TOWARDS EXTRACTION OF VIBRATION-BASED DAMAGE INDICATORS

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Scope of the fact sheet

Present a survey on:

- vibration based methods allowing the estimation of damage indicators that can be used to obtain indications of possible structural anomalies linked to damage.

- algorithms to take into account the statistical variability of the damage features.

Methods and issues

- Data-driven methods
- Model-based methods
- Combined data-driven model-based methods
- Influence of operational and environmental conditions

Data driven methods

Are inverse methods that use models based on experimental response data recorded on the structure instead of physical models.

Damage-sensitive features are extracted from data and their changes used to identify damage.

$$D = d_{inspection} - d_{reference}$$

Fourier based methods	Time series methods	Time variant methods
Fourier analysis is used as the primary signal-processing tool and time-invariant models are defined to follow the structural behavior (*Fan & Qiao, 2011)*	Use statistical tools for developing mathematical models describing measured random signals. *(Fassois & Sakellariou, 2007).*	Develop time-variant models that allow to identify sudden changes in the system characteristics. *(Staszewski & Robertson 2007)*

Fourier based methods – Damage indicators

Detection of stiffness losses

modal frequencies

$$D = f_I - f_R$$

detection

modal shapes
and derivatives

$$D = g\left(\varphi_I\right) - g\left(\varphi_R\right)$$

localization

modal flexibility
and derivatives

$$D = g\left(f_I, \varphi_I\right) - g\left(f_R, \varphi_R\right)$$

operational shapes
and derivatives

$$D = g\left(ODS_I\right) - g\left(ODS_R\right)$$

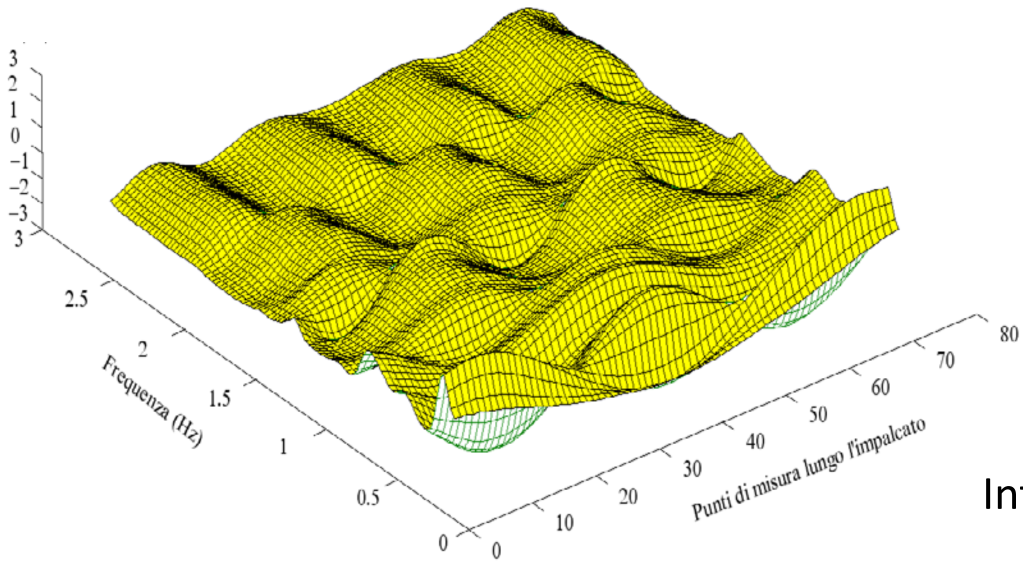
no quantification

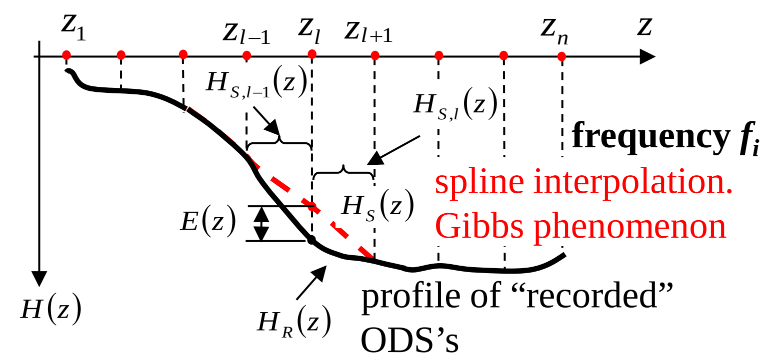
Damage indicators – Curvature estimation

