ADVANCES IN VIBRATION-BASED STRUCTURAL HEALTH MONITORING OF BRIDGES

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Public Works and Government Services Canada

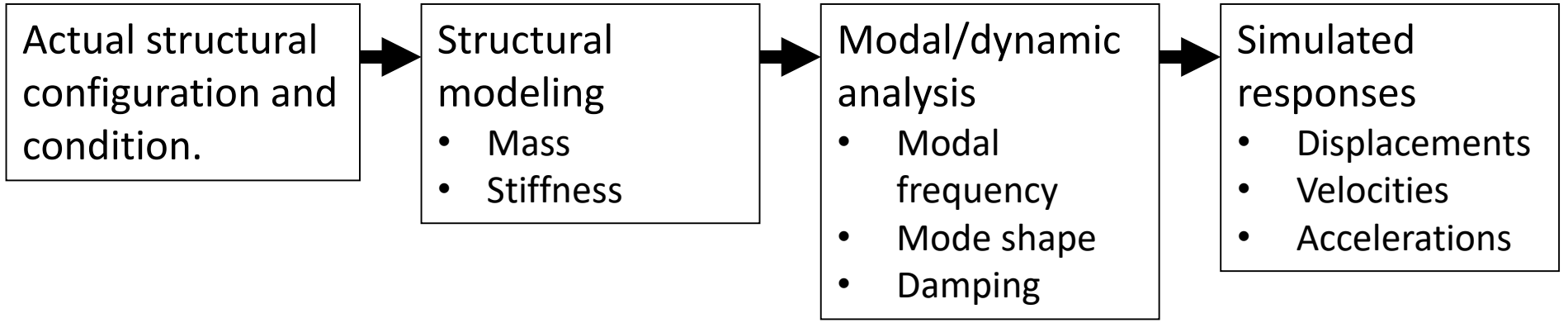
CONFEDERATION BRIDGE PONT DE LA CONFÉDÉRATION

Outline

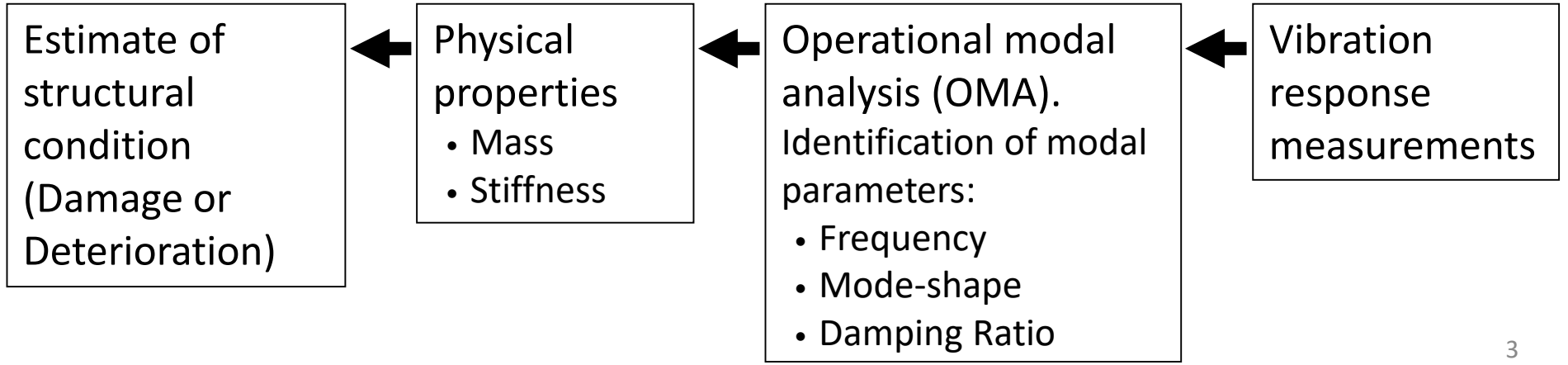
1. **Context** : Vibration based structural health monitoring (VBSHM)
2. **Confederation Bridge** monitoring project
3. **Vibration Instrumentation**
4. **SPPLASH *3*** data processing application
5. **Historical database** of raw and processed vibration response data
6. **Statistical analysis of OMA results**
7. **Conclusions**

Research topic – Vibration based structural health monitoring (VBSHM)

Structural analysis and structural dynamics



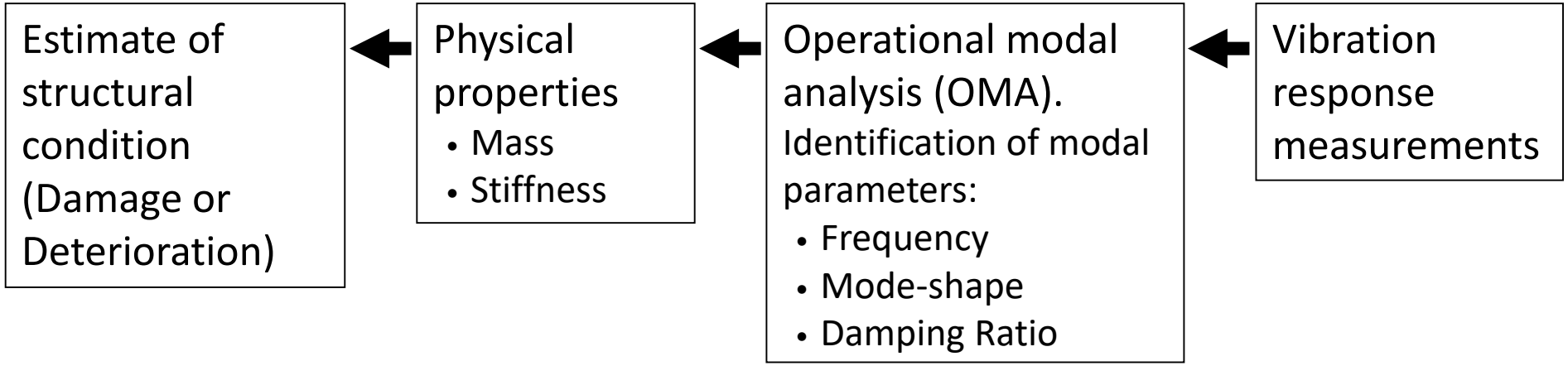
Vibration based structural health monitoring (VBSHM) of civil engineering structures



Research topic - VBSHM

Vibration based structural health monitoring (VBSHM) of civil engineering structures

Vibration responses carry the essential information about structural health :



Theory : Changes in identified modal parameters indicate change in structural condition/damage.

Challenge : Noise and uncertainty of operational response data (vibration measurements) leads to variability of identified modal properties which may obscure the damage effects.

Objectives : To understand and minimize the variability of the identified modal properties and to develop accurate and sensitive vibration based condition assessment techniques that deal with the uncertainty and noise.

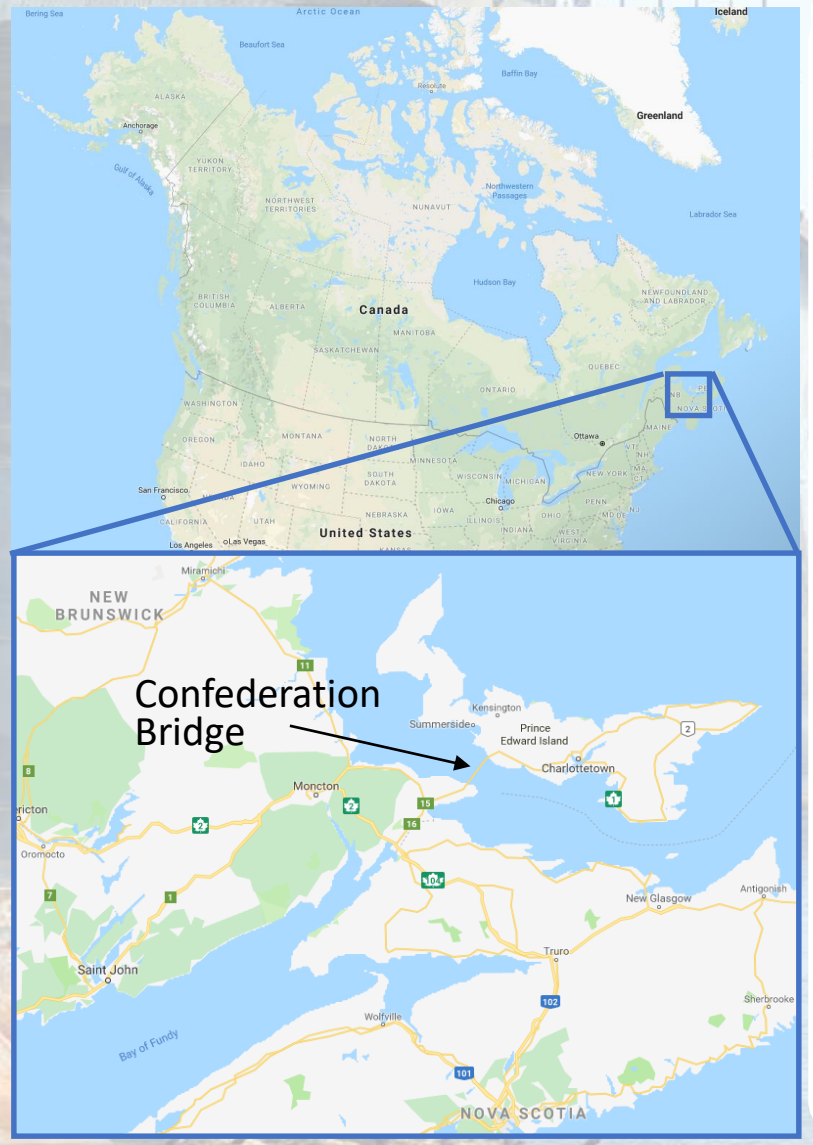
Means : Collecting, processing and analyzing vibration response data on a much larger scale than previously accomplished to establish trends and improve sensitivity of damage detection.

