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COST Action TU 1402 - Workshop 2
28-29 September 2015, Istanbul, Turkey

Fact sheet: monitoring the structural health of the Z24 bridge

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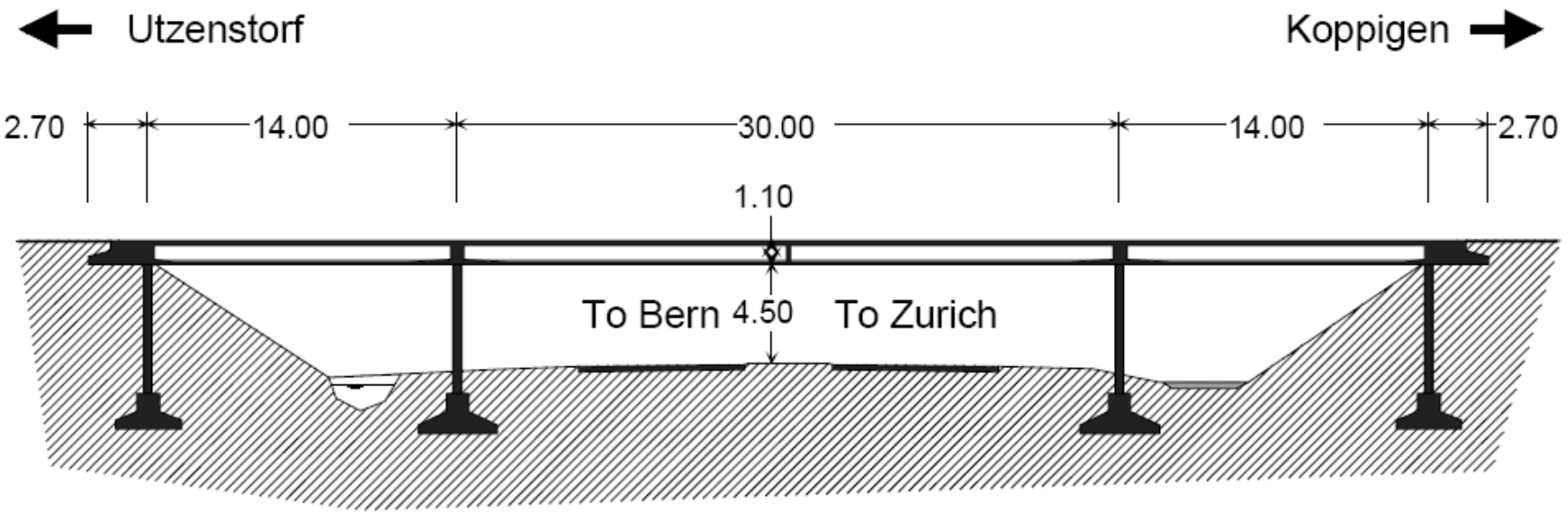
INRIA - Centre de recherche Rennes

The Z24 bridge benchmarks



→ 3-span prestressed concrete highway bridge, built in 1963.
→ Demolished in 1998 due to the construction of a railroad next to the highway.
→ BE-3157 SIMCES (KU Leuven, Aalborg U., EMPA, LMS, Atkins, Sineco, TU Graz).

→ One-year ambient vibration monitoring test, followed by a progressive damage test.
→ Influence of environmental variations and realistic damage on modal characteristics.

→ Long-term monitoring: natural frequencies (benchmark COST F3).
→ Additional short-term monitoring during progressive damage test:
natural frequencies, damping ratios, detailed mode shapes (benchmark IMAC XIX).

Overview of progressive damage test 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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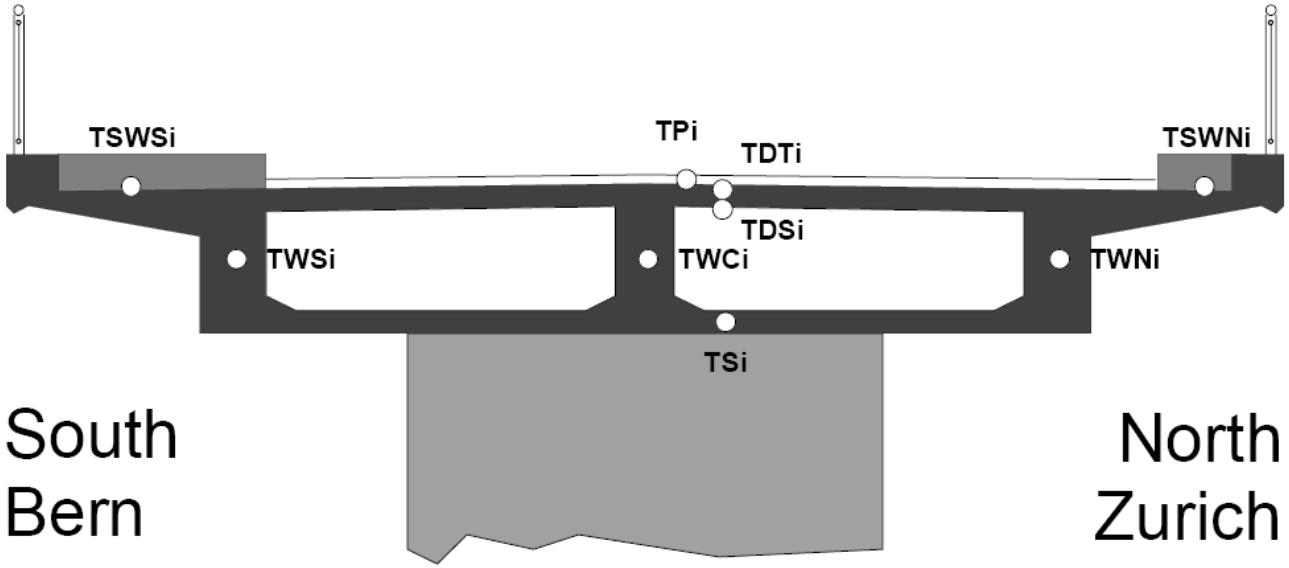
9-10. Spalling of concrete over 12 and $24\mathrm{m}^2$ (vehicle impact, corrosion).
11. Landslide (erosion).
12. Failure of concrete hinge (corrosion).
13-14. Failure of anchor heads (corrosion, overstress).
15-17. Rupture of tendons (corrosion).

Sensing technology



Long-term monitoring

→ 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.

→ Automatic system identification for converting acceleration time series into natural frequency observations

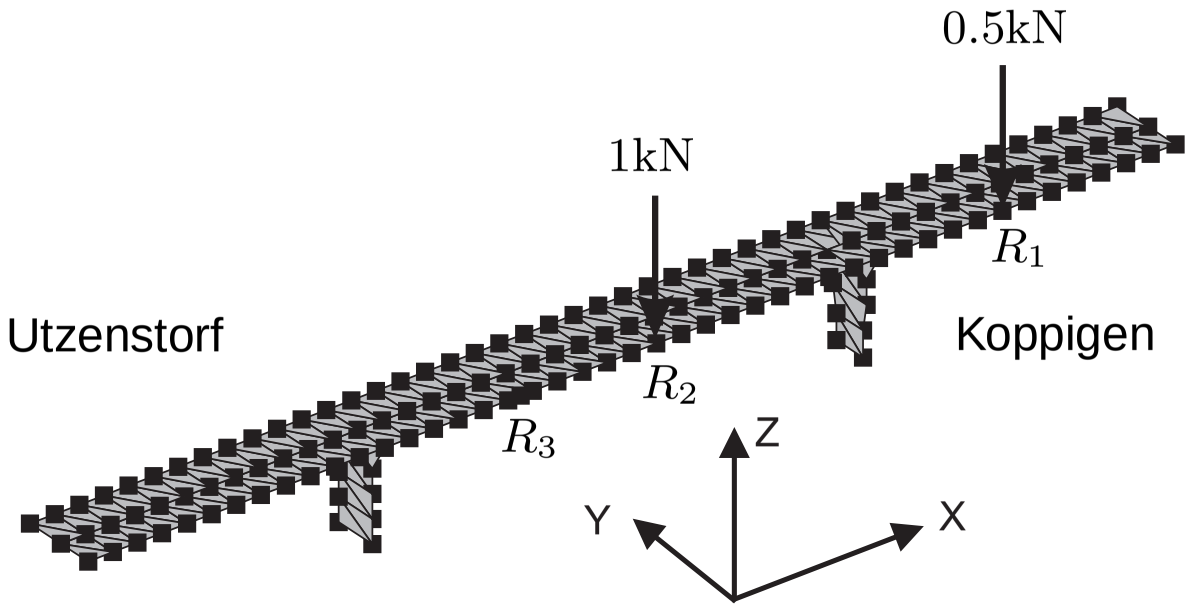
Additional short-term monitoring: sensing technology

Additional short-term monitoring

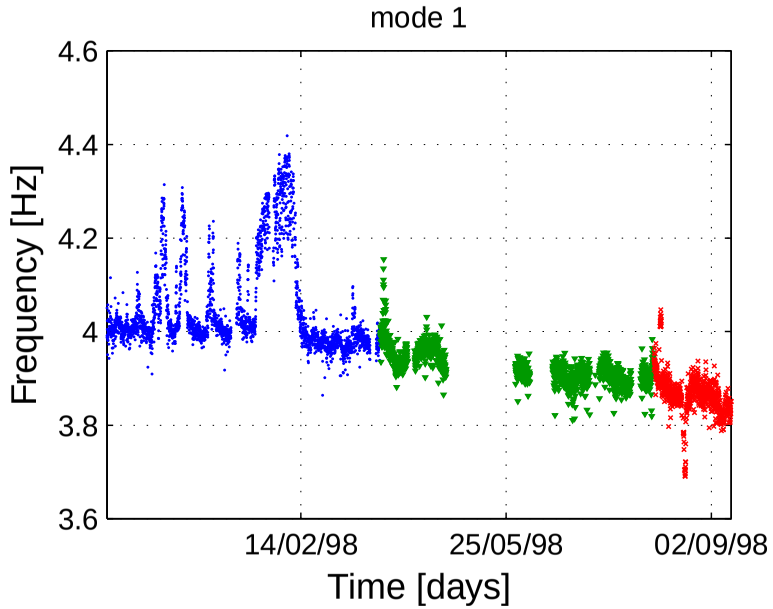
→ Large-scale forced and ambient vibration test before and after each damage scenario.

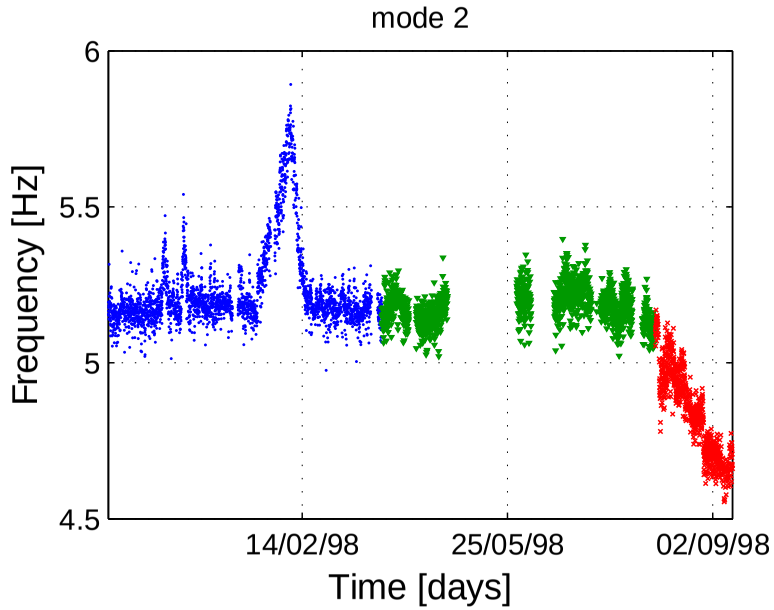
→ Outputs: 291 accelerations, 9 setups, 5 references.

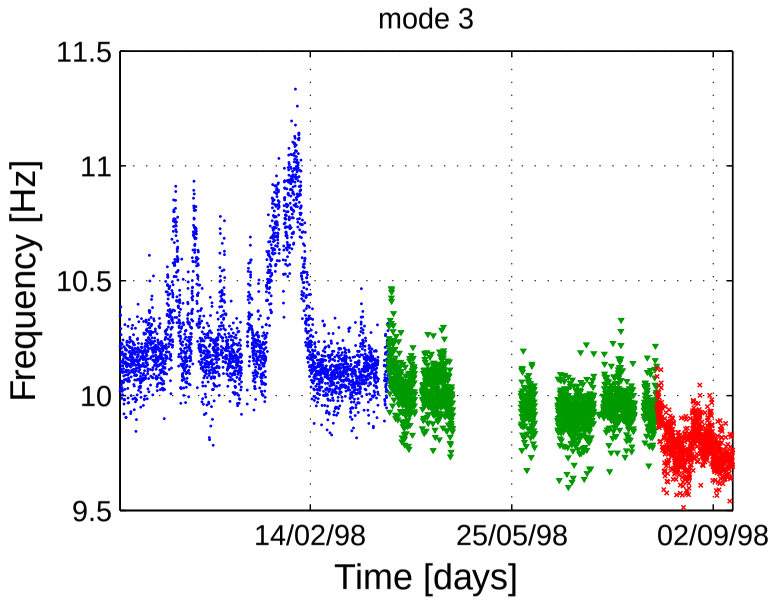
→ Shakers: 1kN at mid span, 0.5kN at side span, vertical, $3 - 30\text{Hz}$