curvature more sensitive to local reductions of stiffness

BUT

curvature estimation challenging due to differentiation of noisy signals

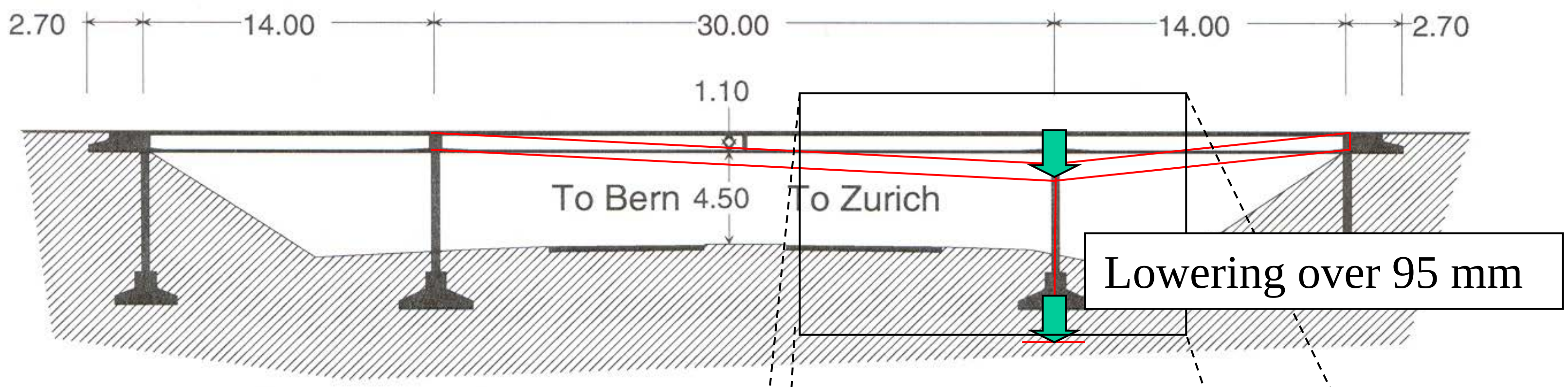


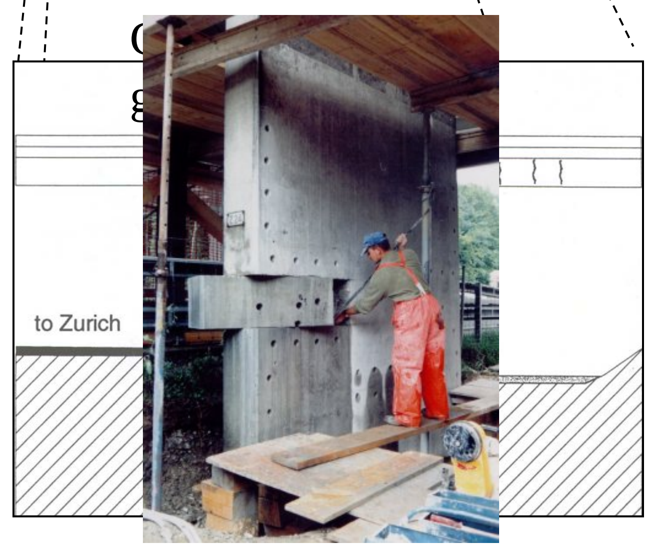


Interpolation method (*Limongelli 2011*)

Finite Difference (*Pandey 1991, Sampaio et al. 1997*)
Gapped Smoothing Method (*Ratcliffe 1997*)
Wavelet transformation (*Poudel et al. 2007, Zhang et al. 2013)*

Model-based methods: application to Z24 bridge





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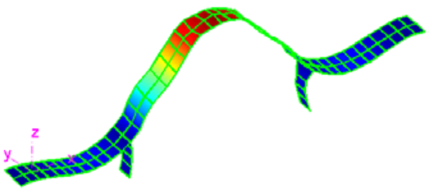
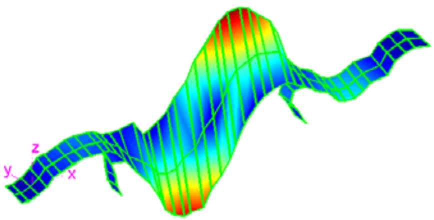
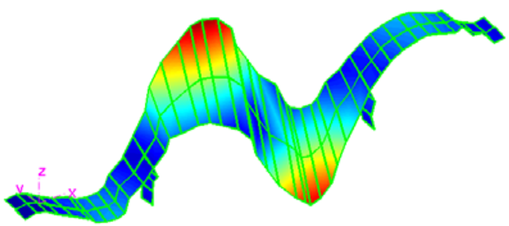
Data in reference (up) and damaged state (bottom)



