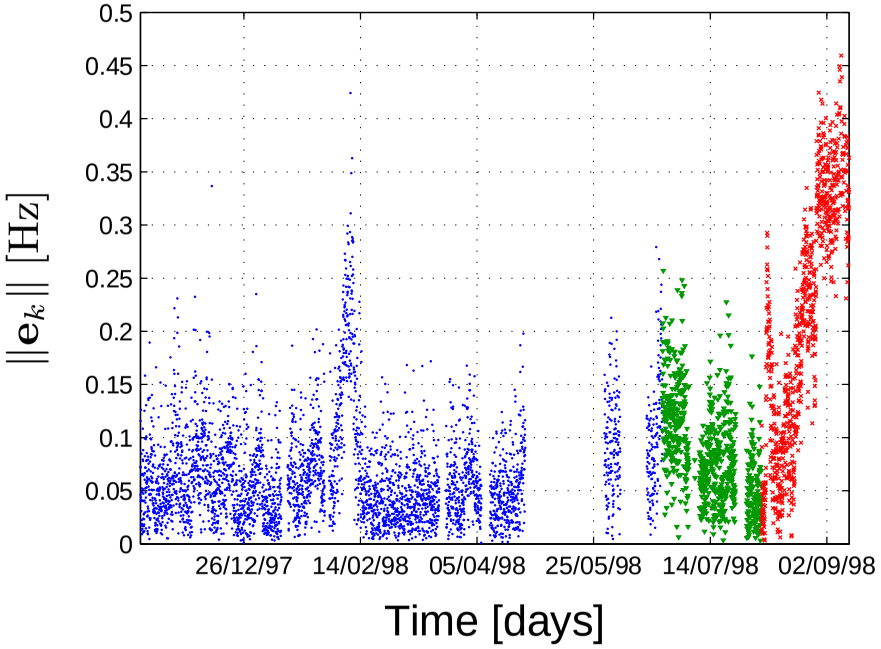


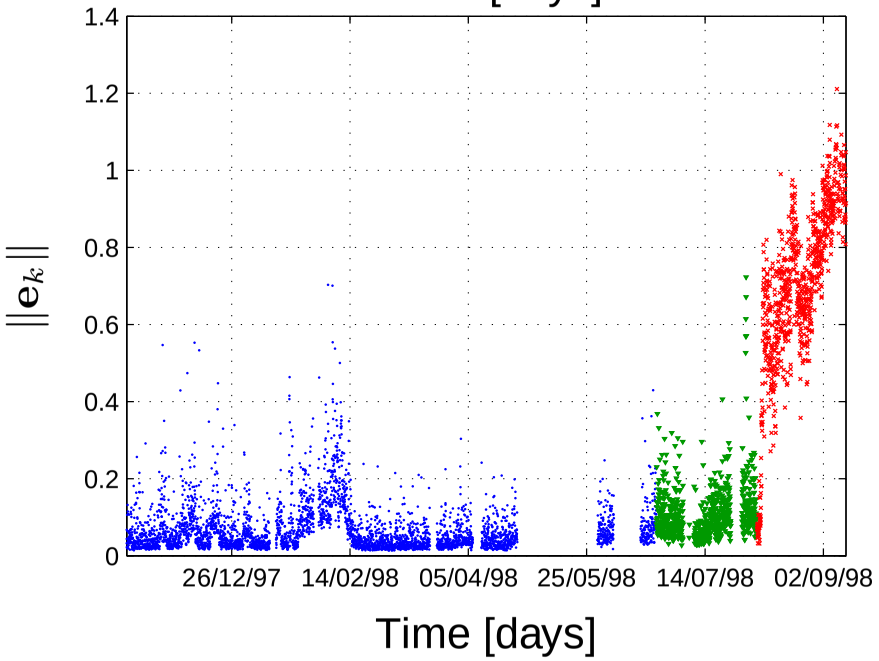
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Z24 bridge: misfit monitoring



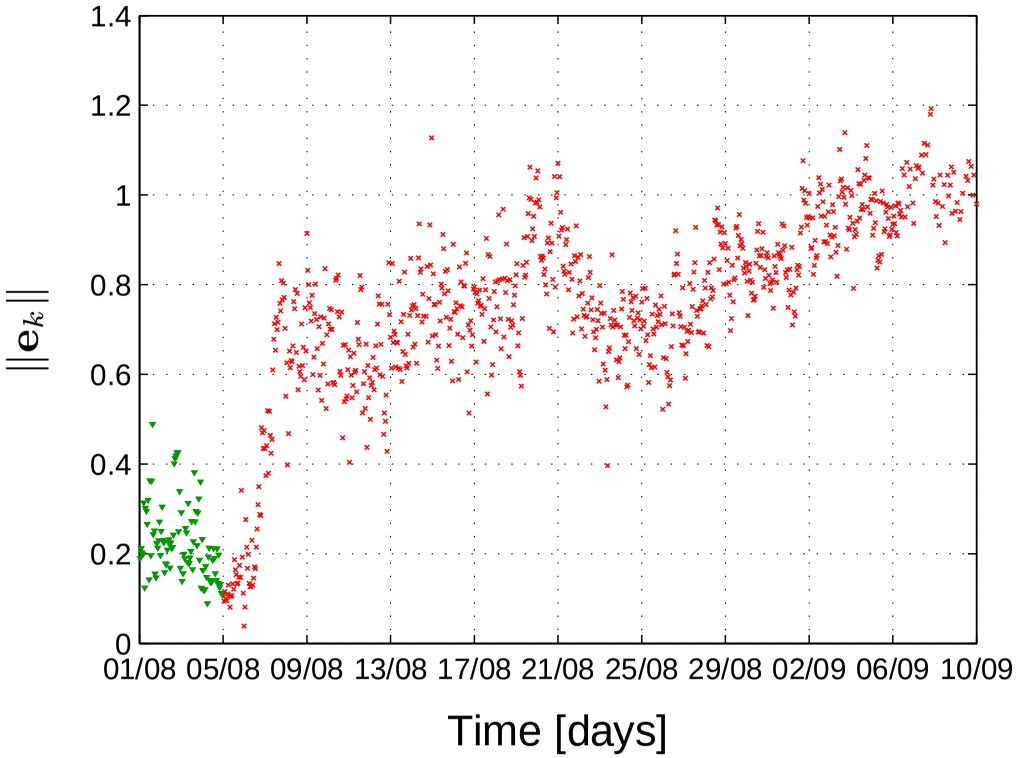






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Z24 bridge: misfit monitoring





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Conclusions

– Kernel PCA is a powerful technique for nonlinear system identification:
  → output-only.
  → nonlinear mapping of output to infinite dimensional space.
  → defined by 2 parameters only.

– Monitoring the misfit with kernel PCA allowed to detect the onset of damage.

– Linear PCA did not yield good results because of the nonlinear temperature-frequency relationship.

[E. Reynders, G. Wursten and G. De Roeck, Output-only structural health monitoring in changing environmental conditions by means of nonlinear system identification. *Structural Health Monitoring*, 13(1):82-93, 2014.]

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