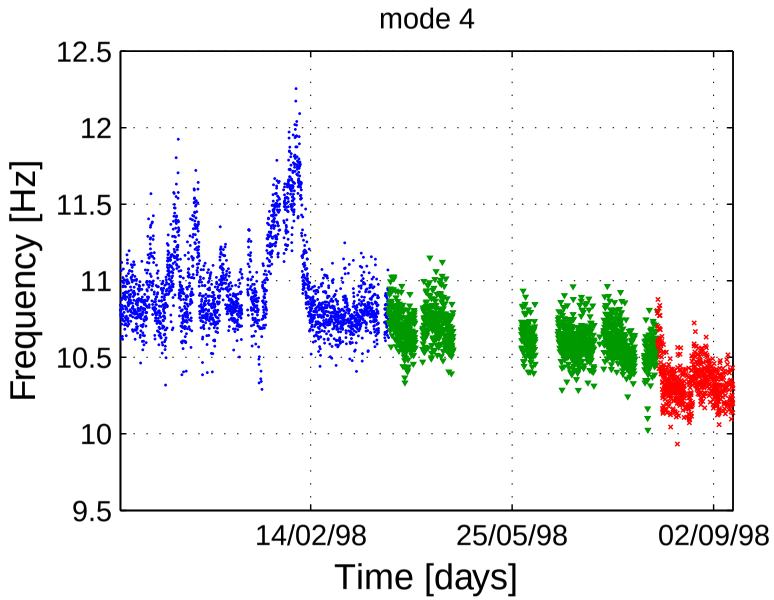


Long-term monitoring: observations









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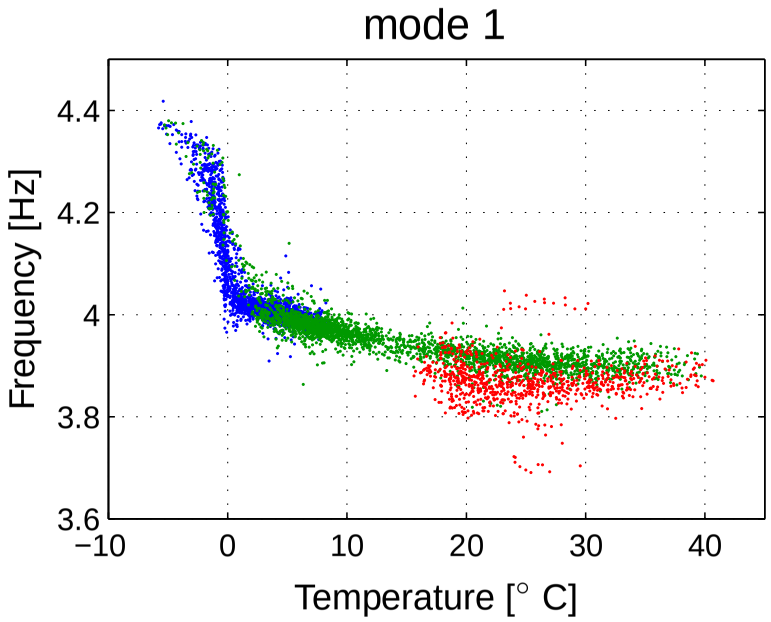
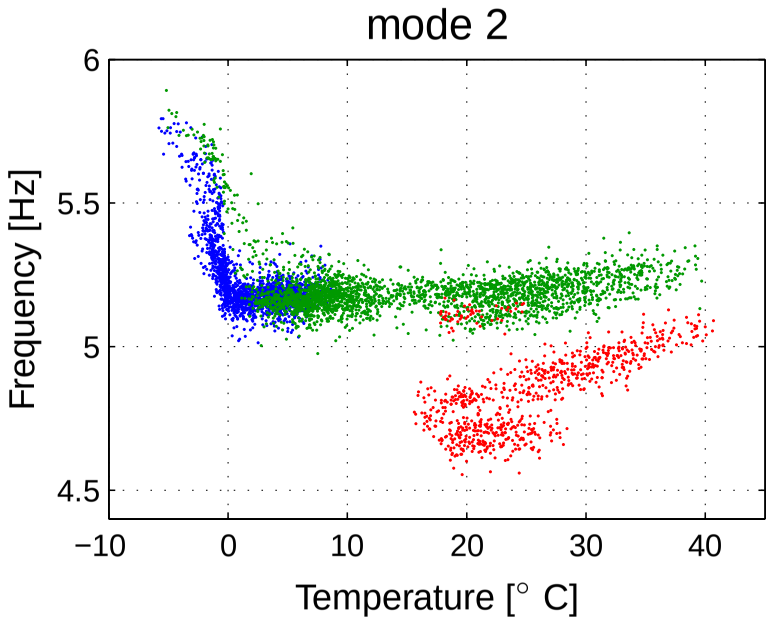
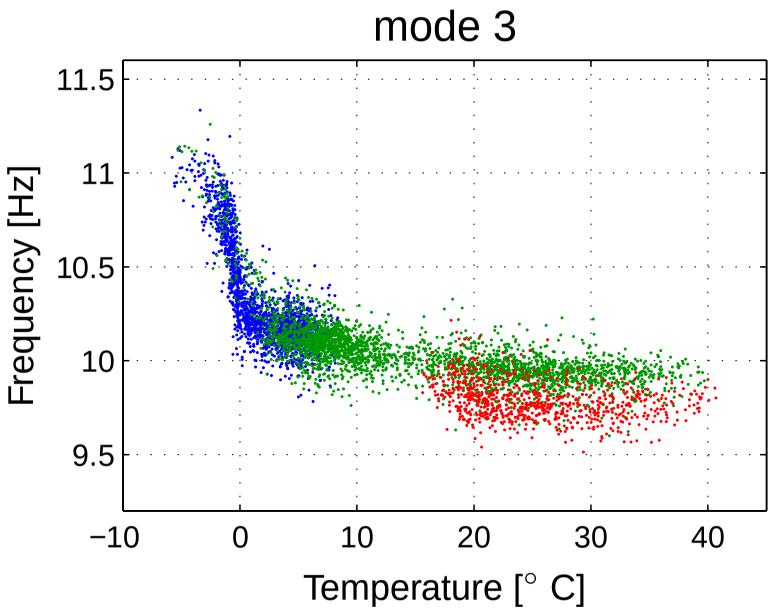
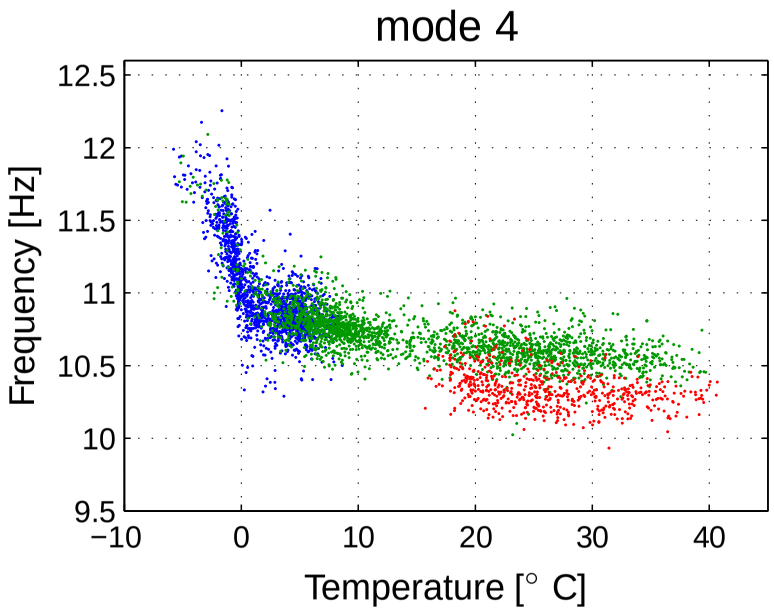
Long-term monitoring: observations





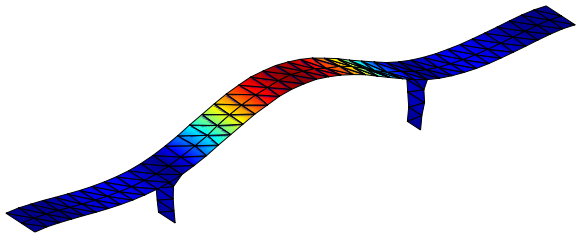




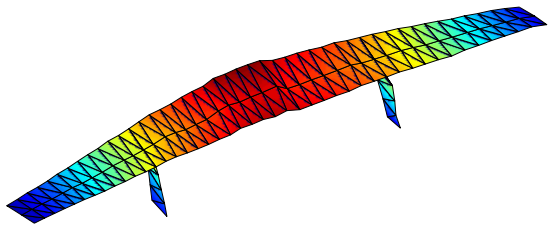
Additional short-term monitoring: observations