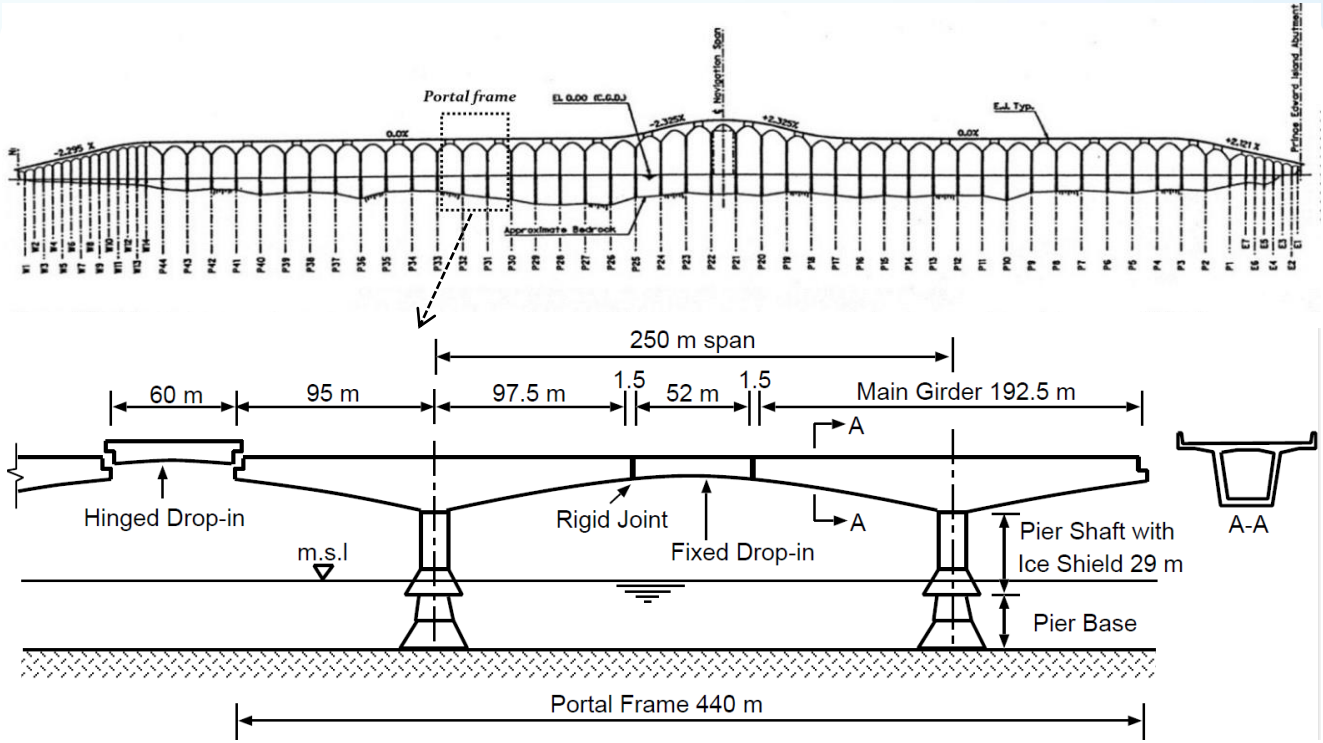
Confederation bridge monitoring project

Public Works and Government Services Canada

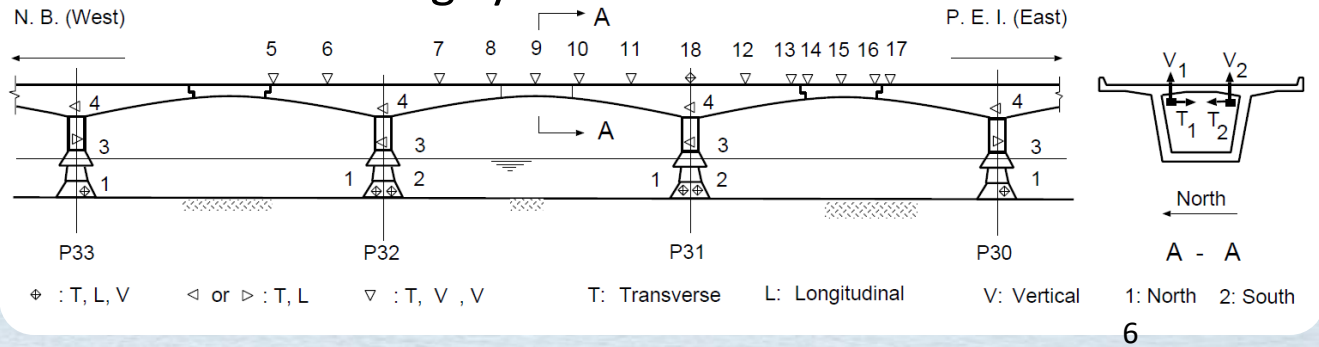
Confederation bridge monitoring project

1. Research topic
2. **Confederation Bridge**
   - Bridge behavior
   - Bridge dynamics
   - Variability
   - SPPLASH v1.0
3. Instrumentation renewal
4. SPPLASH 3
5. Historical database
6. Statistical analysis of OMA results
7. Conclusions





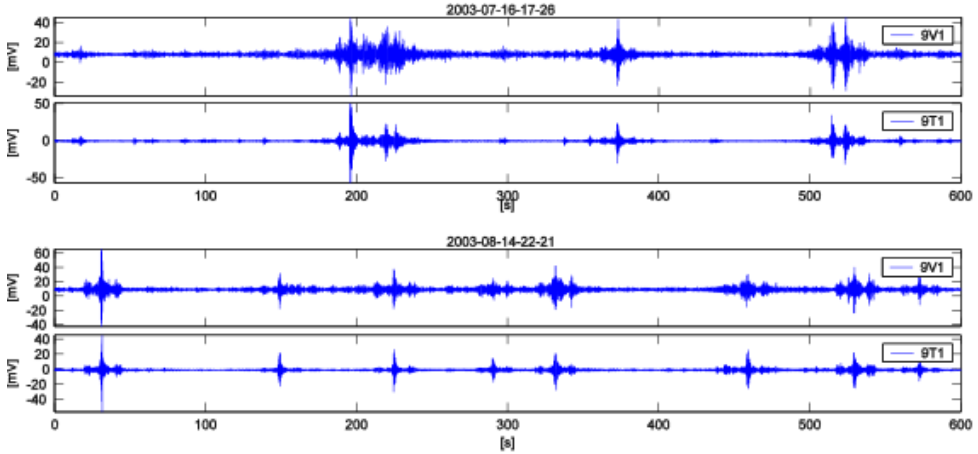
Vibration monitoring system:



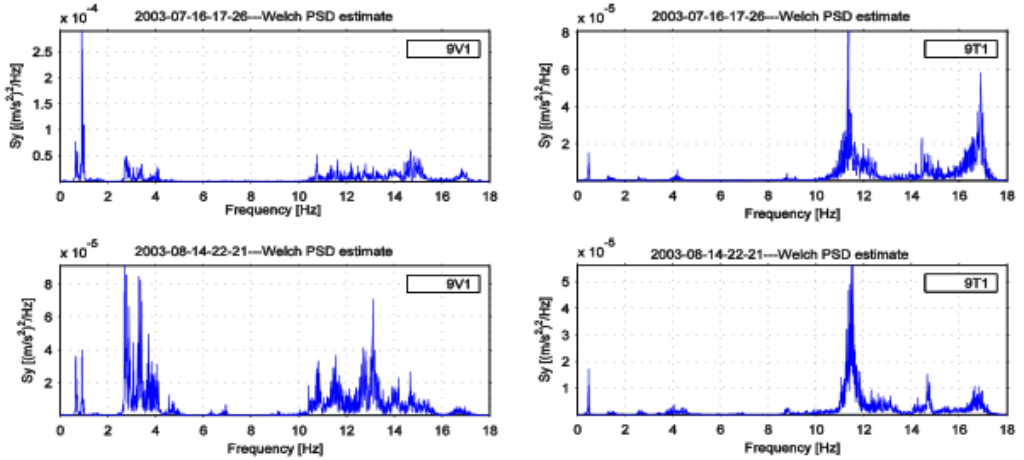
Confederation bridge vibration behavior

Typical traffic data set (10 min)