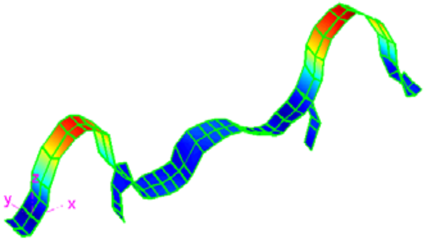
3.89 Hz



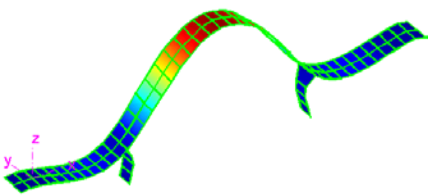
9.80 Hz



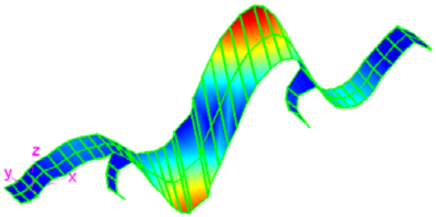
10.30 Hz



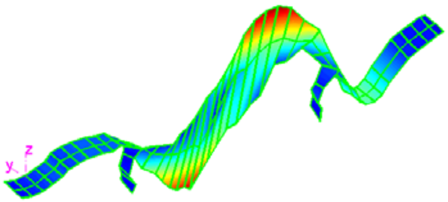
12.67 Hz



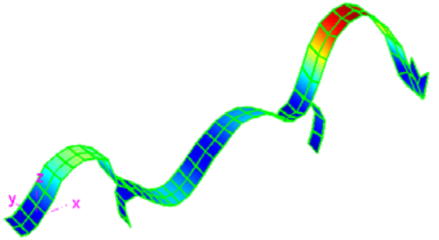
3.67 Hz



9.21 Hz

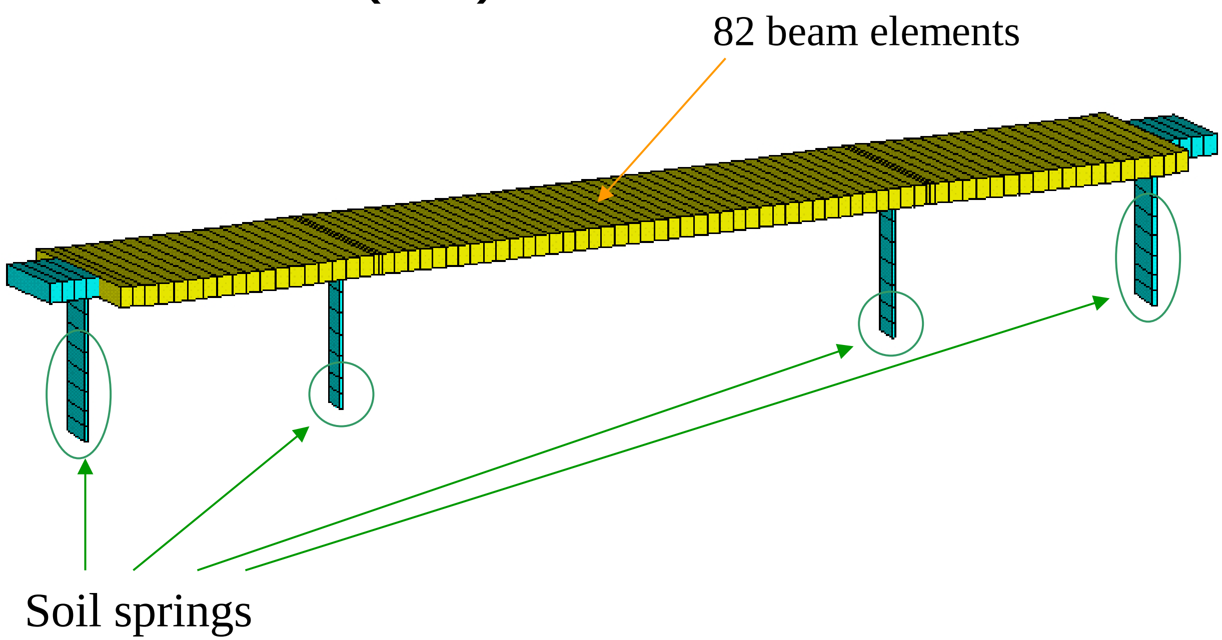


9.69 Hz



12.03 Hz