Ambient vibration test: 6 modes in between each applied damage case

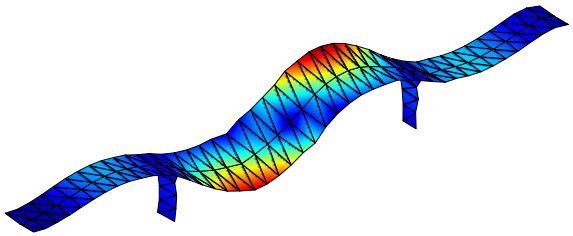
mode 1 - 3.86Hz - 0.8%



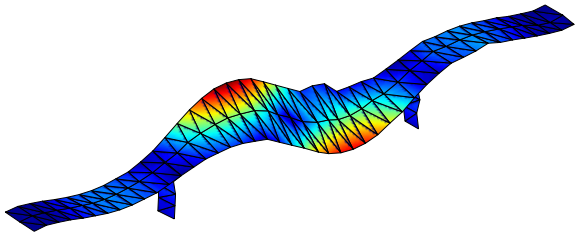
mode 2 - 4.90Hz - 1.4%



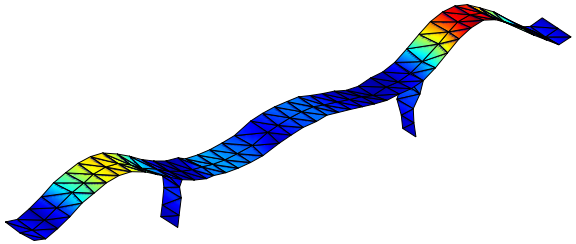
mode 3 - 9.76Hz - 1.4%



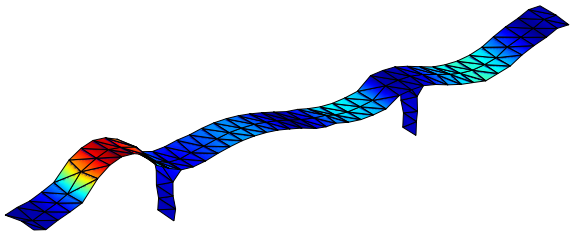
mode 4 - 10.30Hz - 1.3%



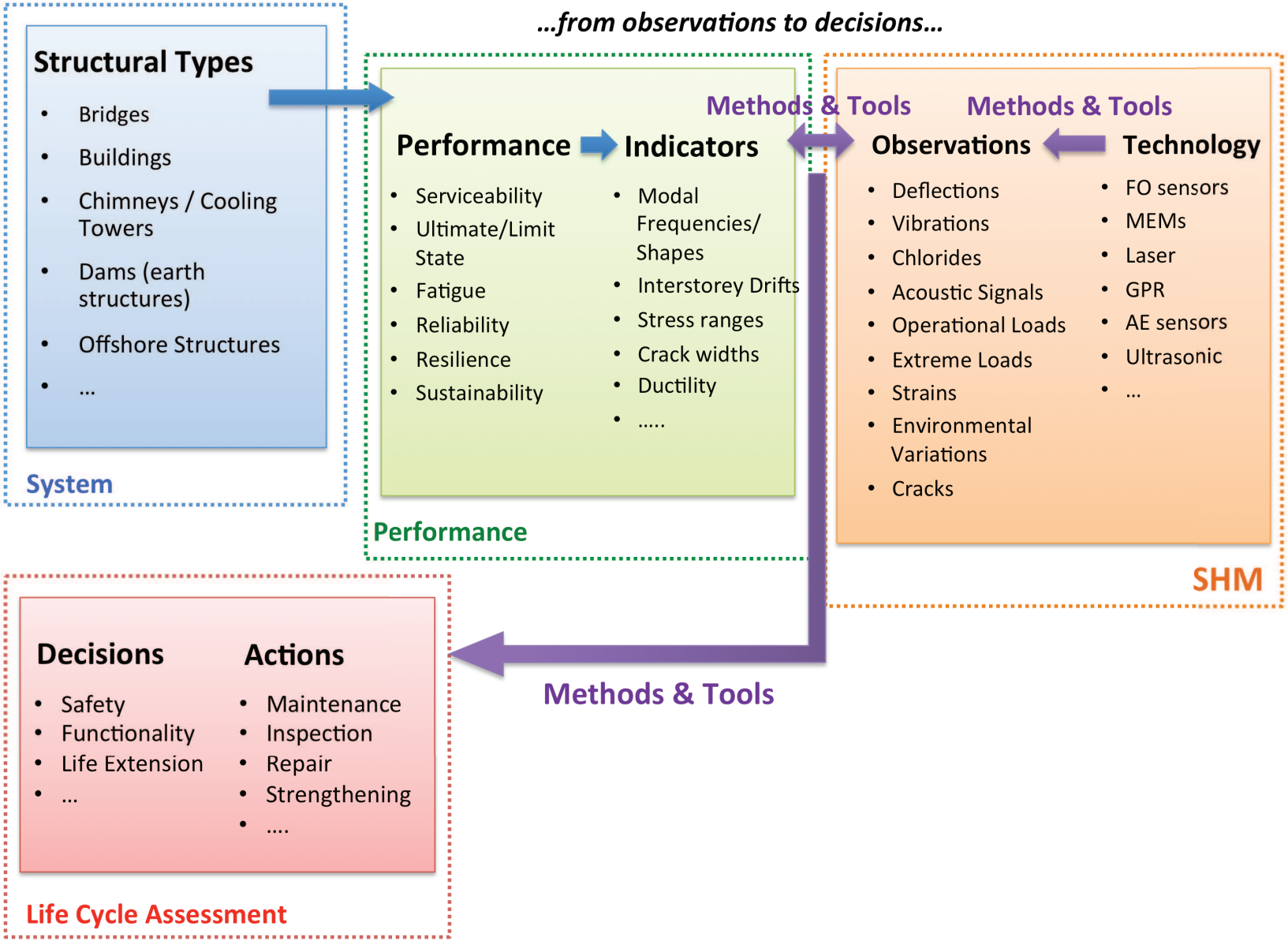
mode 5 - 12.41Hz - 2.8%



mode 6 - 13.25Hz - 3.2%



General framework



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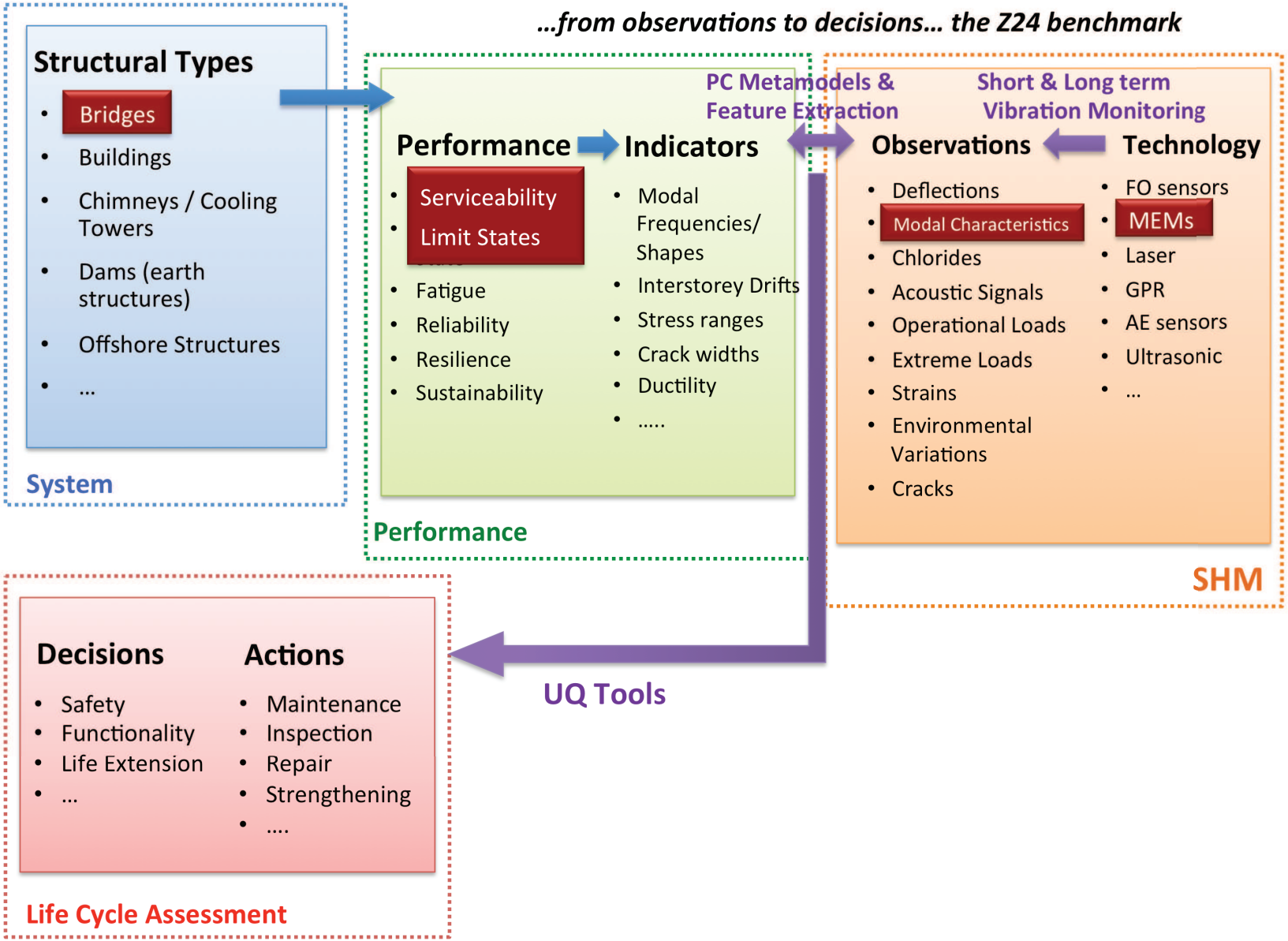
The Z24 bridge benchmarks



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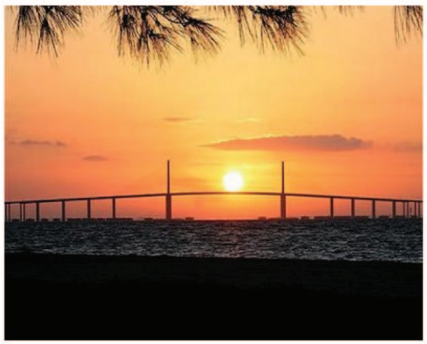
From long-term observations to performance indicators

Extraction of performance indicators based on ambient vibration response measurements.

Problem characteristics

Civil engineering structures are by default operating within continually changing environments.

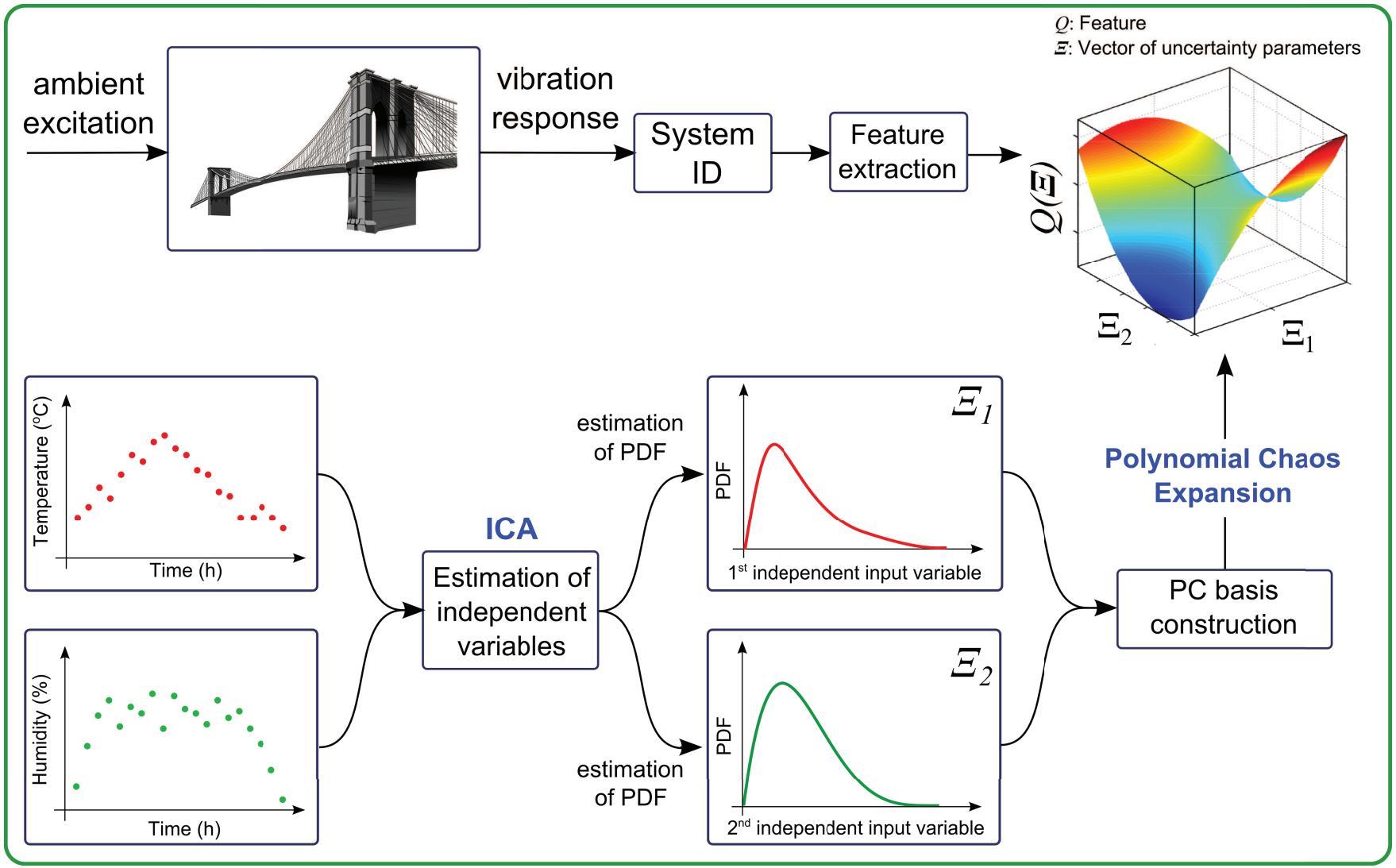
Environmental and other operating condition data should be incorporated into the structural ID framework.

Benefits of fusing operational condition data into structural ID

- Improved understanding of structural dynamics
- Improved design of new systems
- Improved Monitoring
- Condition Assessment
- Life – Cycle Management

From long-term observations to performance indicators

Stochastic Framework Structure



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Polynomial Chaos Metamodels

Problem definition

Consider a system $\mathcal{M}$ characterized by uncertain input parameters represented by independent random variables $\boldsymbol{\xi} = [\xi_1, \xi_2, \ldots, \xi_M]^\mathsf{T}$ of prescribed probability density function $f(\boldsymbol{\xi})$. The dynamic response of $\mathcal{M}$ to a given input excitation $x[t, \boldsymbol{\xi}]$ will also be a random variable:

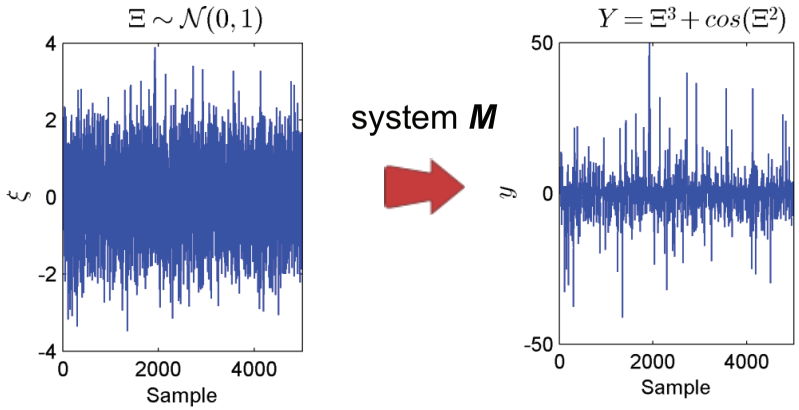
$$y[t, \boldsymbol{\xi}] = \mathcal{M}(x[1, \boldsymbol{\xi}], x[2, \boldsymbol{\xi}], \ldots, x[t, \boldsymbol{\xi}], \boldsymbol{\xi}), \quad t = 1, 2, \ldots, T$$

The PC basis basis $\phi_{\boldsymbol{d}(j)}$ comprises polynomials that are orthonormal with respect to the joint probability density function of $\boldsymbol{\xi}$. Assume the univariate case (single variable):

$$E[\phi_{\boldsymbol{\alpha}}(\boldsymbol{\xi}), \phi_{\boldsymbol{\beta}}(\boldsymbol{\xi})] = \delta_{\boldsymbol{\alpha},\boldsymbol{\beta}} = \begin{cases} 1 & \text{for } \alpha = \beta \\ 0 & \text{otherwise} \end{cases}$$

PDF	Support	Polynomials
Normal (Gaussian)	$(-\infty, \infty)$	Hermite
Uniform	$[-1, 1]$	Legendre
Gamma	(0,1)	Laguerre
Chebyshev	(-1, 1)	Chebyshev
Beta	(-1, 1)	Jacobi

Polynomial Chaos Expansion



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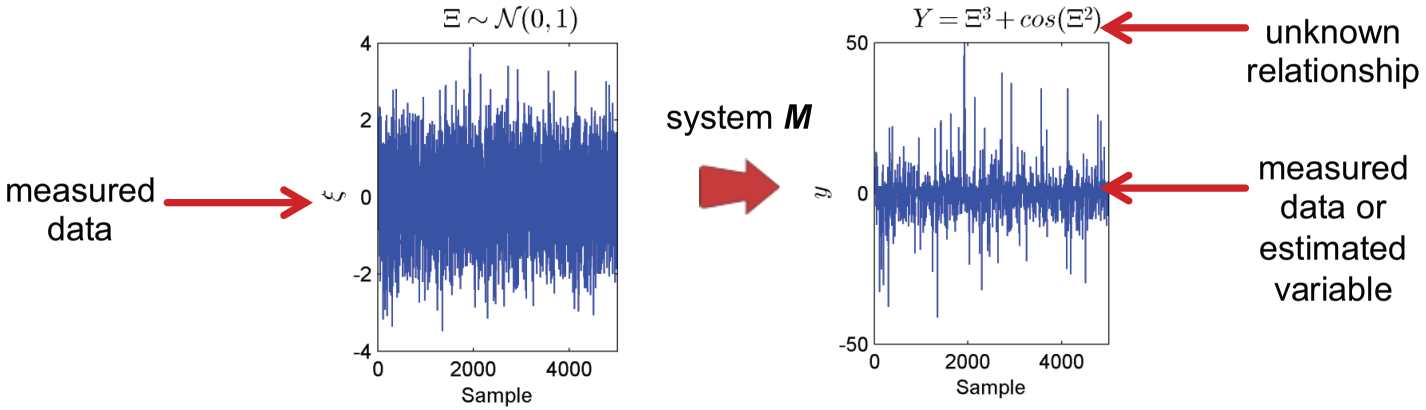

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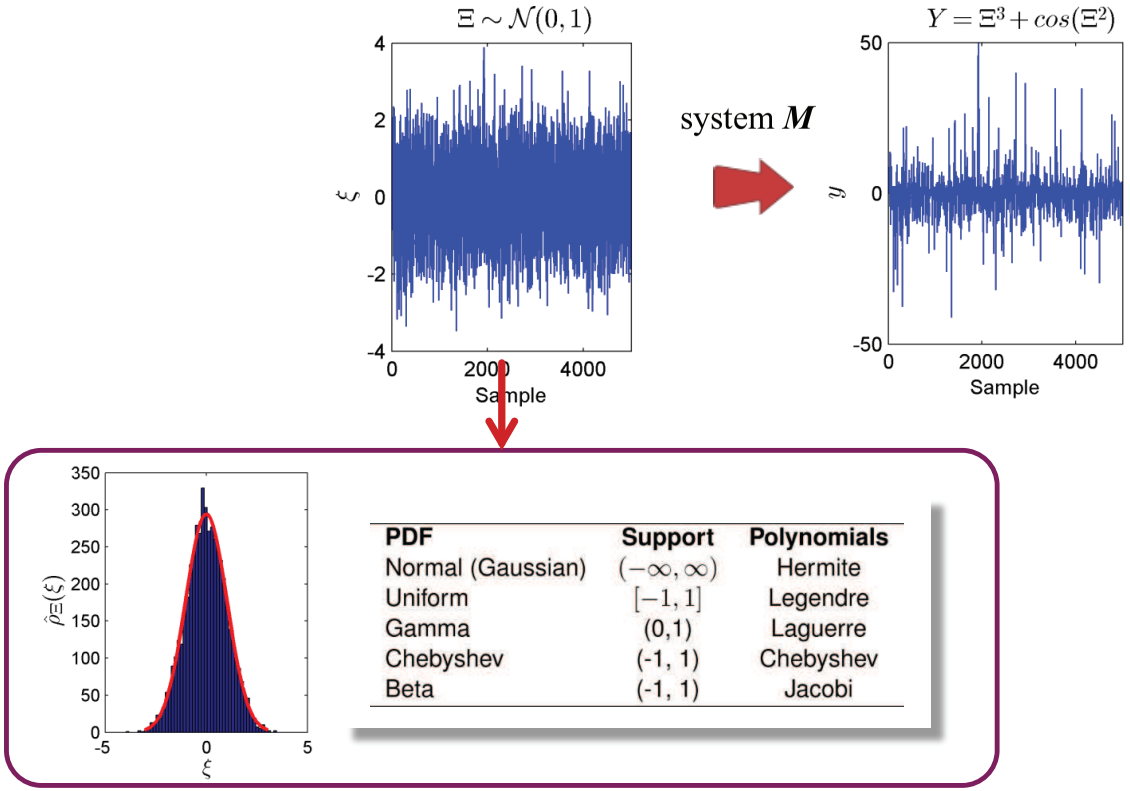