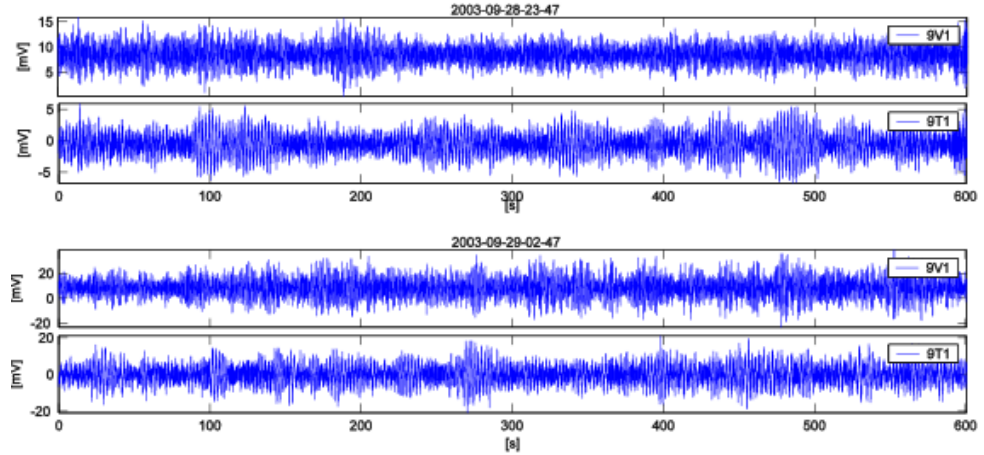
Acceleration time histories:

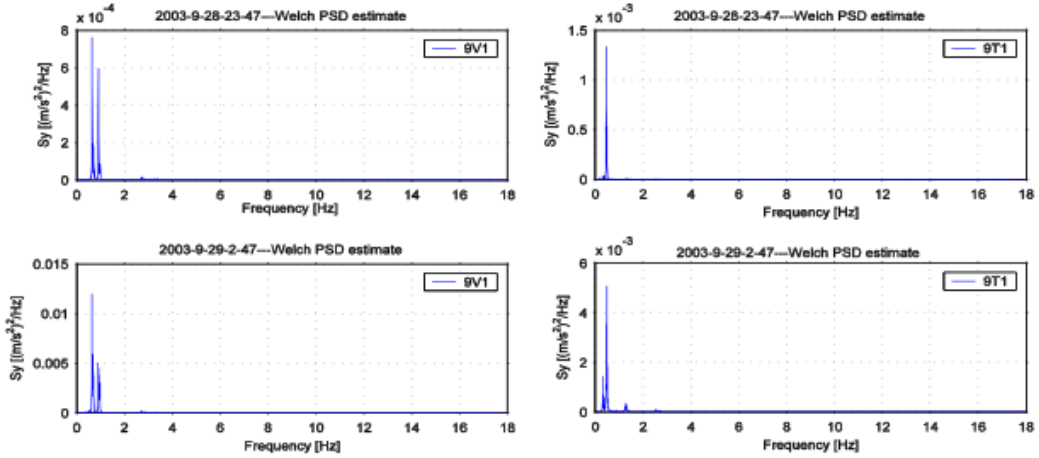


Power spectral density estimates:



Typical wind data set (10 min)





Confederation bridge dynamics

Early operational modal analysis results by various authors

Experimental

Pull test			Ambient Wind & Traffic					Controlled Traffic Test					Design verification Study				Baseline variability study			
Lau *et al.* 2004 [19]			Naumoski *et al.* 2002 [20]		Zhang 2002 [22]			Naumoski *et al.* 2004 [23]		Zhang. 2002 [22]			Londoño & Lau 2003 [24]				Londoño & Lau 2003 [25]			
Frequency (Hz)	Damping (%)	Mode type*	Frequency (Hz)	Mode type*	Frequency (Hz)	Damping (%)	Mode type*	Frequency (Hz)	Mode type*	Frequency (Hz)	Damping (%)	Mode type*	Frequency (Hz)	Damping (%)	Mode type*	Excitation Type	Frequency (Hz)	Damping (%)	Mode type*	Standard deviation of frequency (% of mean)
0.477	3.1	T	0.50	T	0.33	3.85	T	0.50	T	0.33	3.85	T	0.36	0.79	T	Wind	0.474	1.53	T	0.61
1.304	3.7	T	0.70	V	0.47	3.92	T	0.70	V	0.47	3.92	T	0.40	0.35	T	Wind	1.641	1.34	V	0.56
			0.90	T	0.61	6.97	V	0.90	T	0.65	1.81	V	0.65	0.1	V	Wind	1.828	1.56	V	0.53
			1.40	T	0.65	1.81	V	1.00	V	0.96	1.88	T/V	0.71	1.48	V	Storm	2.774	0.91	V	0.50
			1.70	V	0.79	8.15	V	1.40	T	1.47	4.08	T/V	0.91	0.07	V	Wind				
			1.95	T	0.85	1.66	T/V	1.70	V	1.54	1.35	T/V	1.00	0.47	V	Traffic				
			2.80	T	0.96	1.88	T/V	1.95	T	1.68	4.15	V	1.21	0.40	V/L	Traffic				
			2.90	V	1.23	6.13	T/V	2.80	T	1.81	1.01	V	1.62	0.04	V/L	Wind				
			3.30	To	1.34	2.33	T/V	2.90	V	2.77	1.47	V	2.75	0.11	V	Traffic				
			4.20	To	1.54	1.35	T/V	3.30	To	2.84	2.43	V	3.44	0.22	V	Traffic				
			4.80	V	1.81	1.01	V	4.20	To	3.00	2.22	V	3.38	0.10	To	Traffic				
					2.77	1.47	V	4.80	V	3.05	1.32	V	4.71	0.38	V	Wind				
					2.84	2.43	V			3.21	1.24	V	10.42	-	To	Traffic				
					3.00	2.22	V			3.42	1.18	V	10.73	0.02	V	Traffic				
					3.21	1.24	V			3.68	1.8	V	12.7	0.05	V	Traffic				
					3.42	1.18	V			3.88	1.32	V								
					3.88	1.32	V			4.50	1.21	V								
					4.50	1.21	V			4.95	1.62	V								
					4.65	1.82	V			5.12	2.27	V								
					4.95	1.62	V			5.33	0.44	V								
					5.12	2.27	V													
					5.33	0.44	V													

- Peak picking of FFT
- Stochastic subspace identification (SSI)

Variability of identified modal parameters

- Baseline variability – Londono et al. (2003) – 10 datasets :

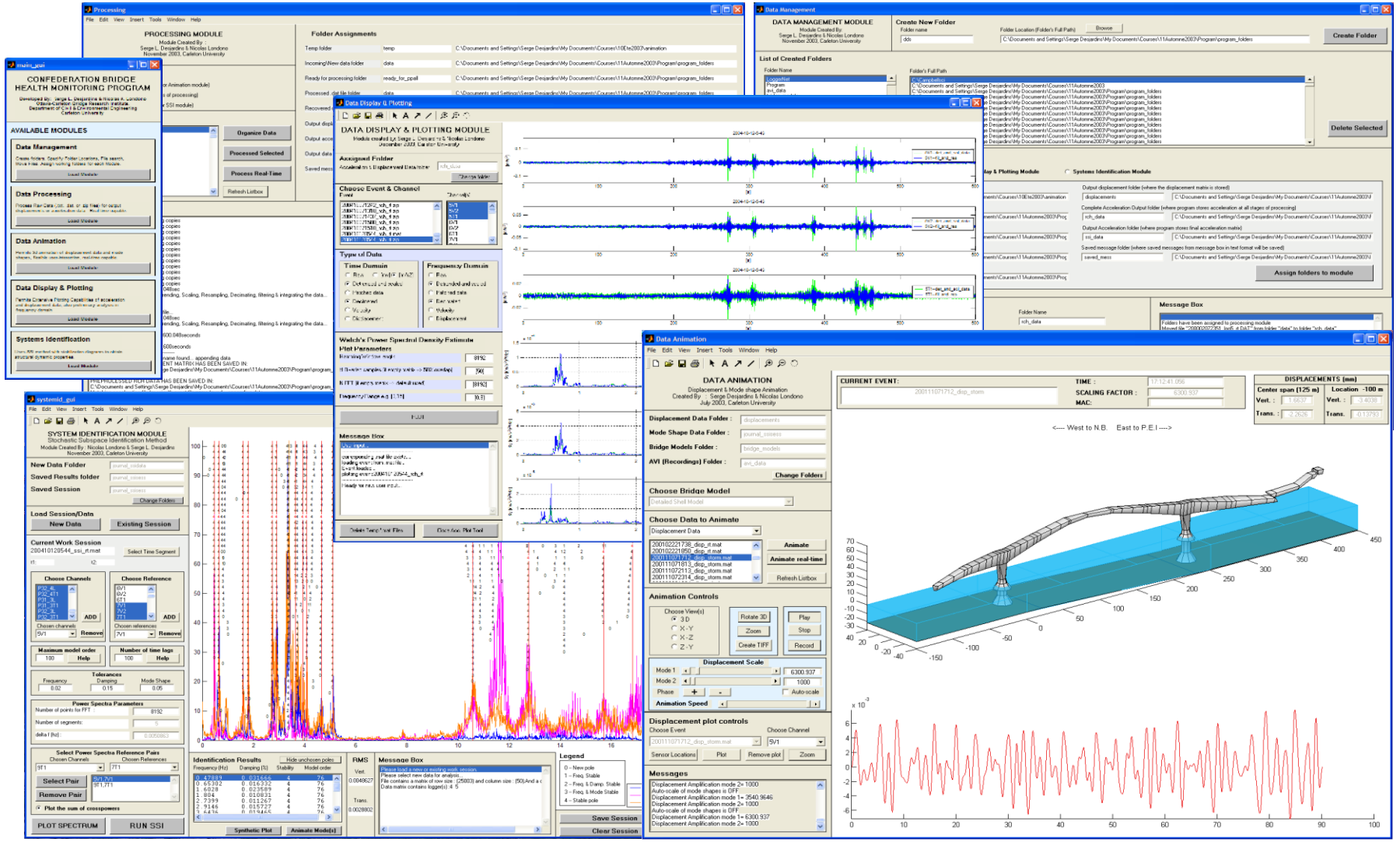
  A baseline variability of 0.6% standard deviation of identified frequencies from data sets of similar loading scenarios and environmental conditions was determined by Londono et al. (2003), which shows that it is possible to retrieve highly consistent modal frequencies