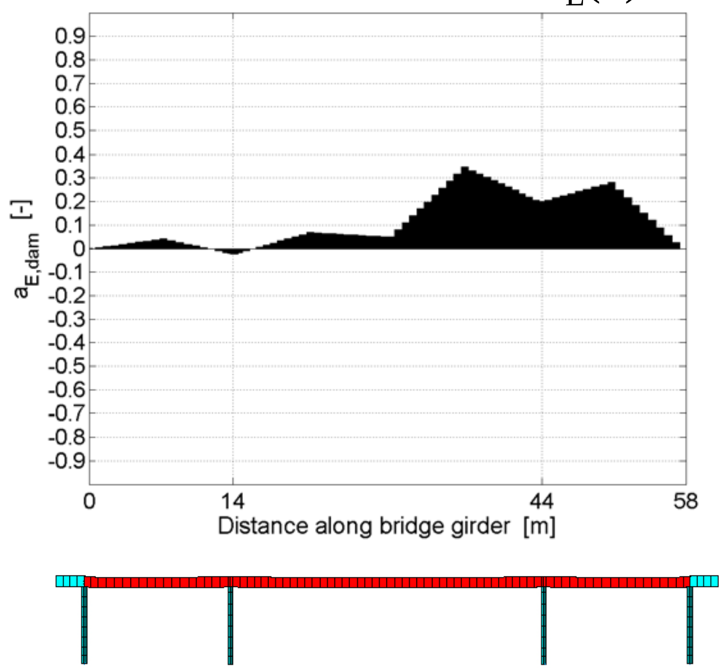
Finite Element (FE) model of the Z24 bridge

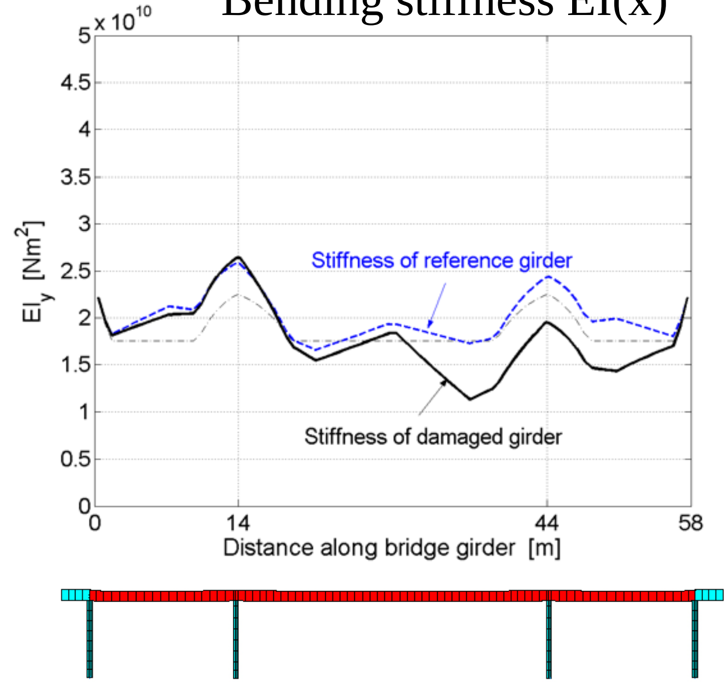


- Damage is identified through the updating of a (linear) FE model, assuming it leads to a local loss of stiffness.
- The model parameterization usually consists of a linear parameterization of the stiffness matrix.