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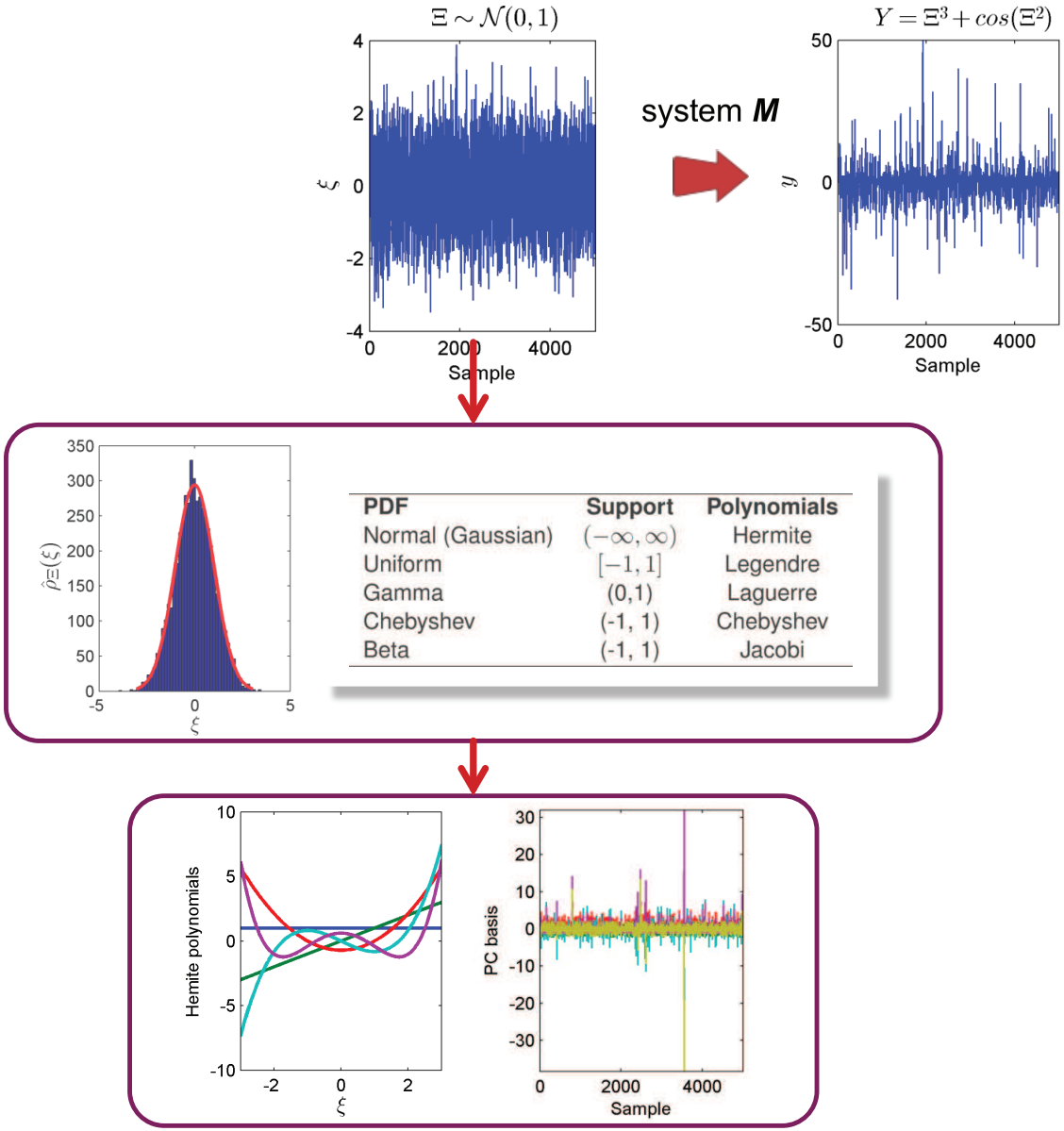

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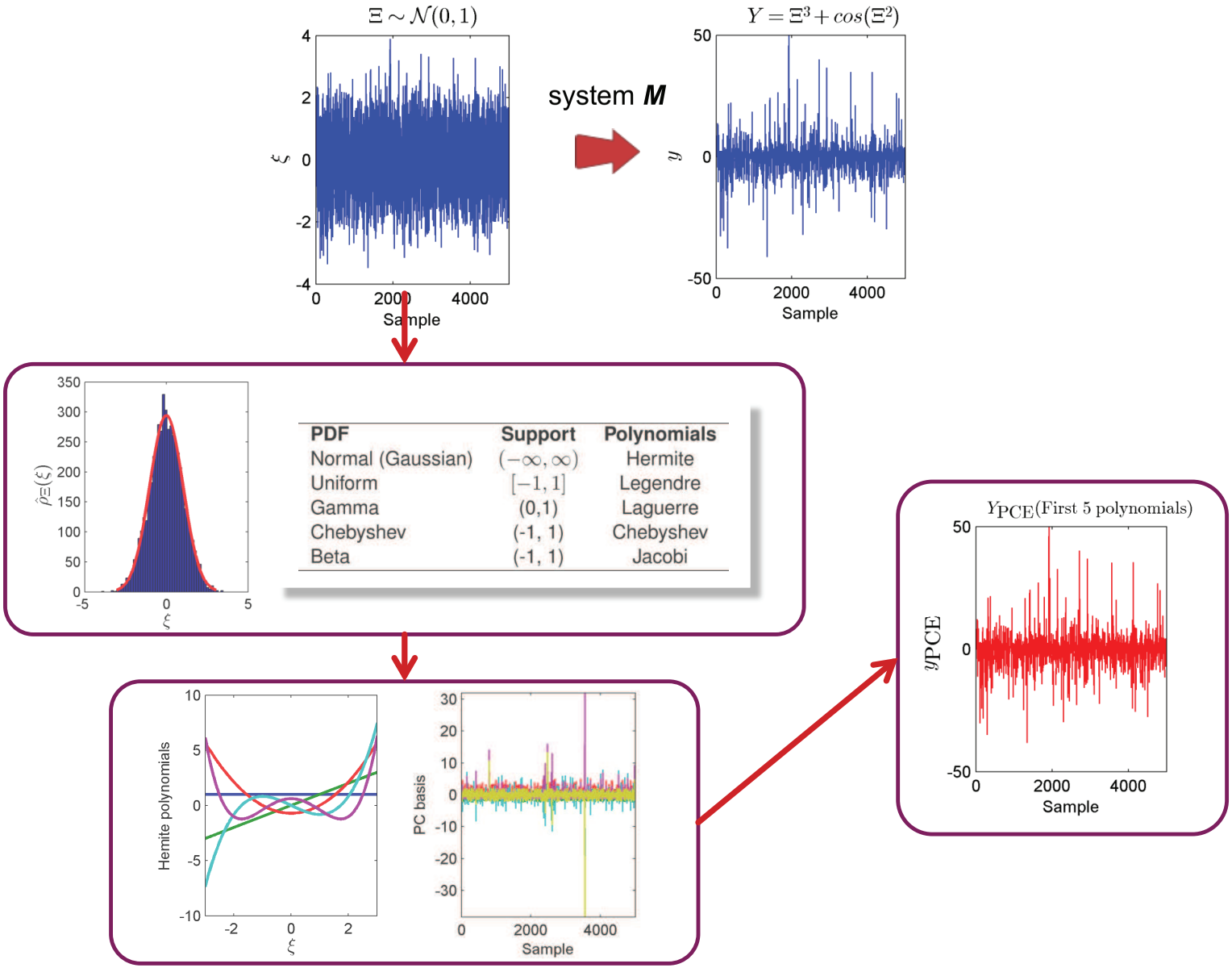

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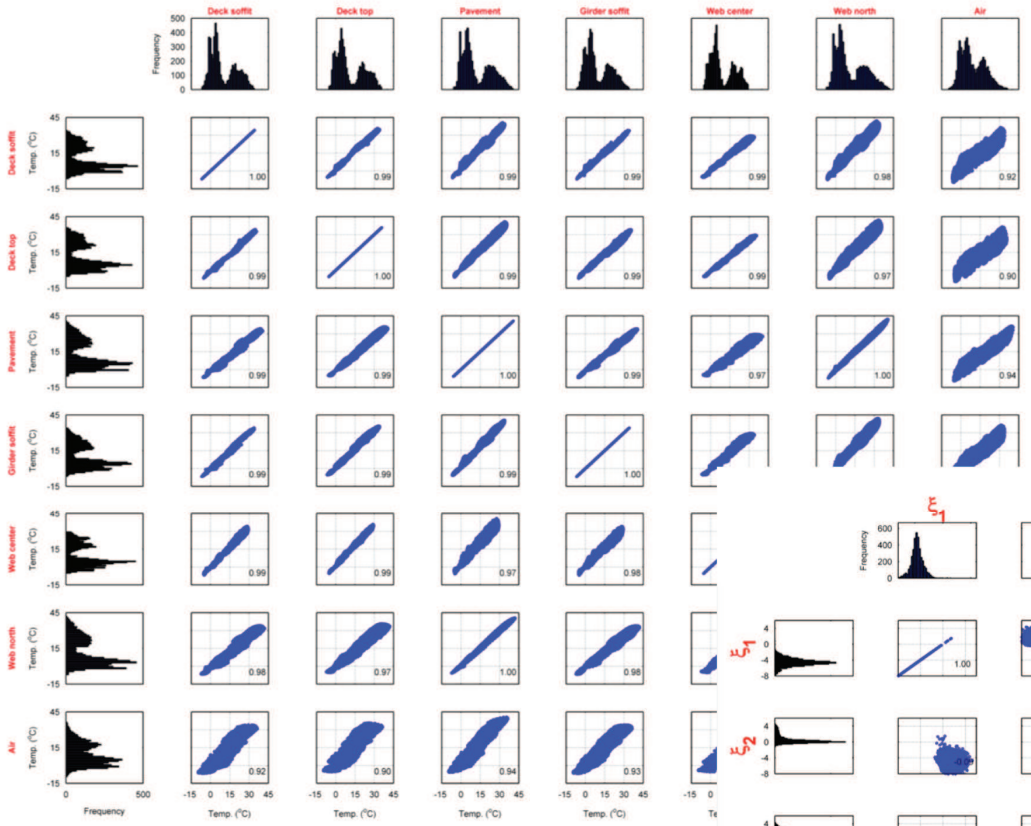
The ICA algorithm



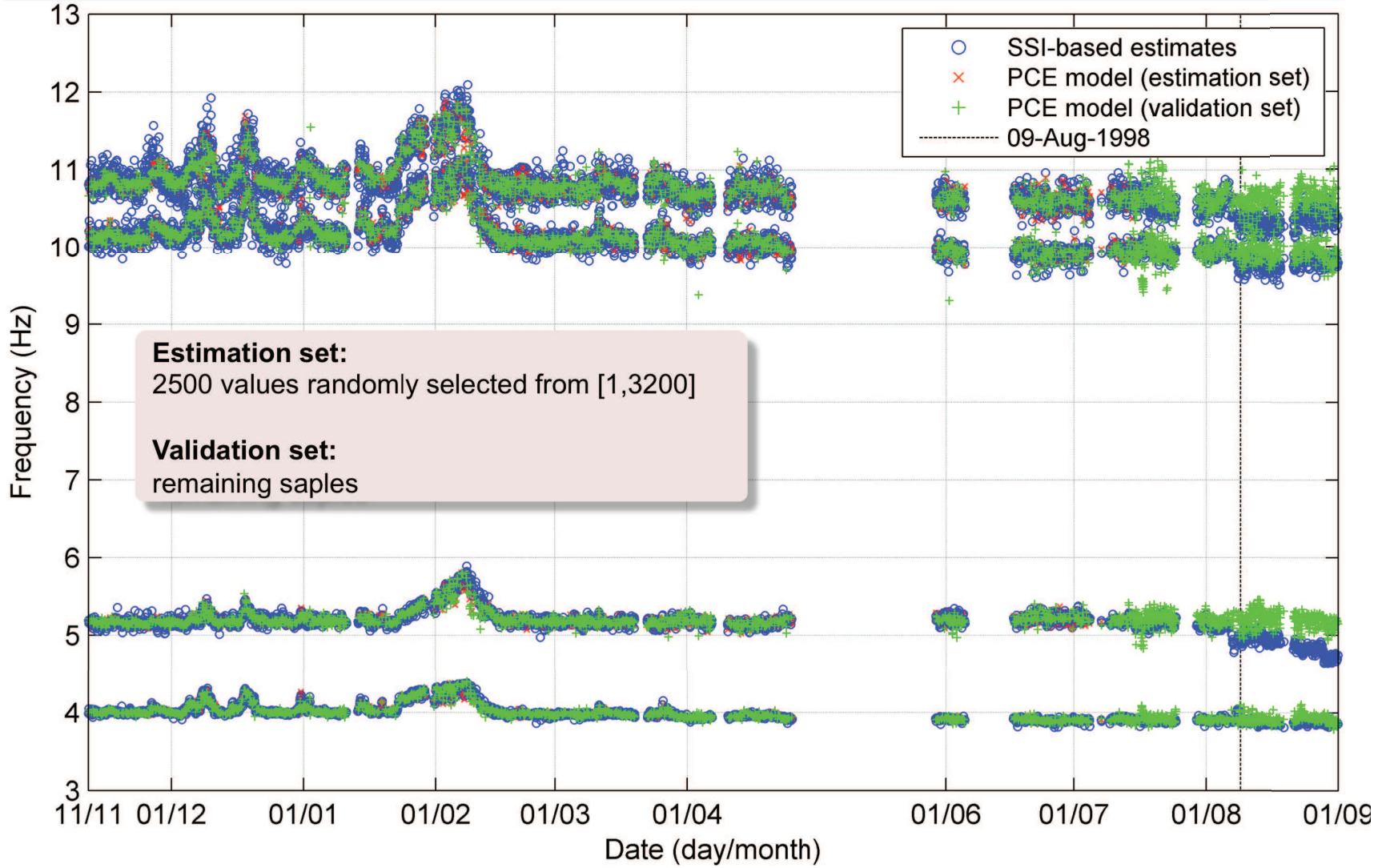
Independent Component Analysis (ICA)

Allows for extraction of salient independent features.