- General variability – Londono et al. (2004) – 42 datasets :

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Frequency average (Hz)	0.474	0.665	1.634	1.820	2.769	3.387	4.641	5.143
std (Hz)	0.007	0.010	0.018	0.031	0.033	0.074	0.093	0.057
std (% of mean)	1.5	1.5	1.1	1.7	1.2	2.2	2.0	1.1
Damping average (ξ %)	2.641	2.945	2.103	2.637	1.583	2.257	2.672	2.283
std (ξ %)	3.177	1.321	1.344	1.900	0.684	1.529	1.449	0.931
std (ξ % of mean)	120	45	64	72	43	68	54	41
MAC average	0.948	0.944	0.982	0.957	0.954	0.878	0.899	0.925

Signal processing platform for analysis of structural health (SPPLASH v1.0)

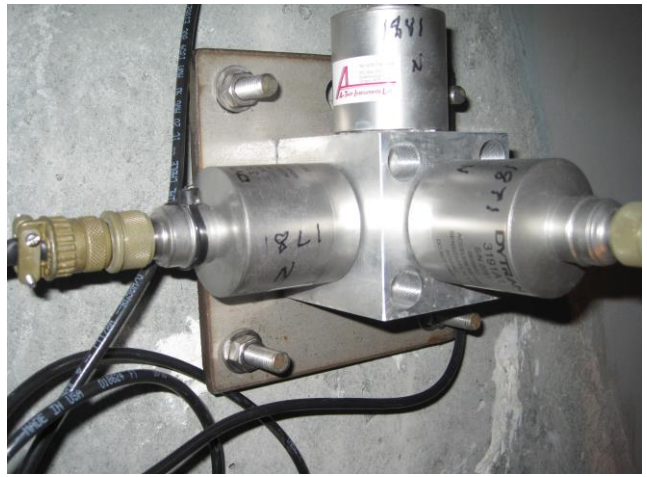
1. Research topic
2. **Confederation Bridge**
   - Bridge behavior
   - Bridge dynamics
   - Variability
   - **SPPLASH v1.0**
3. Instrumentation renewal
4. SPPLASH 𝓑
5. Historical database
6. Statistical analysis of OMA results
7. Conclusions



Desjardins (2005), Desjardins et al. (2006)

Implications of instrumentation renewals on established long-term vibration based monitoring programs

- Long-term vibration monitoring : Instrumentation life cycle < structure design life
- Experience gained from 1st generation of vibration monitoring system
  - Reduction of measurement noise and uncertainty
  - Optimized instrumentation
  - System diagnostics
  - Improved collection parameters
  - Data synchronization
  - Data management
  - Automation



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Vibration instrumentation renewal on the Confederation Bridge from December 2012 to March 2014

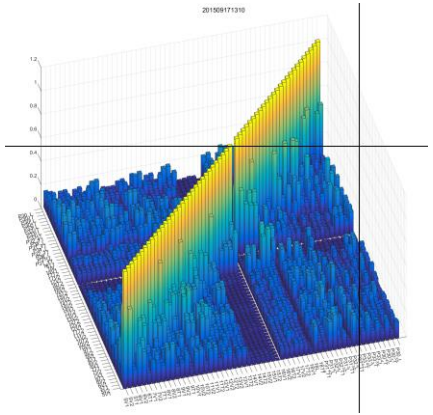
Implications : Multi-state and multi-scale sensor data

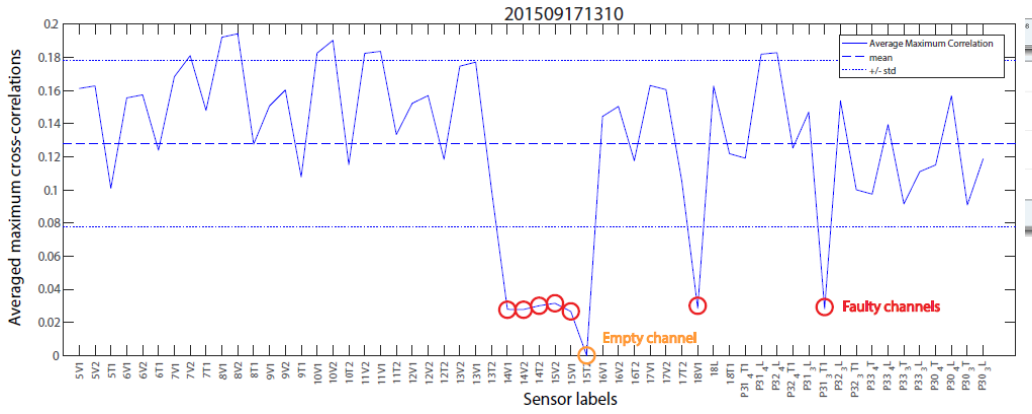
Signal processing platform for analysis of structural health - SPPLASH *3*

1. Research topic
2. Confederation Bridge
3. Instrumentation renewal
4. **SPPLASH v3.0**
   - Database management
   - Data synchronization
   - Streamlined processing
   - Metadata
   - Sensor diagnostics
   - Automated OMA
5. Historical database
6. Statistical analysis of OMA results
7. Conclusions

New developments:

- Database management
- Data synchronization
- Streamlined processing
- Metadata
- Sensor diagnostics
- Automated OMA (AI-FSI)

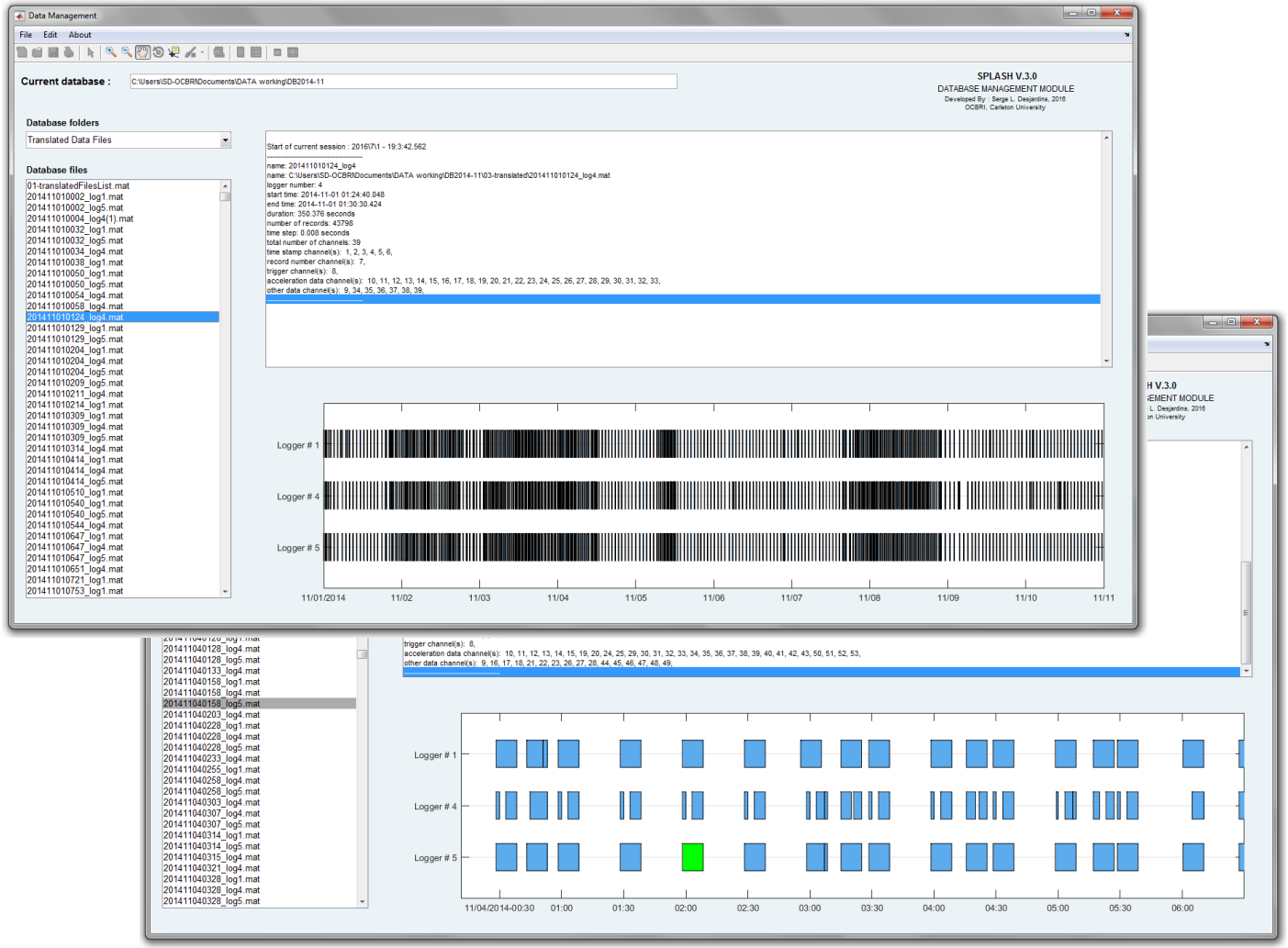




SPPLASH *3* - Database management module

1. Research topic
2. Confederation Bridge
3. Instrumentation renewal
4. **SPPLASH v3.0**
   - **Database management**
   - Data synchronization
   - Streamlined processing
   - Metadata
   - Sensor diagnostics
   - Automated OMA
5. Historical database
6. Statistical analysis of OMA results
7. Conclusions