Results of the FE updating

Correction factors $a_E(x)$ ⟹ Bending stiffness EI(x)



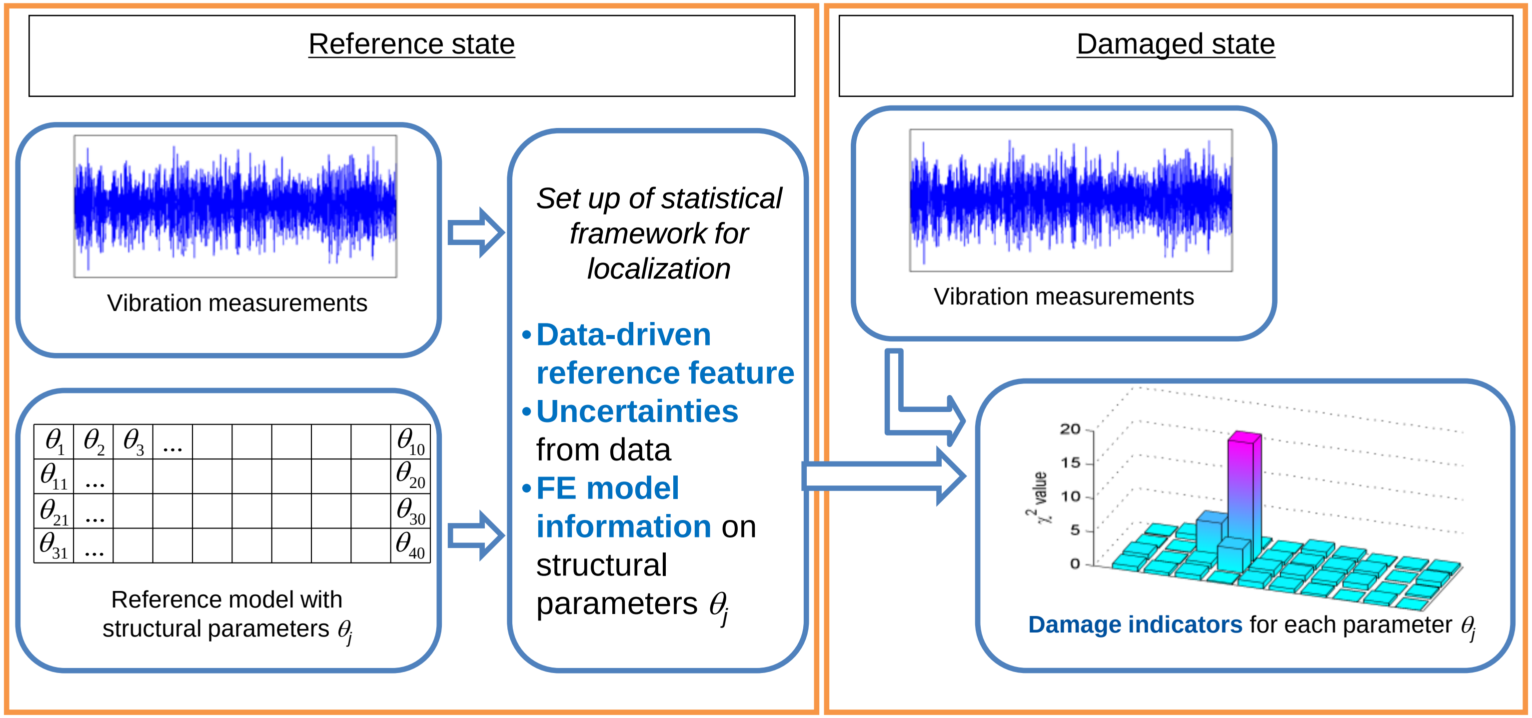


- A weighted least squares problem is solved to identify the model parameters by minimizing the discrepancy between measured and predicted modal data.
- Damage is found above the settled pier with a stiffness reduction up to 32%

Combined data driven-model based methods

- Situated between data-driven and model-based approaches
- Data-driven features are extracted from reference and damaged states and confronted to finite element model
- Definition of damage indicators for each element of model instead model updating
- Indicators: (statistical) distance measures
- Treating localization and quantification separately

Combined data driven-model based methods



Influence of environmental and operational conditions

The problem

Performance assessment based on ambient response measurements (long-term)