Metamodel Prediction vs. Measurement

Multivariate Legendre polynomials of maximum order P = 3 used for the PC basis

ω_n	1	2	3	4
std(PCE error) (Hz) *(estimation set)*	0.0275	0.0528	0.1013	0.1313



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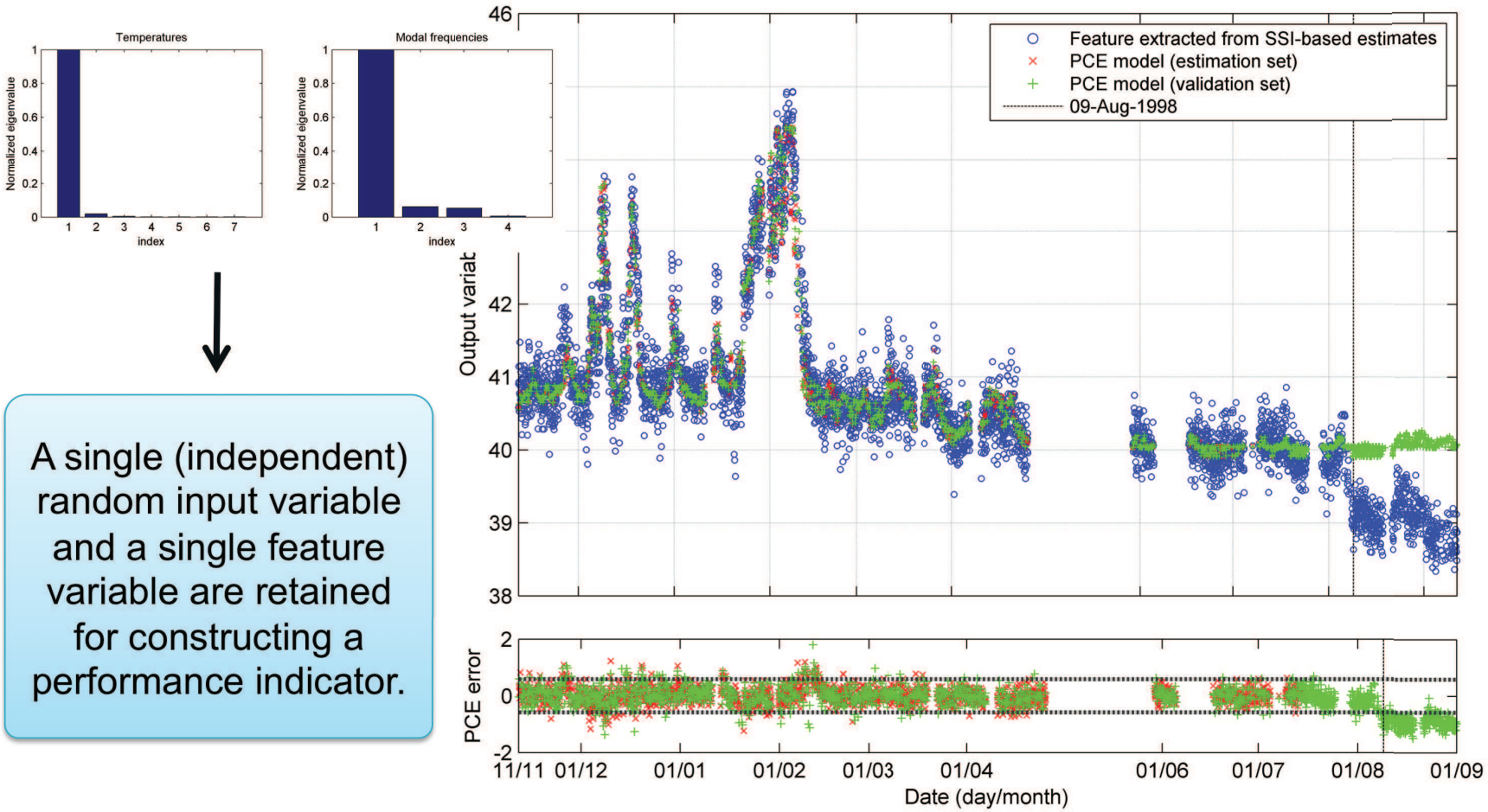
Performance Indicator

An Independent Component Analysis algorithm is utilized for estimating independent random variables from both temperature measurements (input variables) and the estimated natural frequencies (output)



A single (independent) random input variable and a single feature variable are retained for constructing a performance indicator.

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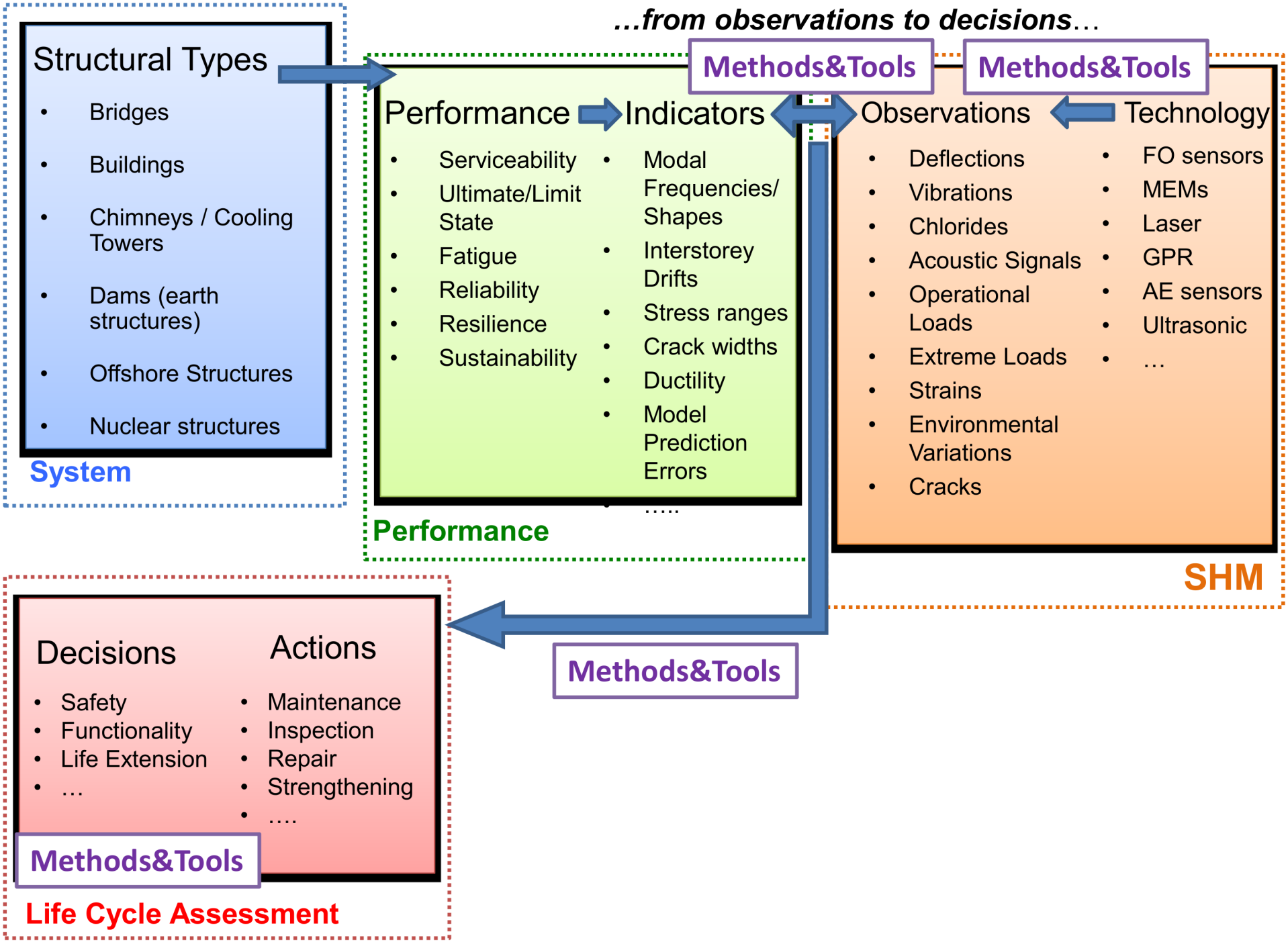

…from observations to decisions…
Structural Types
Bridges
Buildings
Chimneys / Cooling Towers
Dams (earth structures)
Offshore Structures
Nuclear structures
System
Methods&Tools
Performance
Indicators
Serviceability
Ultimate/Limit State
Fatigue
Reliability
Resilience
Sustainability
Modal Frequencies/ Shapes
Interstorey Drifts
Stress ranges
Crack widths
Ductility
Model Prediction Errors
…..
Performance
Methods&Tools
Observations
Technology
Deflections
Vibrations
Chlorides
Acoustic Signals
Operational Loads
Extreme Loads
Strains
Environmental Variations
Cracks
FO sensors
MEMs
Laser
GPR
AE sensors
Ultrasonic
…
SHM
Methods&Tools
Decisions
Safety
Functionality
Life Extension
…
Actions
Maintenance
Inspection
Repair
Strengthening
….
Methods&Tools
Life Cycle Assessment

From short-term sensing data to modal characteristics

Modal parameter estimation with subspace-based system identification

→ Output-only sensor data y_k under unknown ambient excitation

→ Identification of system matrices (A, C) of discrete-time state space model from y_k

→ Modal parameters are obtained from eigenvalues and eigenvectors of (A, C)

$$\begin{aligned} \mathcal{M}\ddot{z} + \mathcal{C}\dot{z} + \mathcal{K}z &= \nu \\ y &= L\ddot{z} + e \end{aligned} \quad \longleftrightarrow \quad \begin{aligned} x_{k+1} &= Ax_k + v_k \\ y_k &= Cx_k + w_k \end{aligned}$$

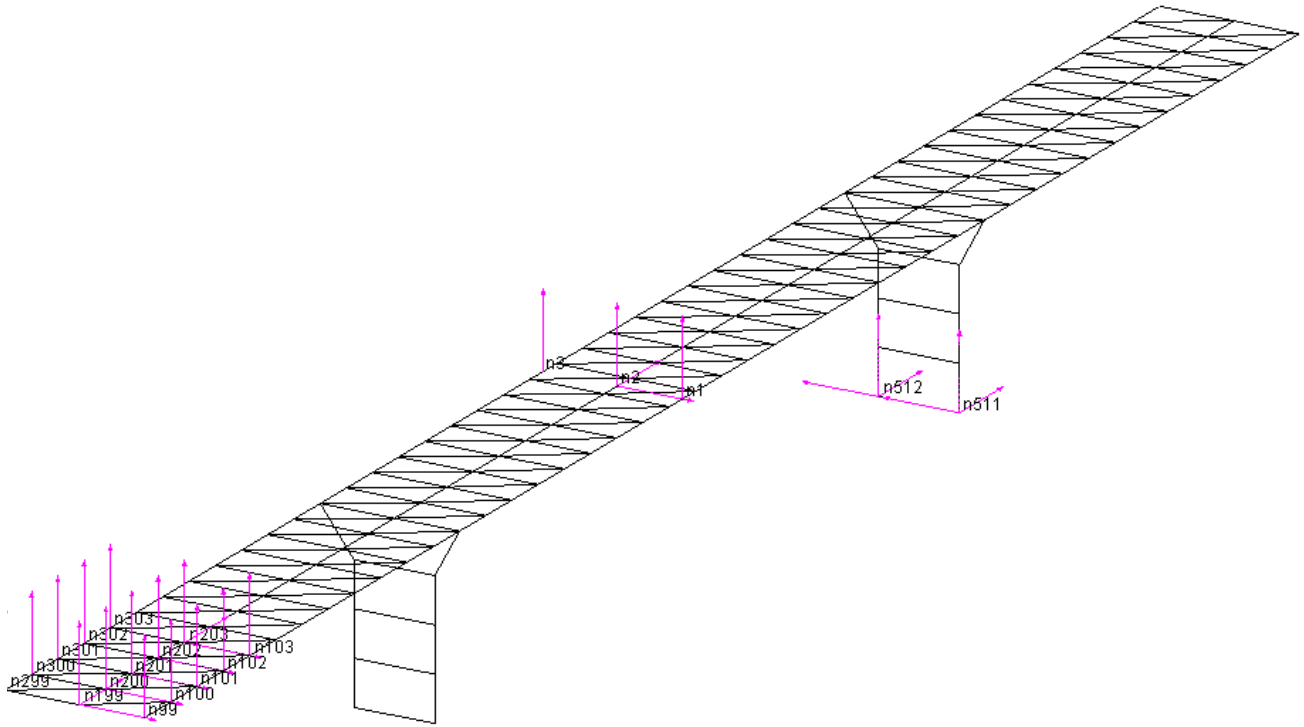
Methods

→ Modal parameter identification from multiple measurement setups with moving and fixed sensors

→ Uncertainty quantification of estimates

From short-term sensing data to modal characteristics

Sensor configuration in 9 measurement setups



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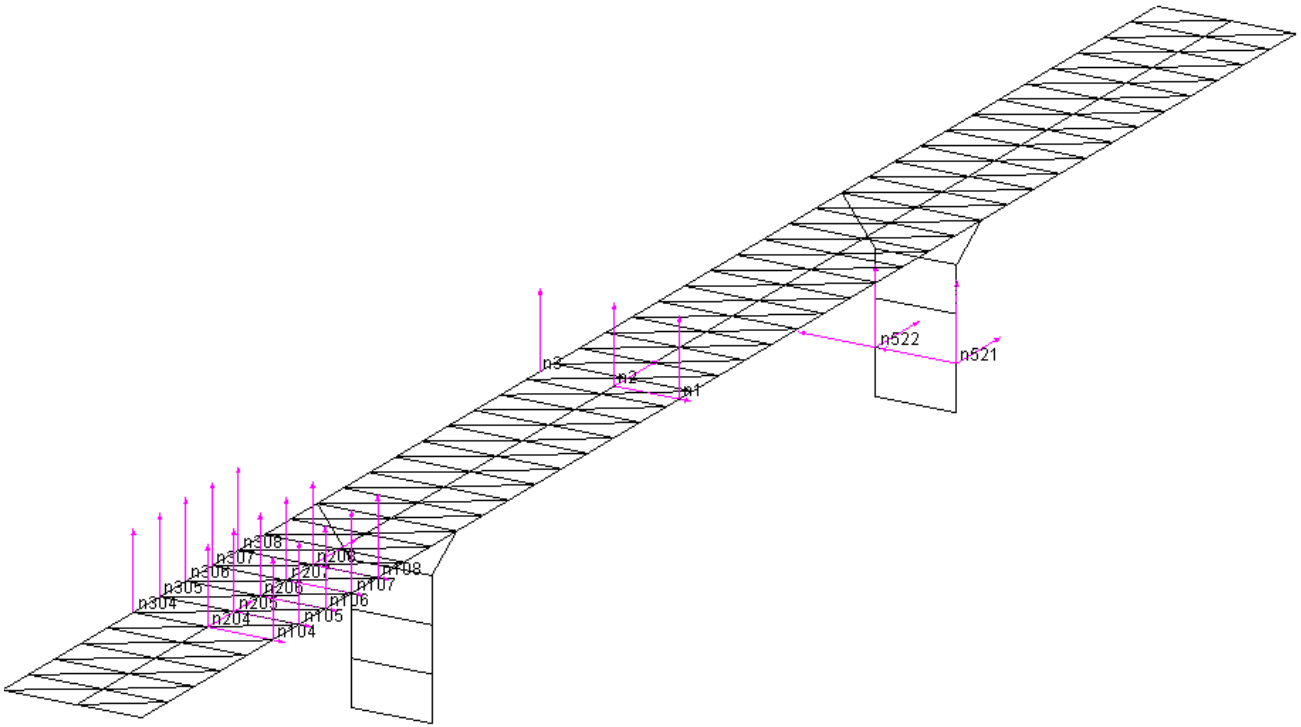