- Database creation
- Folder structure
- Data processing
- Database viewer
- Metadata extraction and visualization



SPPLASH 3

- Data synchronization – across all data loggers
- Streamlined processing
- Metadata:

Raw/translated logger data files:
- Name
- Logger number
- Full path inside database
- Raw header information
- Translated header information
- Start time of data record
- End time of data record
- Duration
- Number of samples
- Time step
- Trigger information
- Channel mapping

Processed event data files:
- Name
- Full path to processed file inside database
- Start time of event
- Logger data files included in event
- Duration of processed acceleration
- Duration of processed displacements
- Time step of individual logger records
- Common time step for event
- Trigger record
- Decimation factor
- number of samples for interpolation
- Faulty channels
- Empty channels

Individual processed signal:
- Response label
- Logger number
- Logger file name
- Header label
- Logger channel number
- Scaling factor
- Processing operations performed
- Signal statistics (max, min, std, rms, etc…)

SPPLASH 3 - Sensor diagnostic

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2. Confederation Bridge
3. Instrumentation renewal
4. **SPPLASH v3.0**
   - Database management
   - Data synchronization
   - Streamlined processing
   - Metadata
   - **Sensor diagnostics**
   - Automated OMA
5. Historical database
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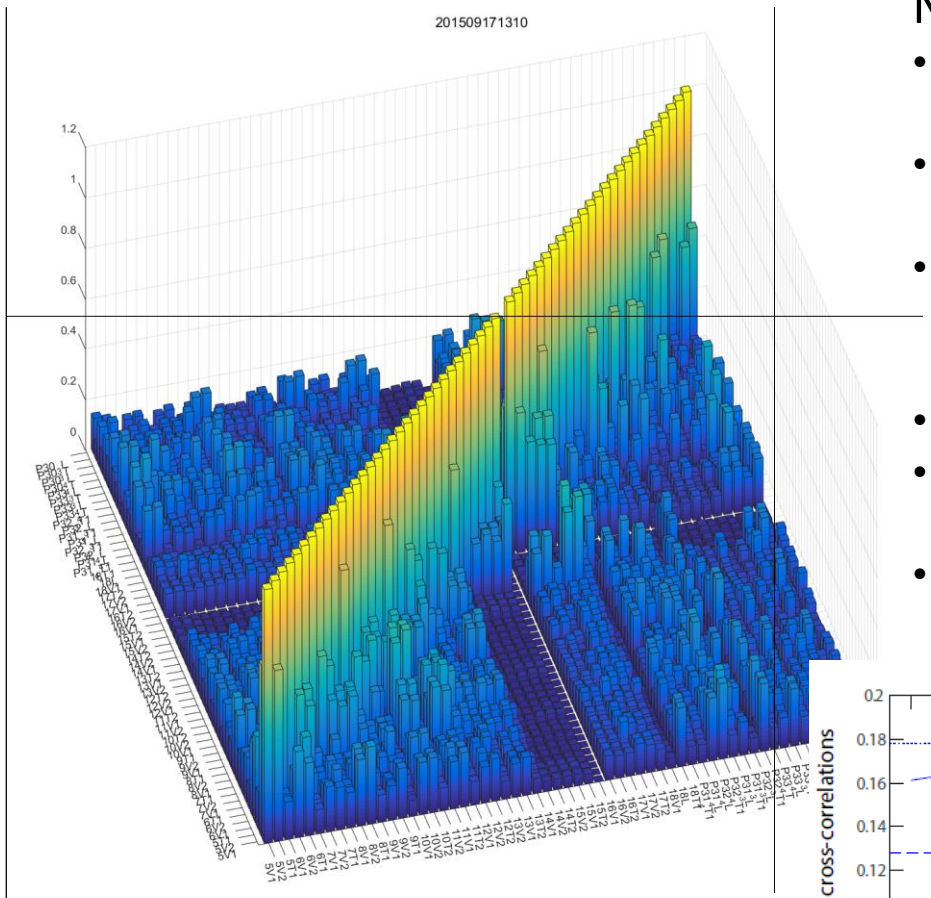
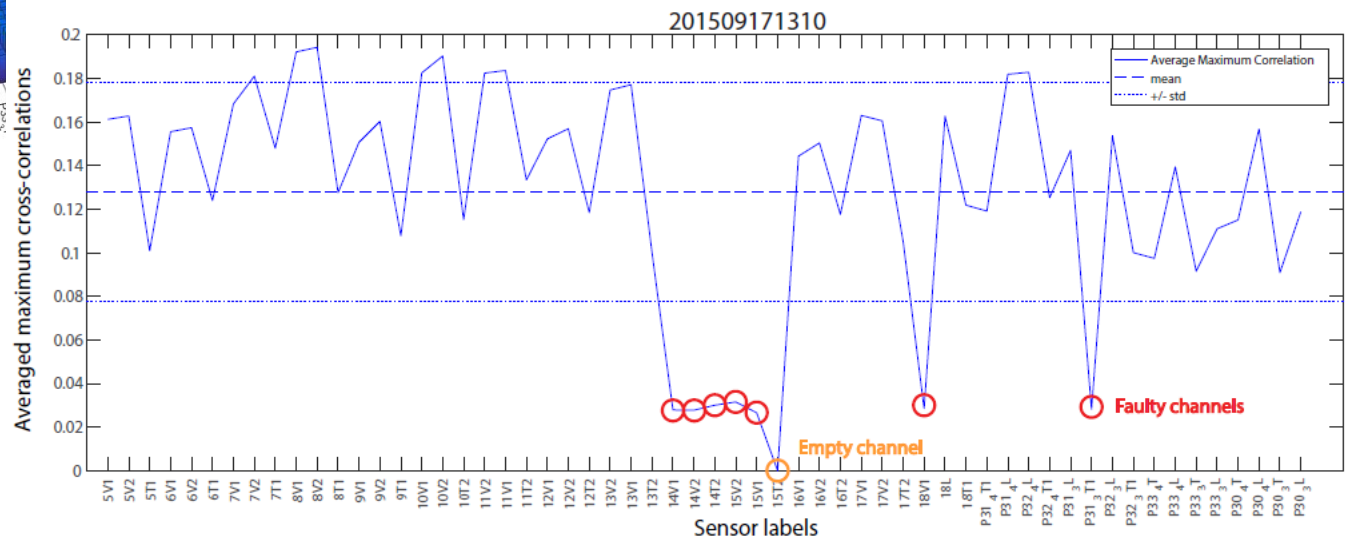


New algorithm :

- Normalized cross correlations are calculated between each channel and every other channel.
- The normalization is done with respect to the maximum value of the-auto correlations.
- The maximum absolute value of each correlation is saved in a symmetric matrix of size equivalent to the number of channels (3D plot).
- Valleys represent possibly faulty or empty channels.
- An average of the maximum cross correlations values for each sensor is calculated.
- Faulty or empty sensors are identified when the calculated average falls below one standard deviation.