Problem characteristics

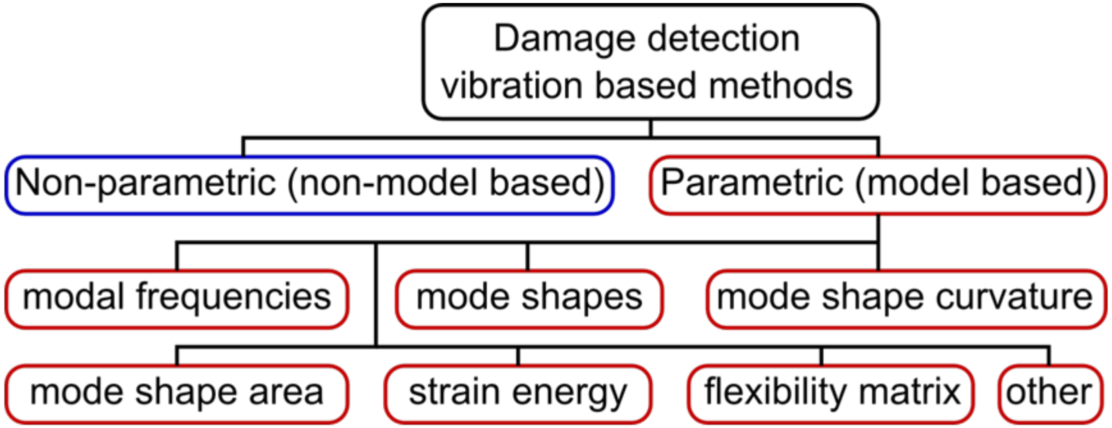
Civil engineering structures are by default operating within a continuously changing environment.

Environmental and other operating condition data should be incorporated into the structural ID framework.

Why involve environmental conditions data into structural ID?

- Improved understanding
- Complete description of dynamics
- Improved design
- Improved monitoring (damage detection)

Influence of environmental and operational conditions



Changes due to environmental conditions must be distinguished from those induced by damage.

State-of-the-art

Multi-models

A conventional model is identified for each operational condition. Regression or interpolation is then used *(Worden et al. 2002, Sohn et al. 1999, Peeters et al. 2001, Kim et al. 2006)*

Functional models

Data from various experiment are processed together. A global model with functional dependence of its parameters on the measured environmental conditions is estimated *(Lekkas et al. 2009, Hios et al. 2009)*