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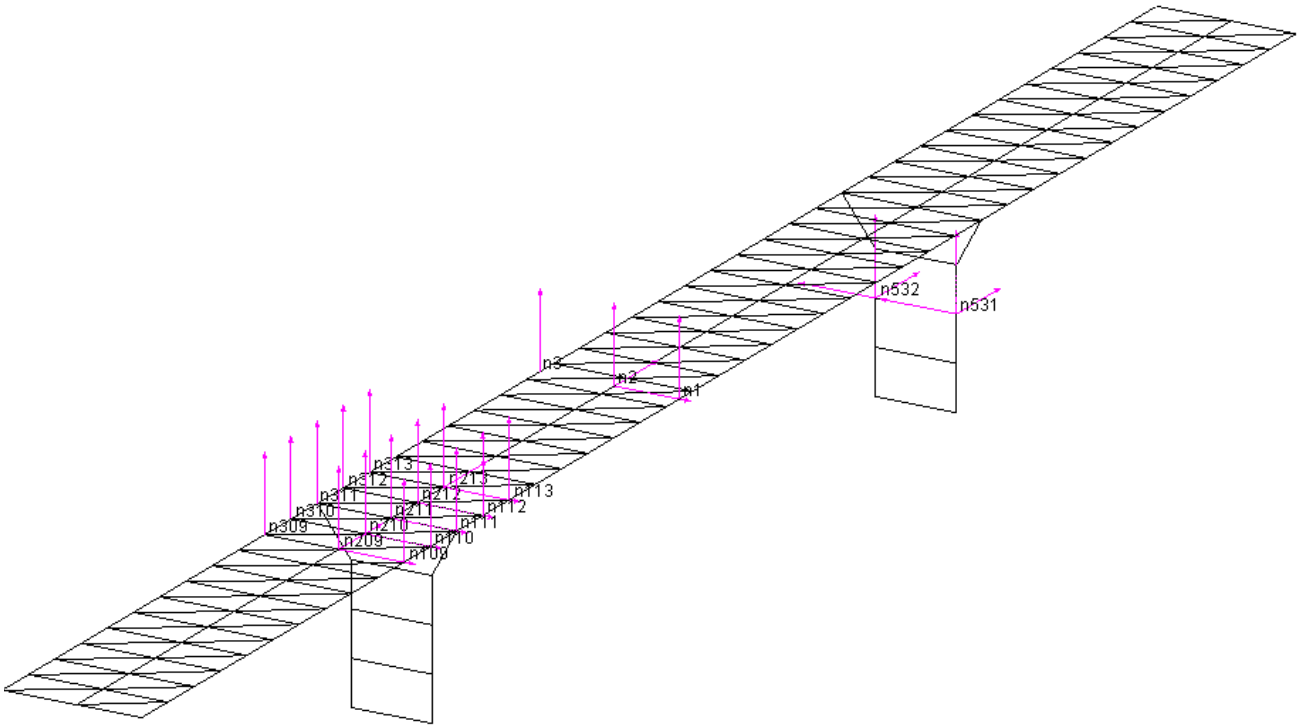

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From short-term sensing data to modal characteristics

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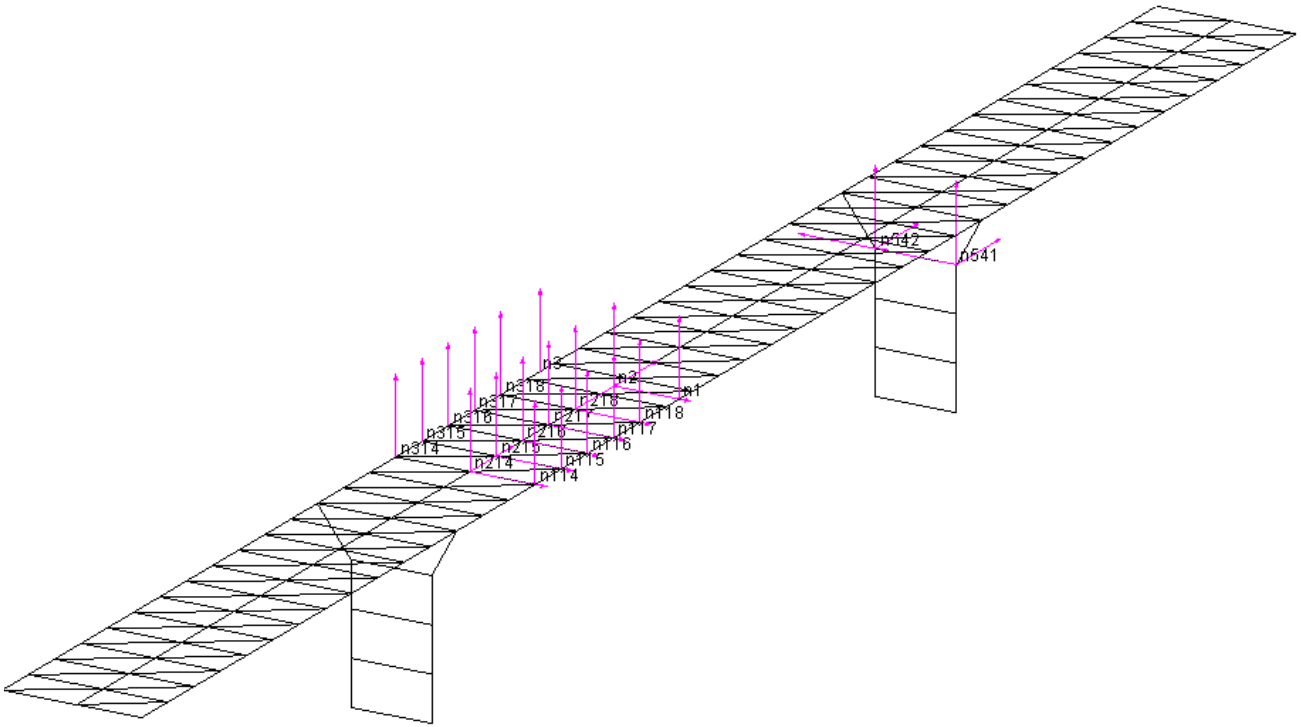

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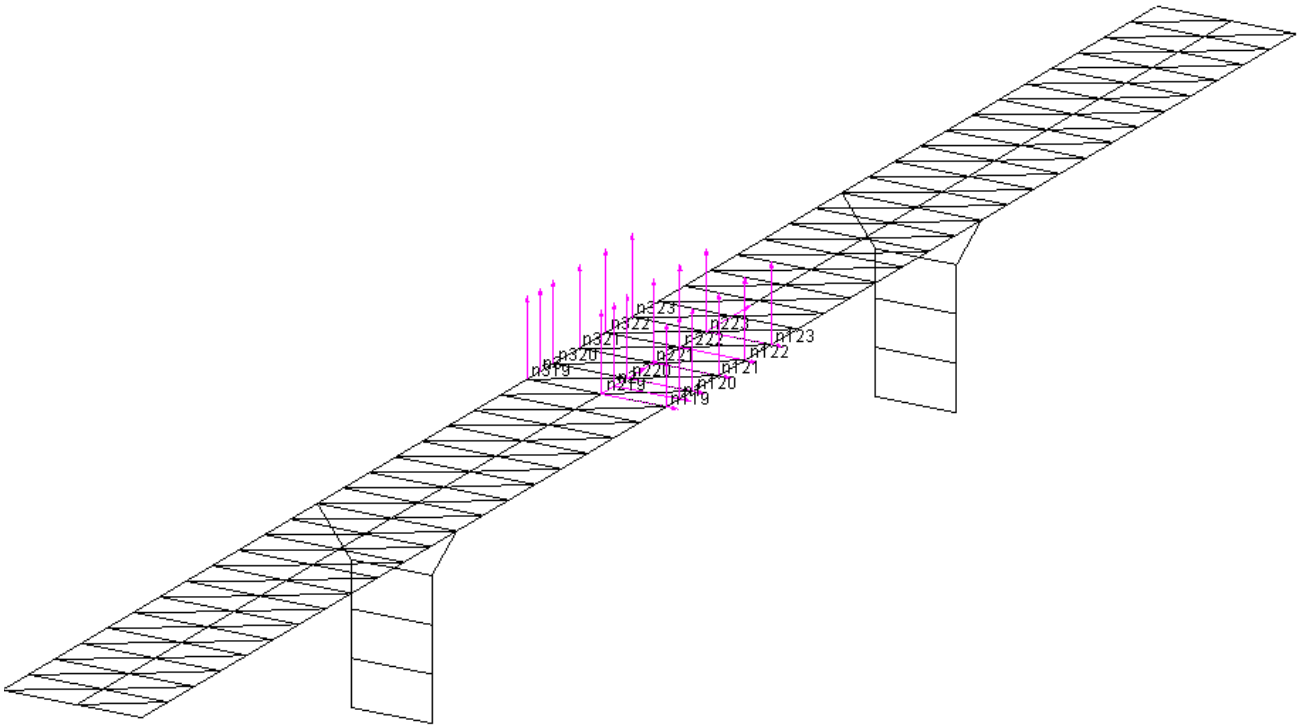

From short-term sensing data to modal characteristics

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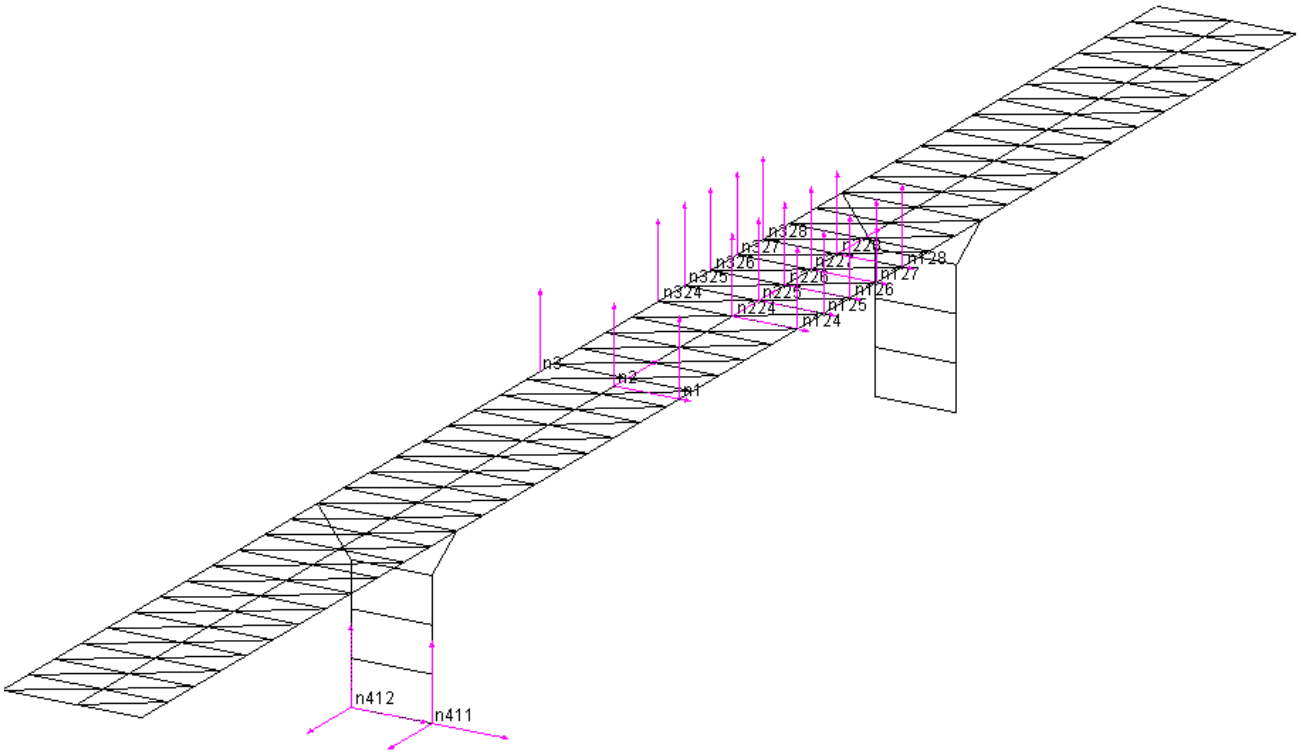

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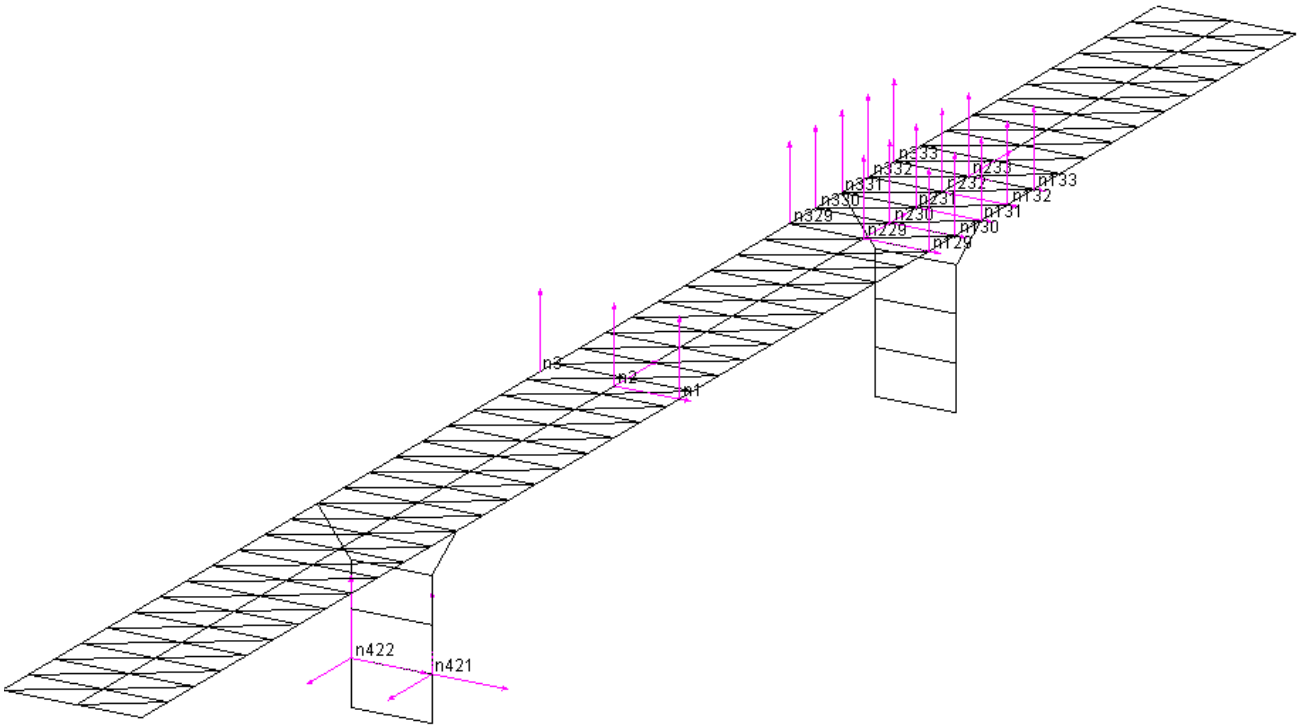