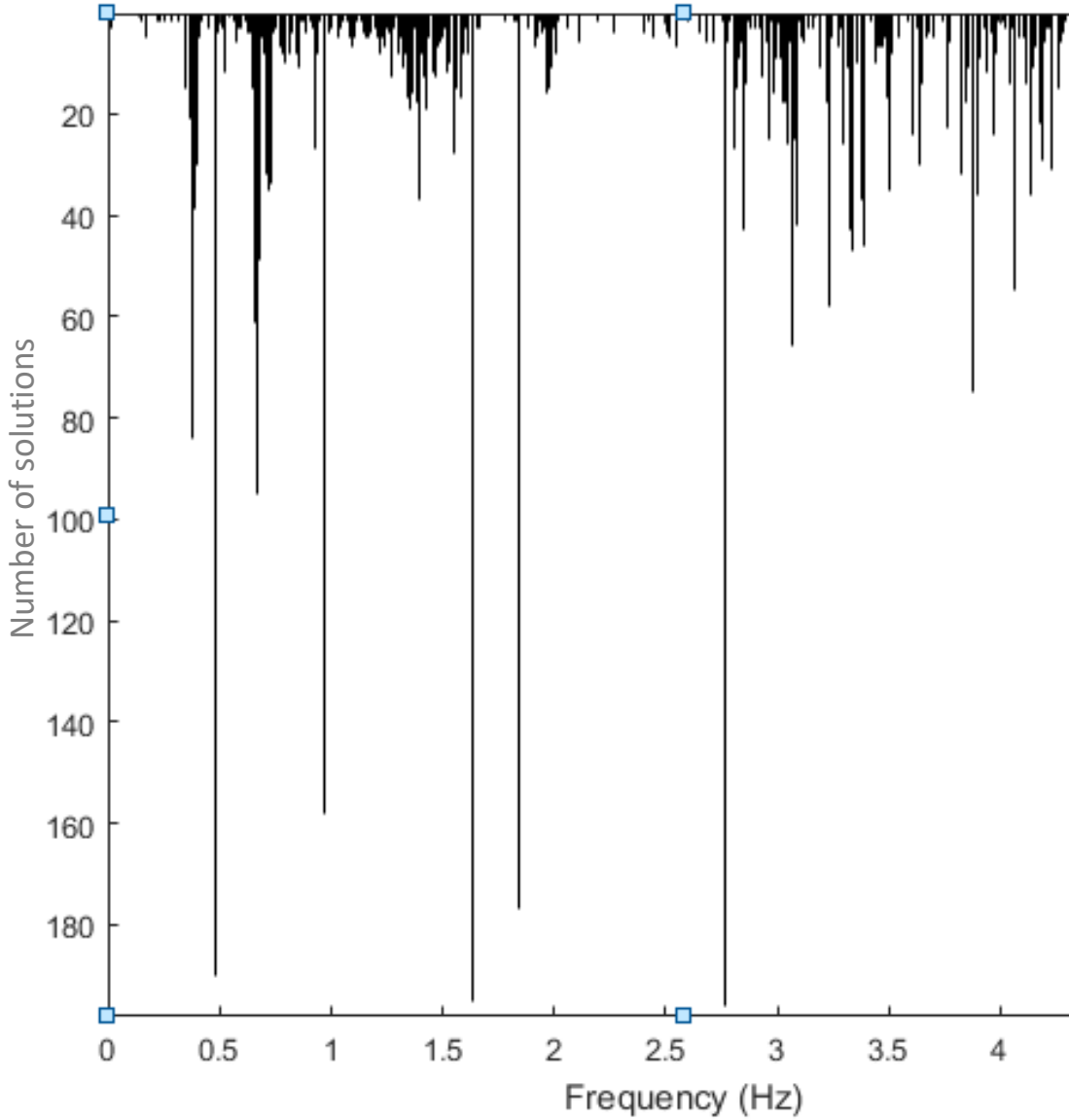
SPPLASH *3* – Automated OMA
Automated In-line full space identification (AI-FSI)

- Full space identification (FSI vs SSI)
  - Data correlation using all responses

$$\hat{\mathbf{R}}_i = \frac{1}{N}\sum_{k=1}^{N} \mathbf{y}_{k+i}(\mathbf{y}_k)^T$$

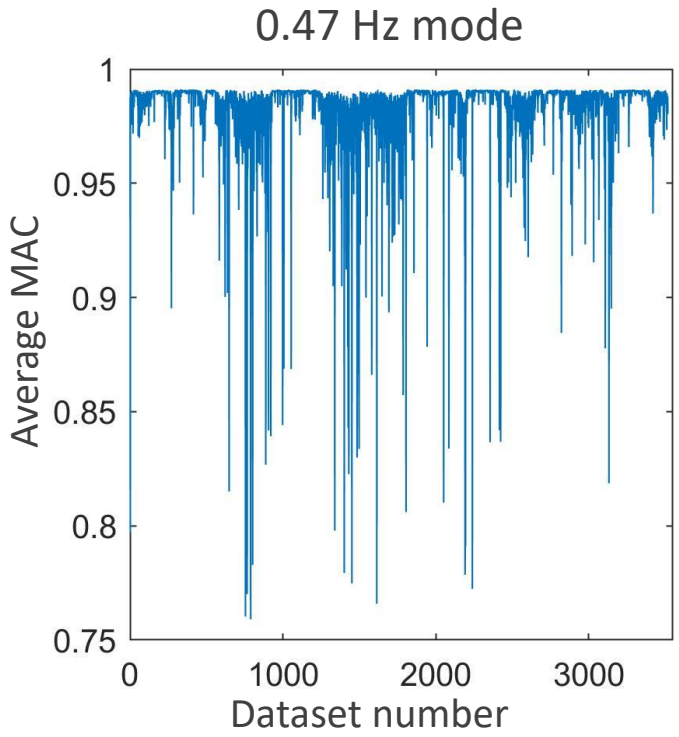
- Automated modal parameter estimations (MPE)
  - From FSI solution (stabilization diagram)
  - Solution poles are clustered in solution bins according to mode compatibility
  - Tolerances : frequency = 1%; mode shape = 5%; damping = 15%.
  - Modal assurance criterion (MAC) :

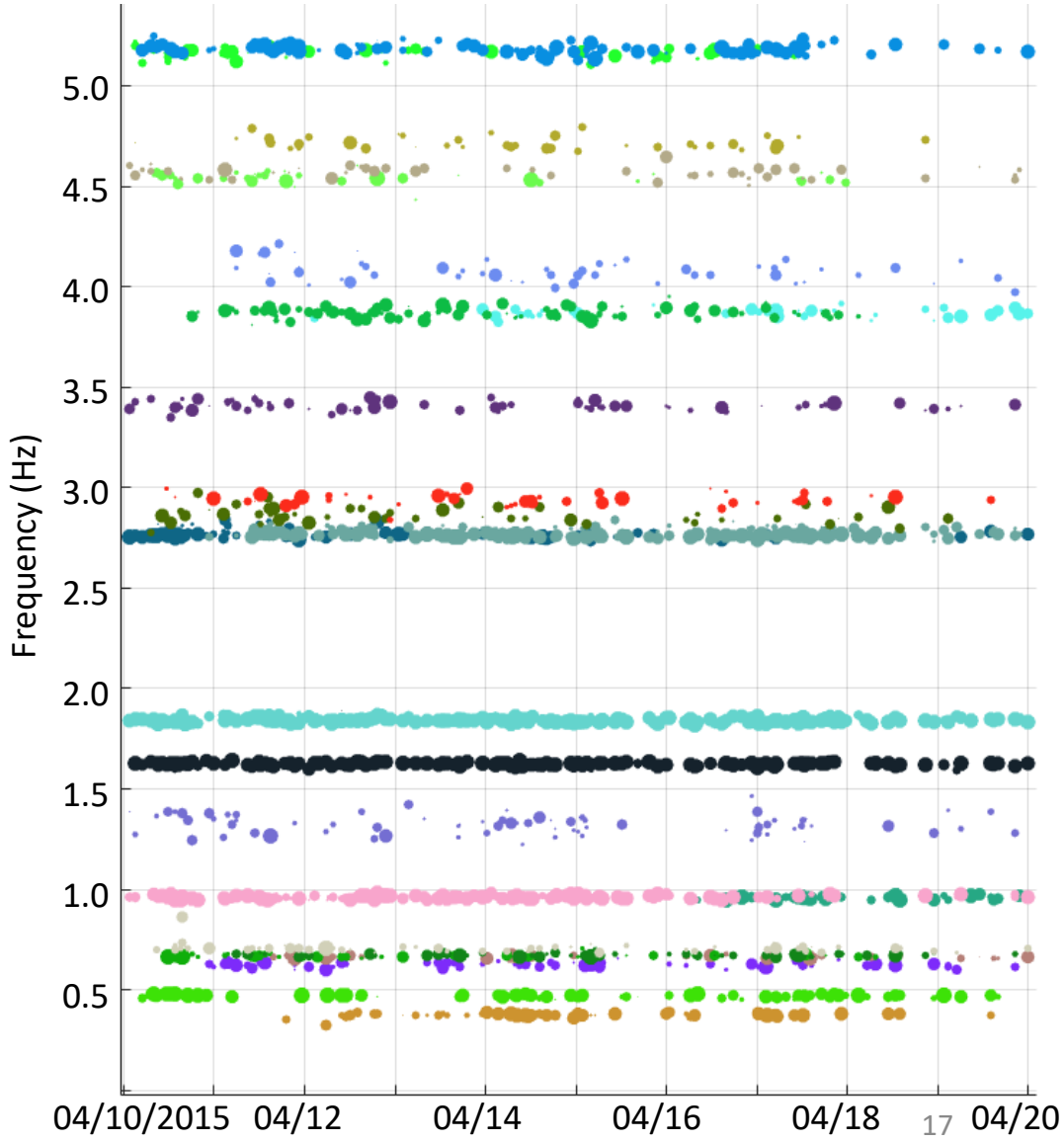
$$MAC(\boldsymbol{\psi}_i, \boldsymbol{\psi}_j) = \frac{\left|\boldsymbol{\psi}_i^* \boldsymbol{\psi}_j\right|^2}{\left(\boldsymbol{\psi}_i^* \boldsymbol{\psi}_i\right)\left(\boldsymbol{\psi}_j^* \boldsymbol{\psi}_j\right)}$$



SPPLASH 3 – Automated OMA
Automated In-line full space identification (AI-FSI)

- Mode tracking by recursive reduction of MAC matrix
  - First stage : Clustering around dominant modes
  - Second stage : MAC matrix reduction
    - ➢ Subclusters of true mode solutions