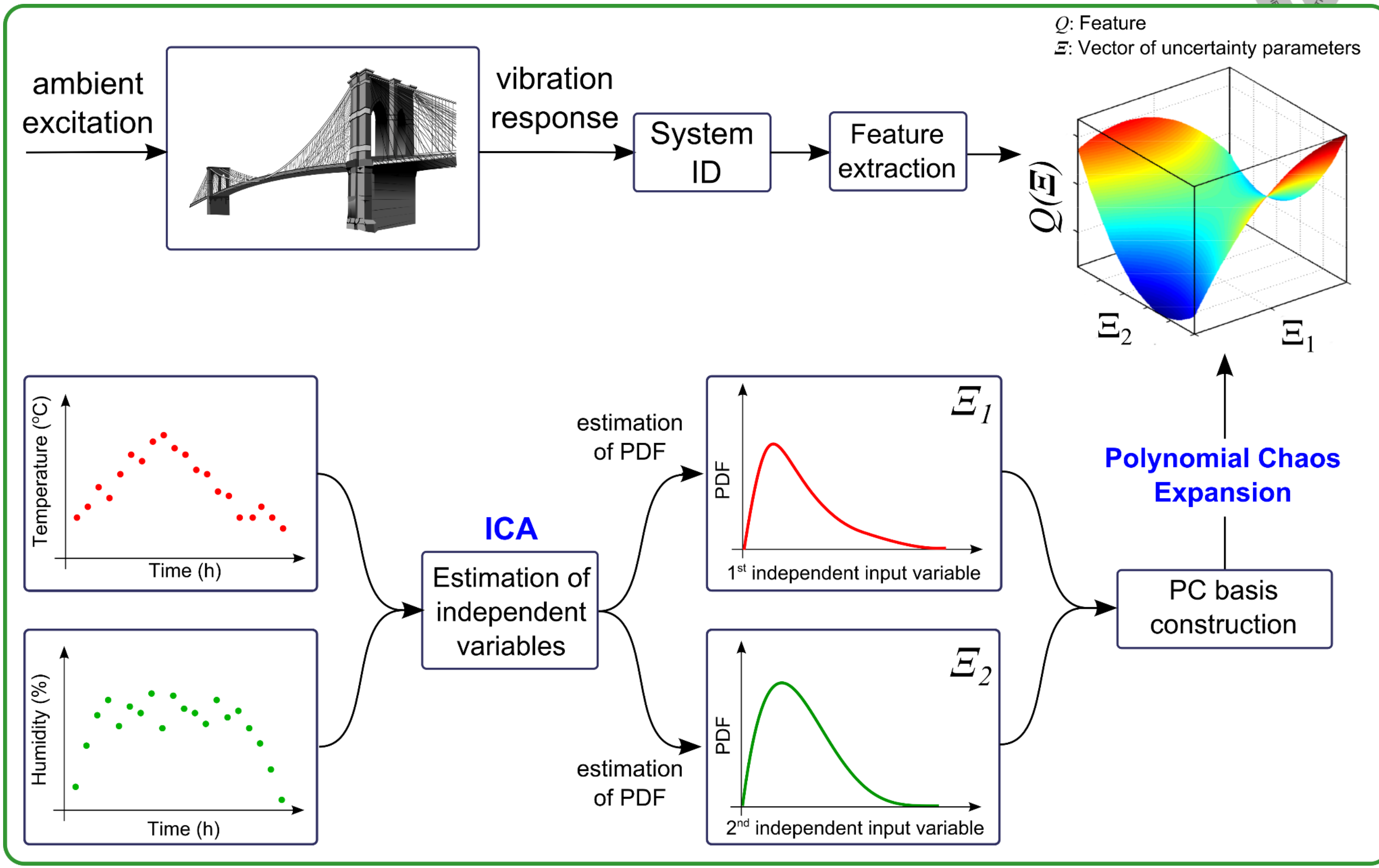
Feature extraction

Extract features sensitive to damage but insensitive to environmental conditions.

- Pattern recognition technique (PCA, Factor analysis, and other; *Deraemaeker et al. 2008, Kullaa 2006, Sohn et al. 2002*)
- Subspace model based residual techniques *(Balmés et al. 2008)*

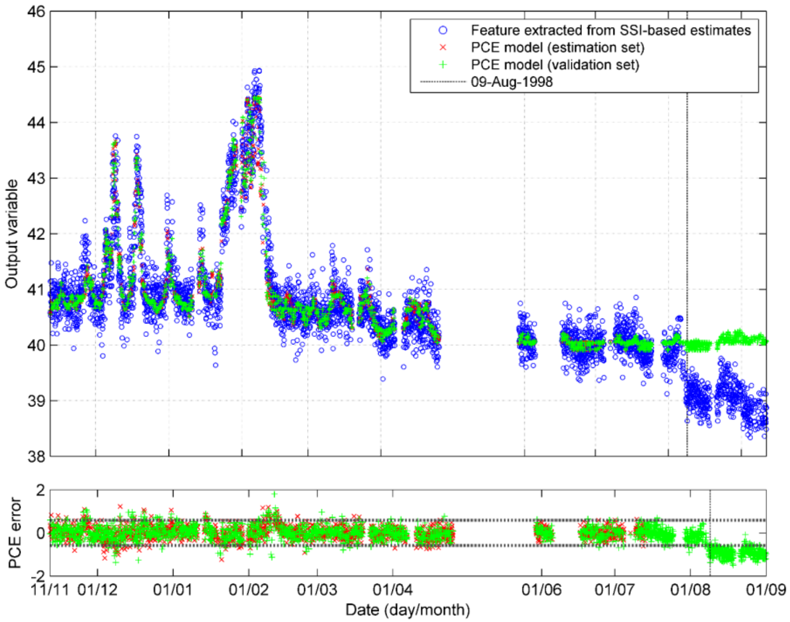
COST TU1402: Quantifying the Value of Structural Health Monitoring

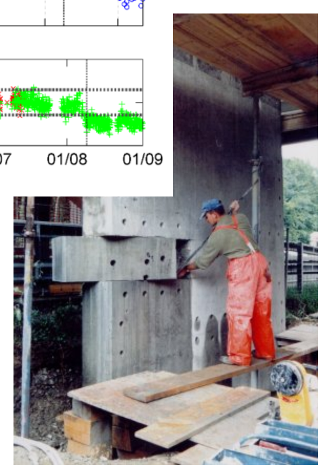
Accounting for environmental and operational conditions