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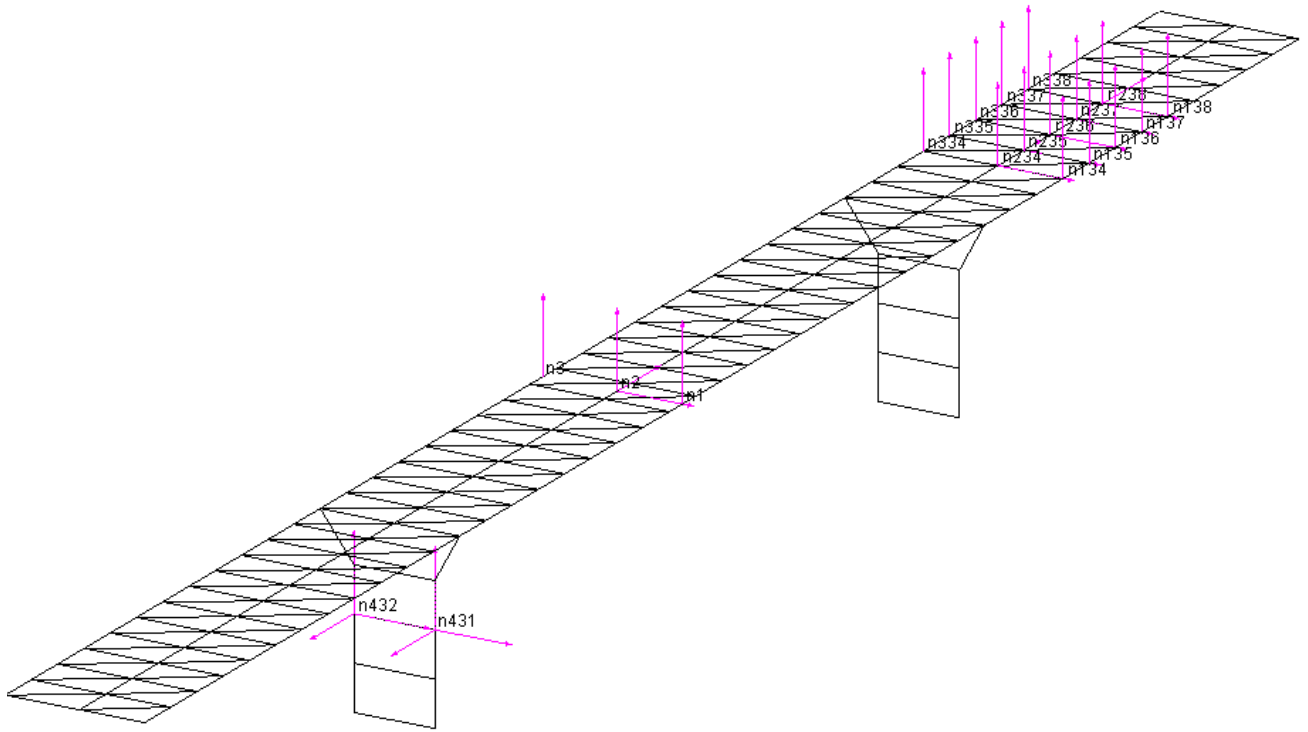

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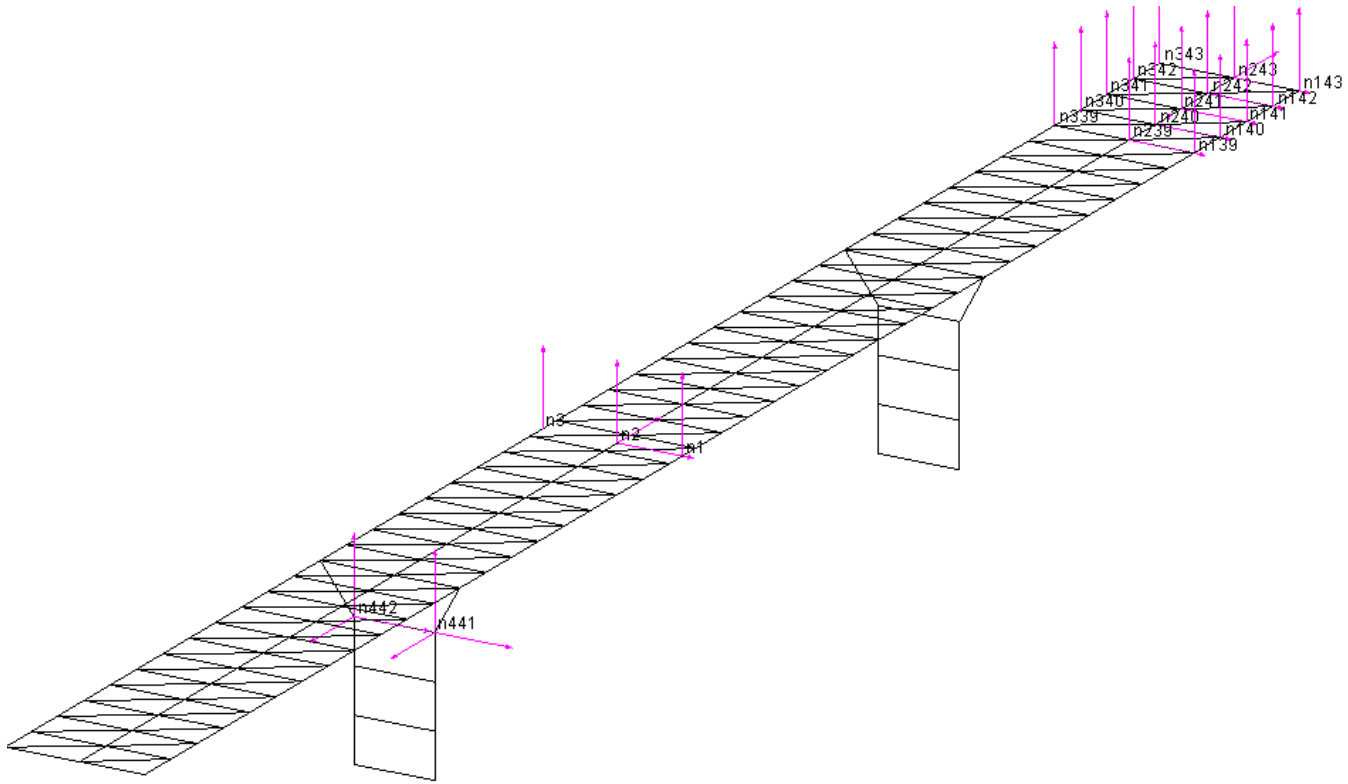

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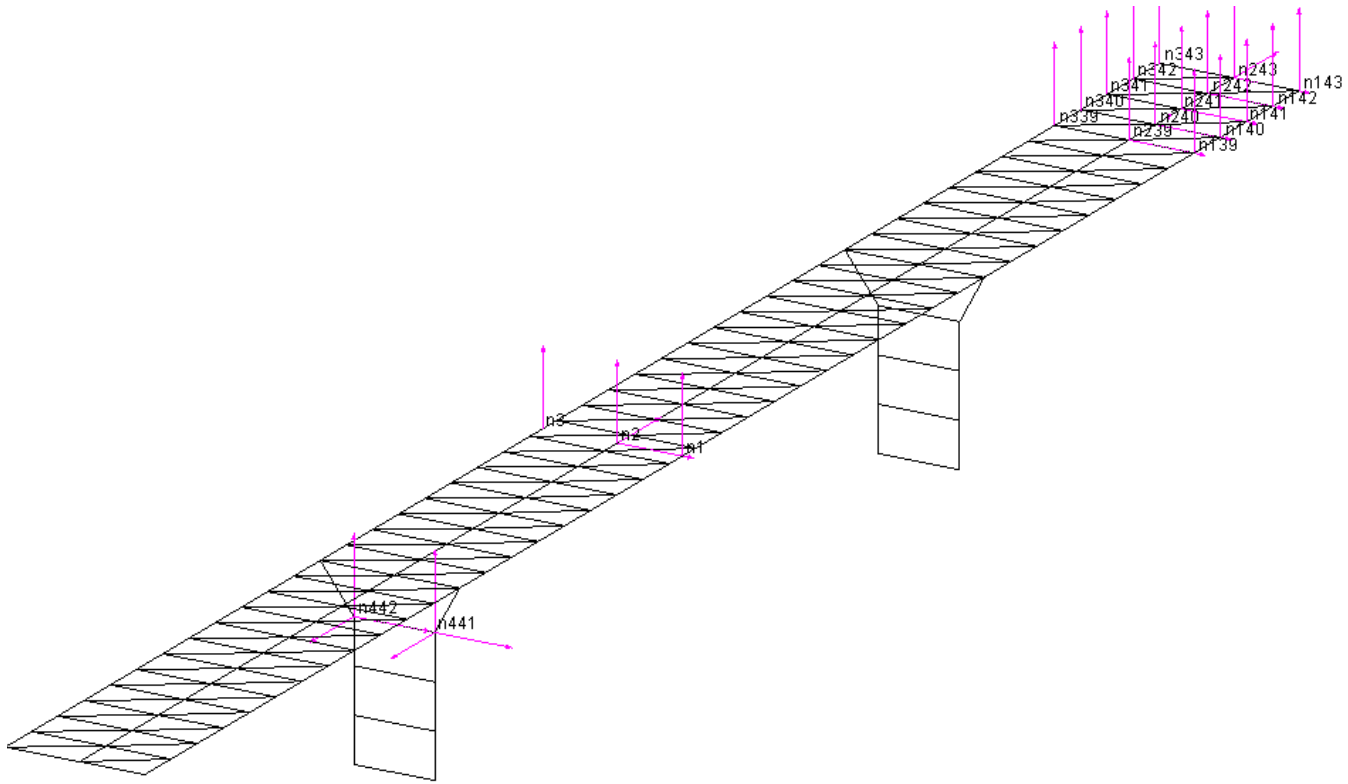
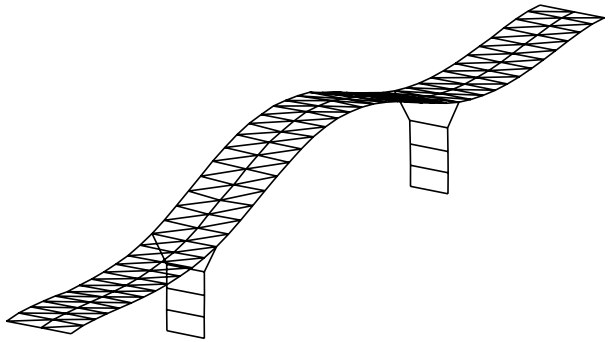


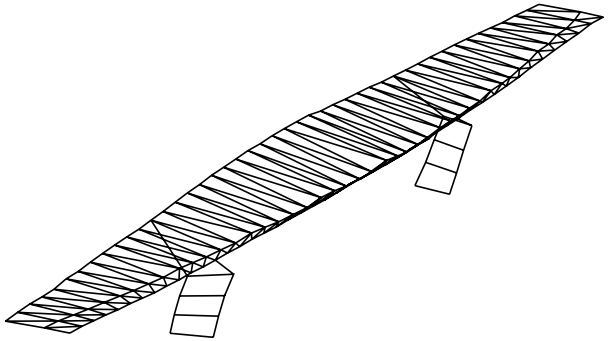
→ “Normalization” of data with respect to fixed sensors and merging for global system identification