Historical database

- 20 years of vibration data collection

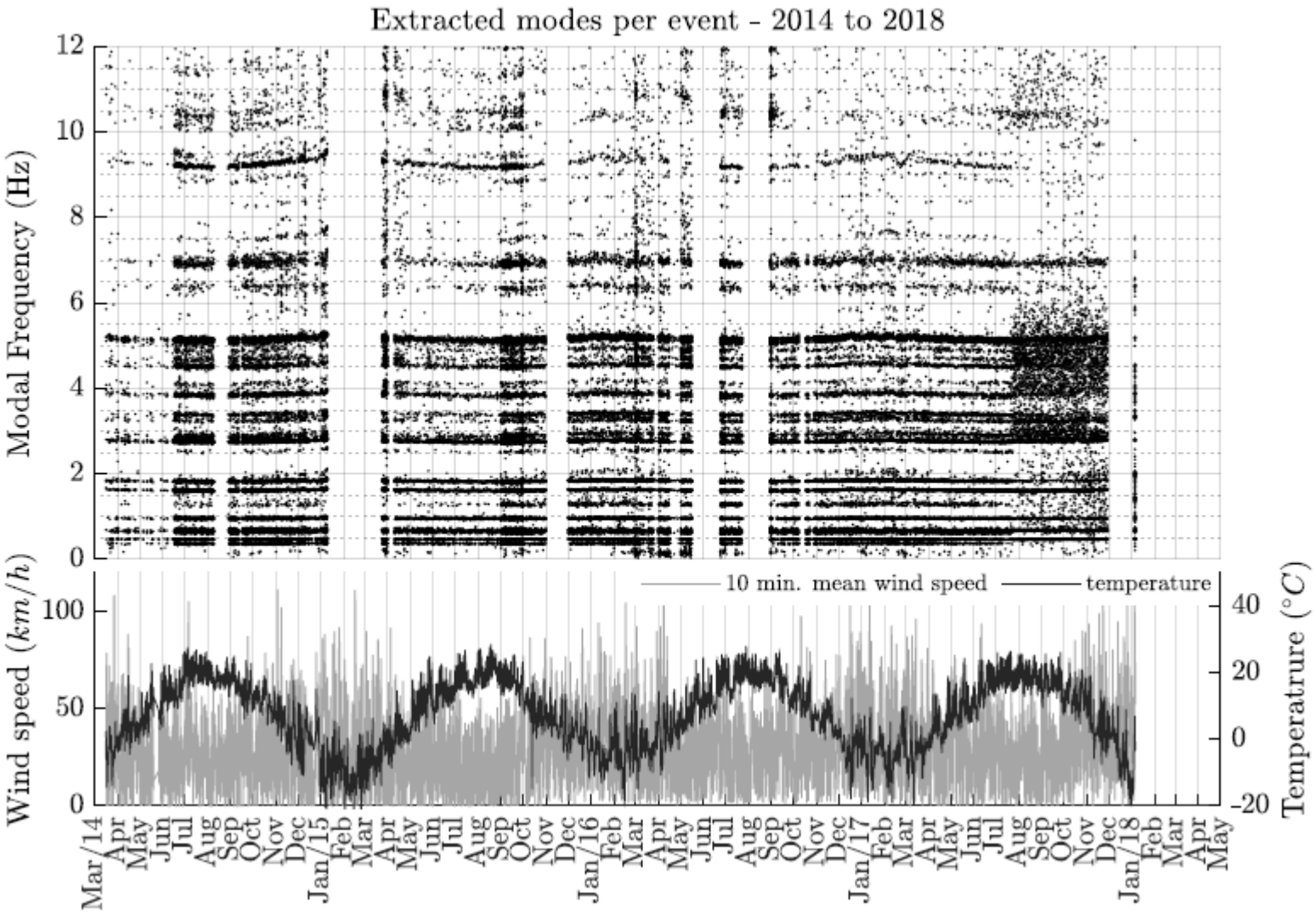
	February 1998 to February 2014	March 2014 to May 2018	Total
Number of logger files	72 846	455 079	527 925
Number of partial events	55 530	97 812	153 342
Number of full events	1579	101 339	102 918
Total Number of events	57 109	199 151	256 260
Recorded duration of partial events (hours)	7226	16 302	23 528
Recorded duration of full events (hours)	76	16 890	16 966
Total recorded duration - all events (hours)	7302	33 192	40 494
Size on disk of raw data (MB)	846 871	6 100 197	6 947 068
Size on disk of processed data (MB)	5 067 643	14 383 402	19 451 045

28 TB

- Database of raw and processed data
- Facilitates large scale targeted research

Historical database

- Database of OMA estimates



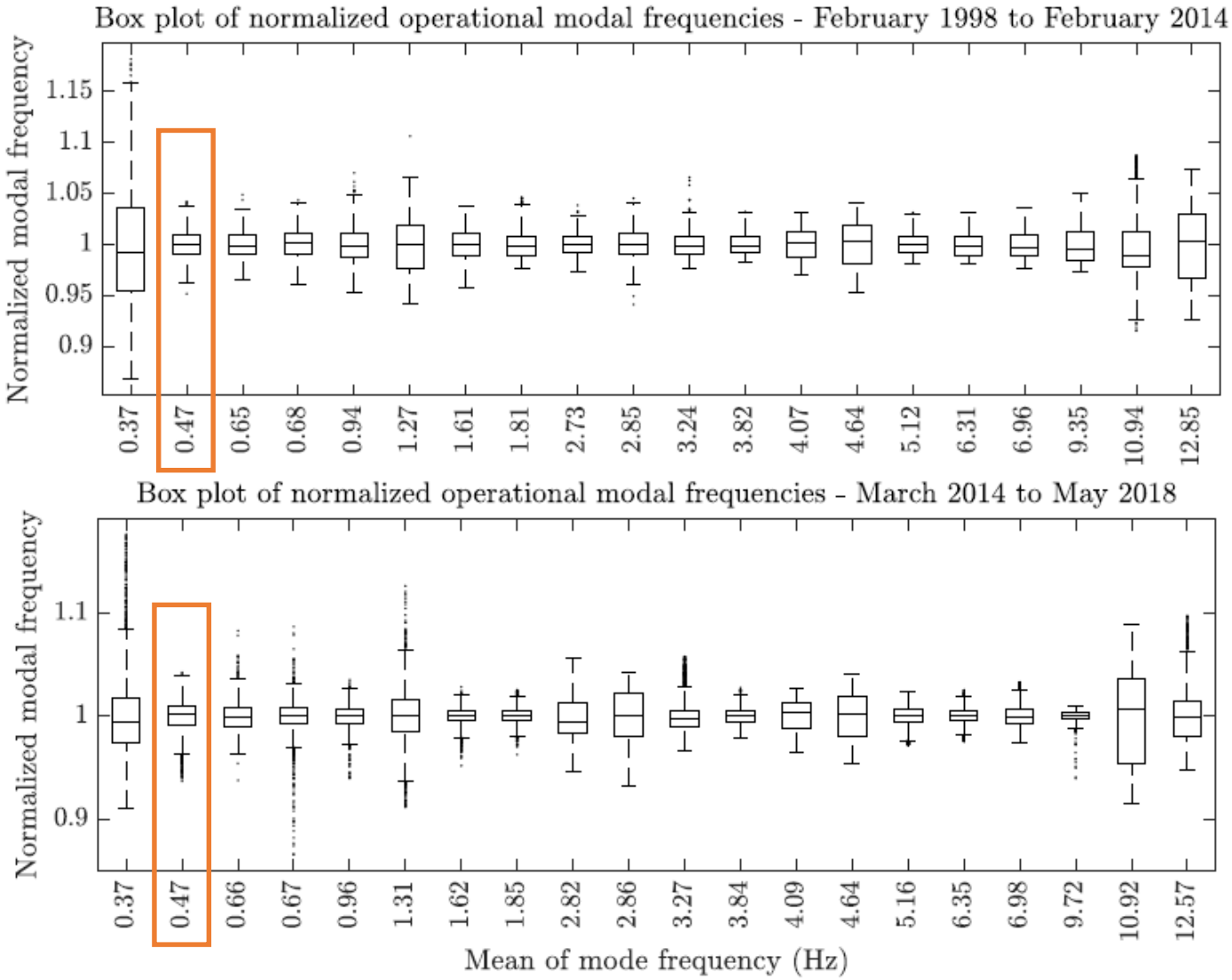
- Over 13 000 datasets analyzed with the AI-FSI technique
- Baseline for healthy structure
- Permits identification of temporal trends to improve damage detection techniques which deal with noise and uncertainties
- 1.7M wind and temperature samples

Historical database

- Variability of OMA estimates

March 2014 to May 2018

Mode Frequency average (Hz)	Interquartile range IQR (%)	Standard deviation (Hz)	Standard deviation (% of mean)	MAC average	Number of identifications
0.374	4.46	0.016	4.33	0.840	2411
0.470	1.91	0.007	1.48	0.966	4203
0.663	1.89	0.010	1.46	0.844	1662
0.674	1.58	0.011	1.56	0.937	4030
0.958	1.37	0.010	1.06	0.919	3156
1.306	3.22	0.036	2.76	0.890	2718
1.618	1.07	0.013	0.83	0.944	3649
1.852	0.98	0.015	0.78	0.905	2896
2.819	2.97	0.058	2.07	0.976	4042
2.860	4.14	0.072	2.50	0.935	2861



*Operational modal estimates can be reliably, consistently and **automatically** extracted from highly uncertain and noisy data on a much larger scale than was previously undertaken.*