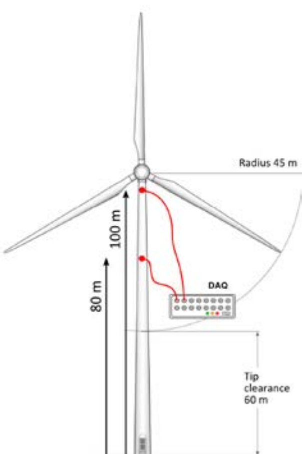


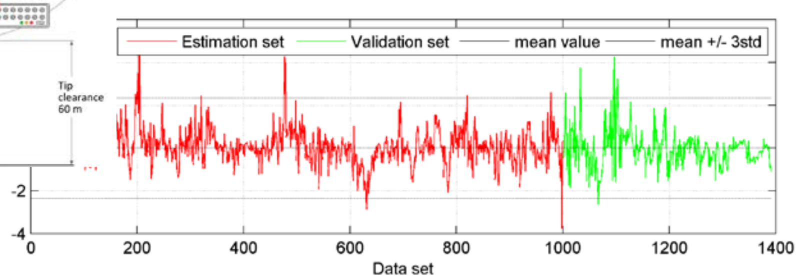
Spiridonakos & Chatzi, 2014: The ICA-PCE metamodeling approach to extracting a global system model

Construction of robust performance indicators

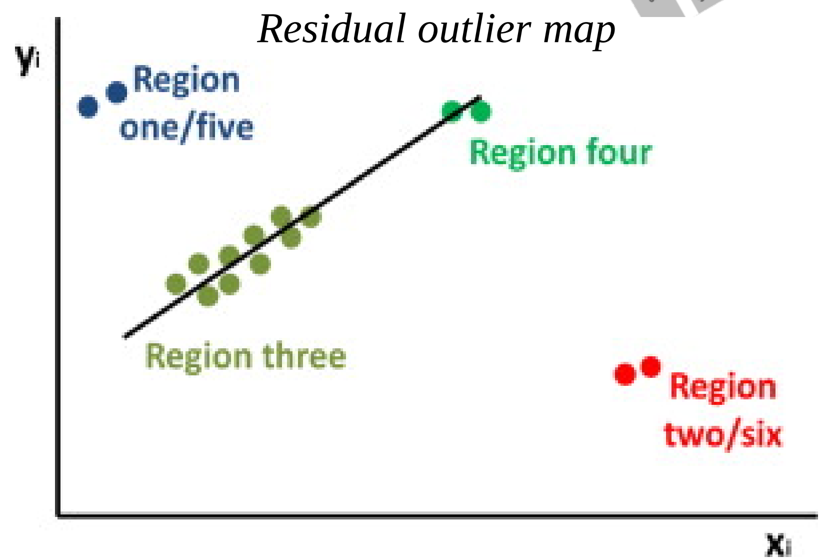








Spiridonakos & Chatzi, 2015



Residual outlier map description.

Region	Classification
One	Vertical outlier
Two	Bad leverage points
Three	Normal points
Four	Horizontal outlier–good leverage points
Five	Vertical outlier
Six	Bad leverage points

Dervilis, Worden, & Cross, 2015

Application areas

- Extensively developed and used for civil and mechanical and aerospace engineering (bridges and buildings, a few on dams, less on offshore due to noise and change of mass)
- Rotating machinery monitoring, due to several favourable conditions (ease of access, control of environmental factors, small scale).
- Aeronautical engineering to monitor almost all components critical for flight performance such as gears, rotating shafts, bearings and rotors.

Critical appraisal – damage features

modal frequencies

advantages: ease of physical interpretation, accurate estimation

limitations: global information level, used for damage detection alone (localization limited to lab or numerical models)

modal shapes and derivatives

advantages: permit damage localization

limitation: less accurate, not extremely sensitive to moderate changes

operational shapes and derivatives

advantages: no modal extraction errors, information from entire frequency range

limitations: more affected by noise in non-resonant ranges

Critical appraisal – Methods

data driven methods

advantages: lower computational demand, suitable for real time monitoring

limitations: usually quantify estimate damage, inadequate for prognosis

model based methods

advantages: allow damage quantification

limitations: scarcely compatible with automated monitoring, do not capture loss of strength, prone to ill-posedness and ill-conditioning

combined methods

advantages: built on physical information, feasible for arbitrary structural types, no ill-posedness, require less accuracy than FE

limitations: analysis less profound than with updating, require careful definition of the data-to-model distance measure and its statistical evaluation

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