Modal parameter estimates

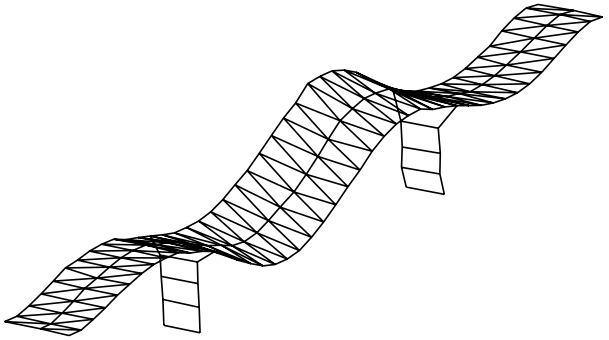
mode 1: 3.86 Hz, 0.6%



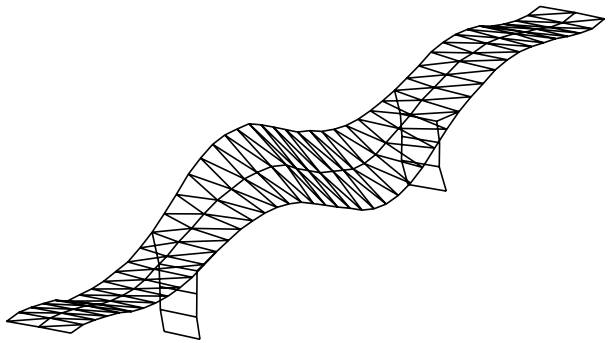
mode 2: 4.88 Hz, 1.4%



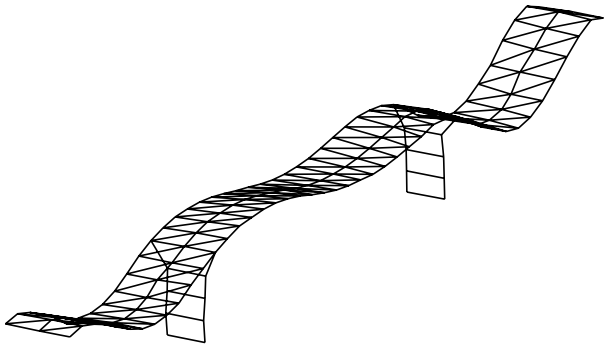
mode 3: 9.79 Hz, 1.4%



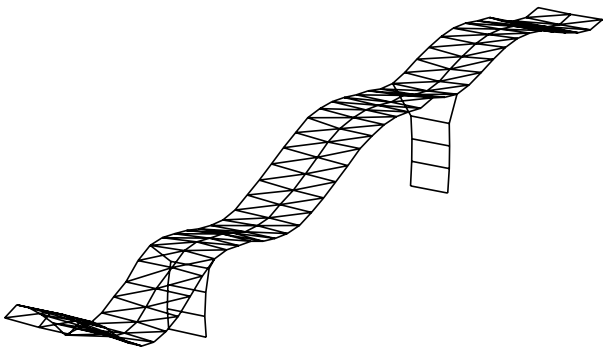
mode 4: 10.3 Hz, 1.9%



mode 5: 12.3 Hz, 3.4%

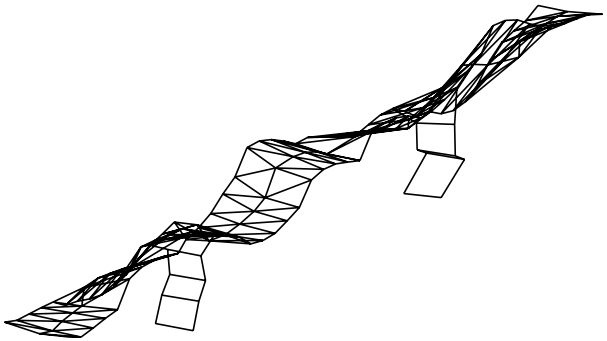


mode 6: 13.3 Hz, 3.5%

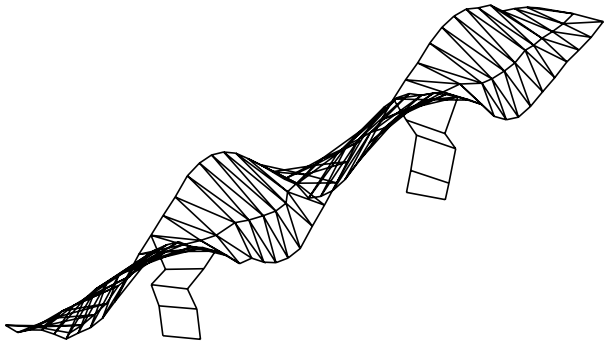


Modal parameter estimates

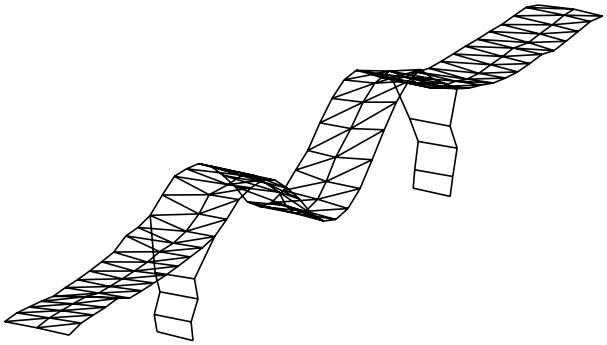
mode 7: 17.2 Hz, 7.2%



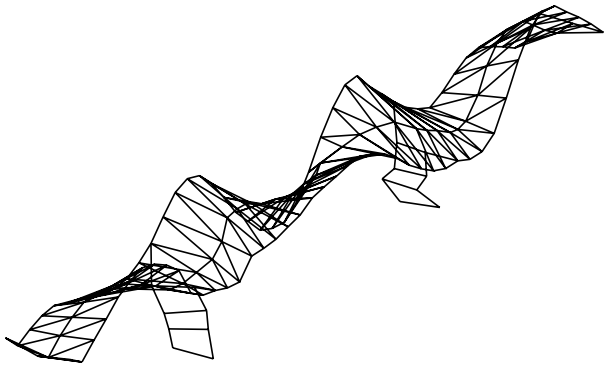
mode 8: 19.2 Hz, 2.8%



mode 9: 19.8 Hz, 4.0%



mode 10: 26.8 Hz, 4.9%

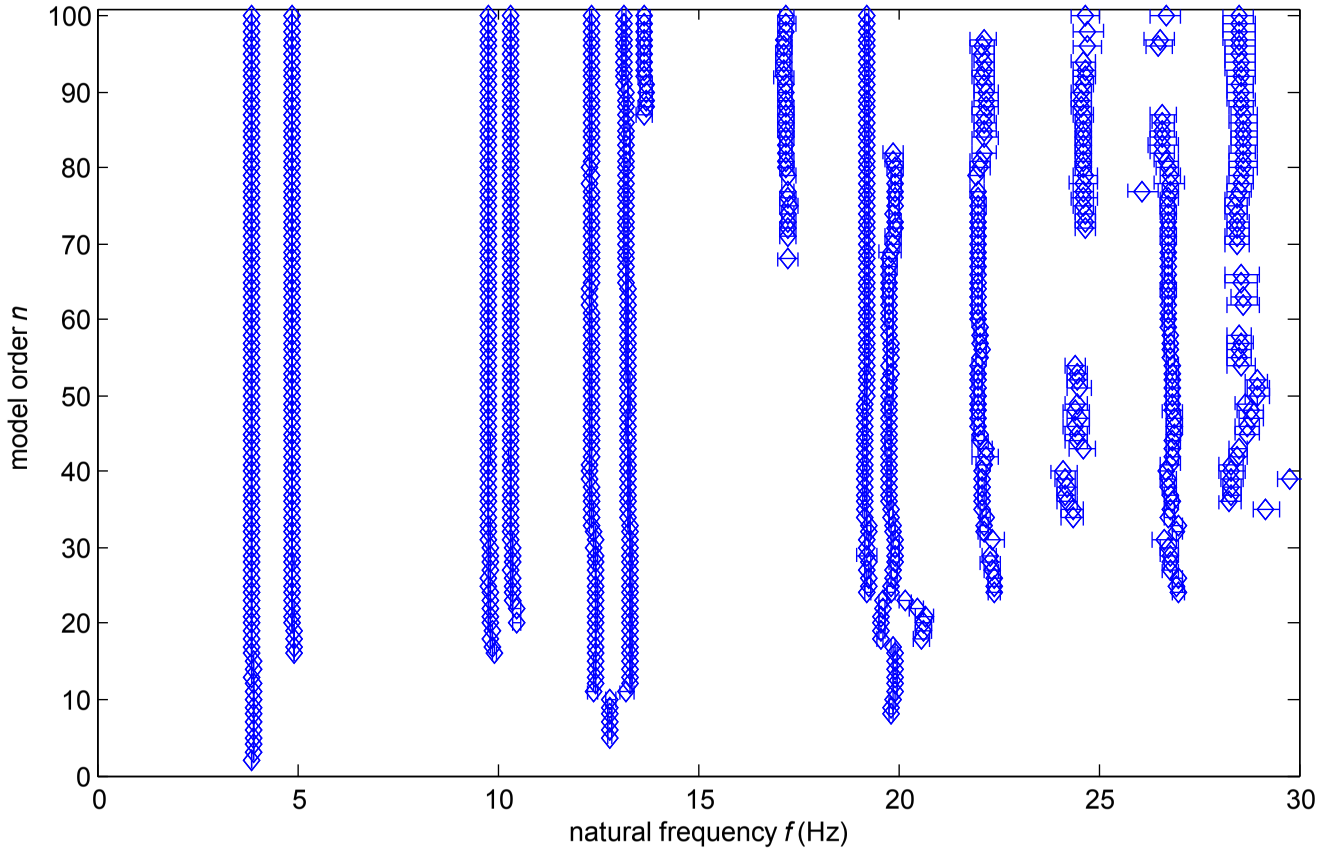


Uncertainty quantification

- → Sources of uncertainty: unknown inputs, measurement noise, finite data
- → Modal parameter estimates are (asymptotically) Gaussian

$$\hat{f} \sim \mathcal{N}(f, \sigma_f^2)$$

- → Estimate modal parameter f and its standard deviation σ_f on the same dataset
- → Estimates for frequencies, damping ratios and mode shapes



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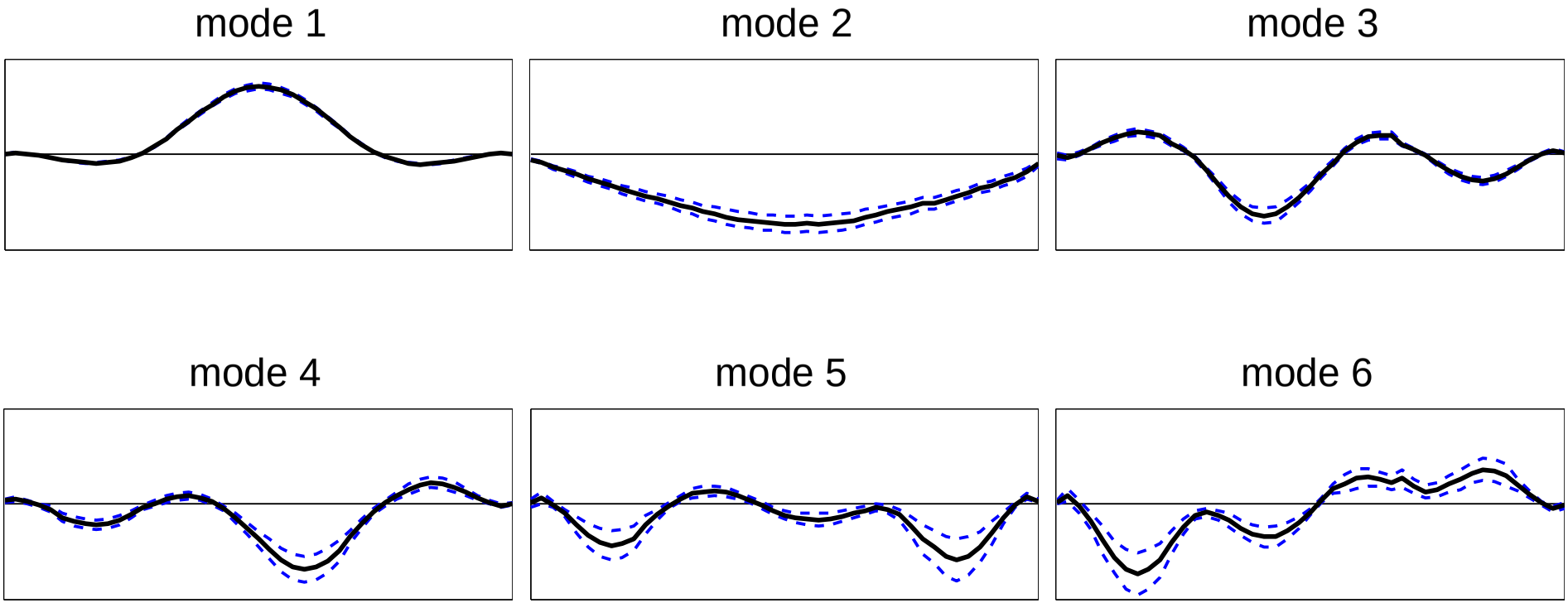
Uncertainty quantification

Identified frequencies and damping ratios with coefficients of variation.

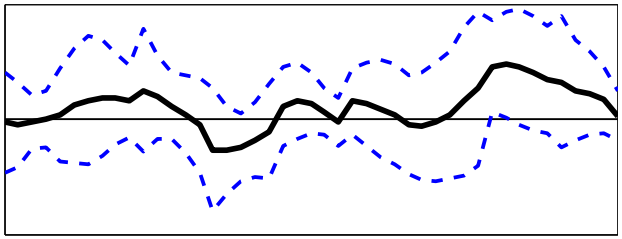
Mode	f_i (Hz)	$100\,\sigma_{f_i}/f_i$	ξ_i (%)	$100\,\sigma_{\xi_i}/\xi_i$
1	3.864	0.05	0.61	8.8
2	4.883	0.05	1.43	4.7
3	9.787	0.06	1.36	3.6
4	10.32	0.09	1.87	5.4
5	12.33	0.19	3.40	4.9
6	13.27	0.16	3.47	4.3
7	17.20	0.95	7.18	14
8	19.22	0.21	2.83	8.6
9	19.79	0.23	3.97	5.5
10	26.83	0.58	4.86	13

Uncertainty quantification

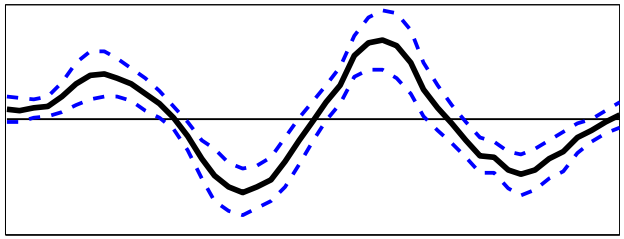


Uncertainty quantification

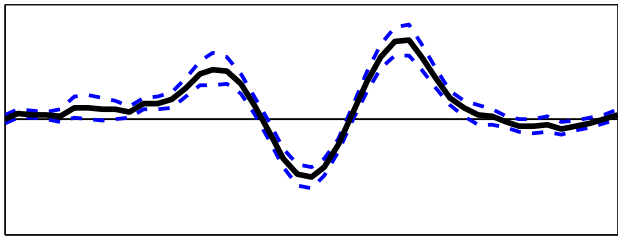
mode 7



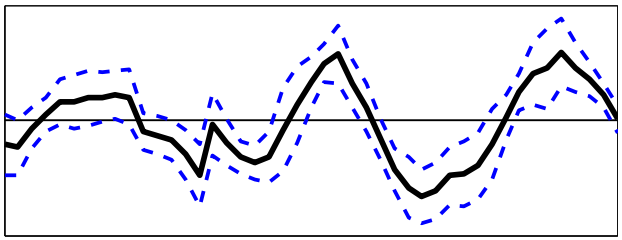
mode 8



mode 9



mode 10



References

Many benchmark results have already been reported by meany researchers.

Overviews can be found in

→ E. Reynders and G. De Roeck. Vibration-based damage identification: the Z24 benchmark. In M. Beer, I.A. Kougioumtzoglou, E. Patelli, and I.S.-K. Au, editors, Encyclopedia of Earthquake Engineering. Springer, 2015.

→ E. Reynders and G. De Roeck. Continuous vibration monitoring and progressive damage testing on the Z24 bridge. In C. Boller, F.K. Chang, and Y. Fujino, editors, Encyclopedia of Structural Health Monitoring, pages 2149-2158. John Wiley & Sons, New York, NY, 2009.

→ B. Peeters and C. Ventura. Comparative study of modal analysis techniques for bridge dynamic characteristics. Mechanical Systems and Signal Processing, 17(5):965-988, 2003.