Condition assessment by statistical analysis of OMA estimates

1. Research topic
2. Confederation Bridge
3. Instrumentation renewal
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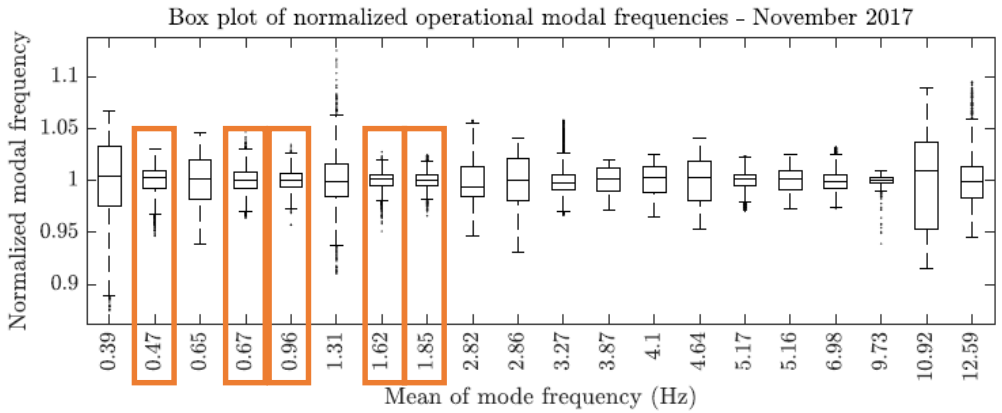
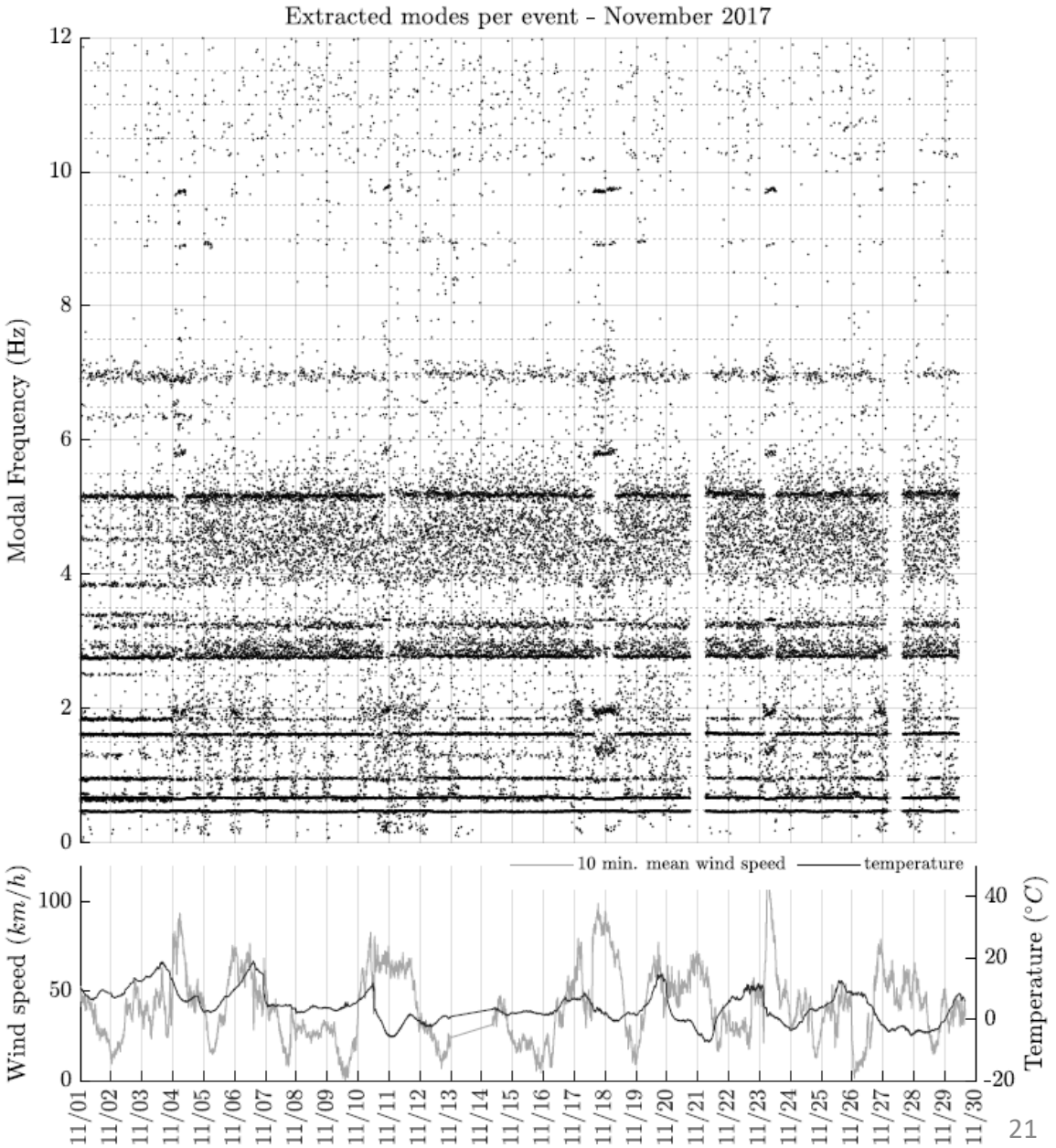
6. **Statistical analysis of OMA results**
7. Conclusions

- Data from November 2017
- Continuous collection (3910 full datasets)
- Variability :





Condition assessment by statistical analysis of OMA estimates

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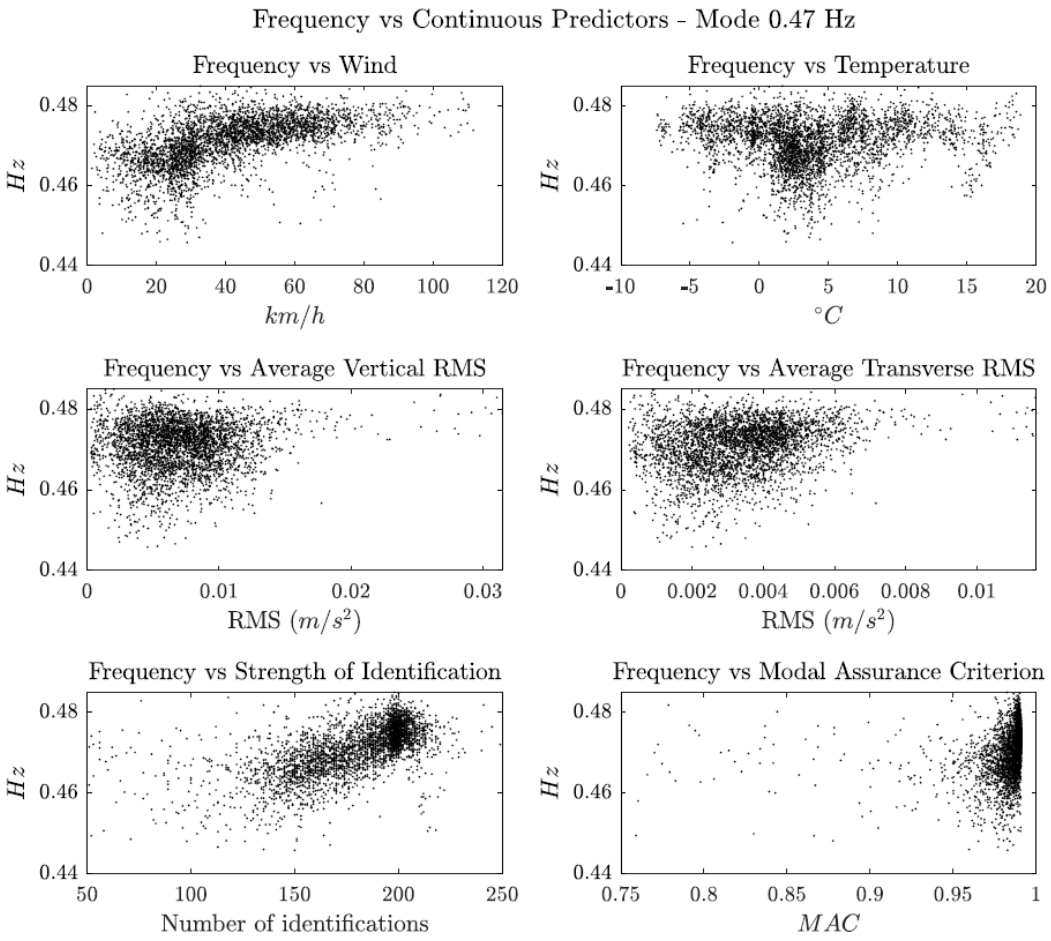
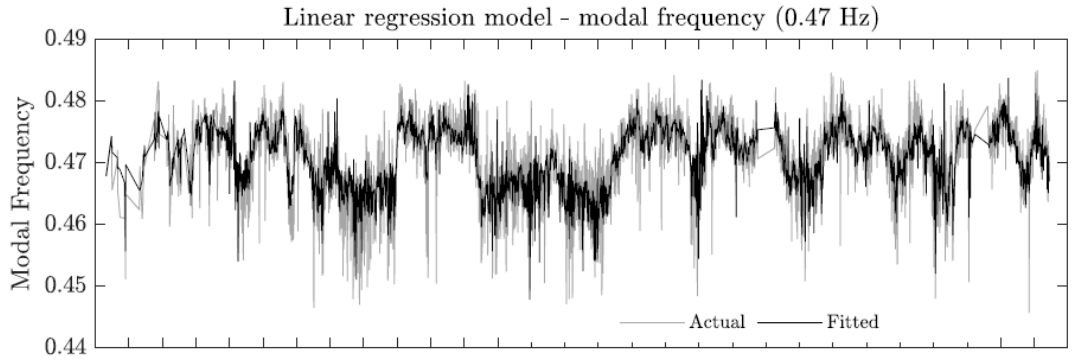
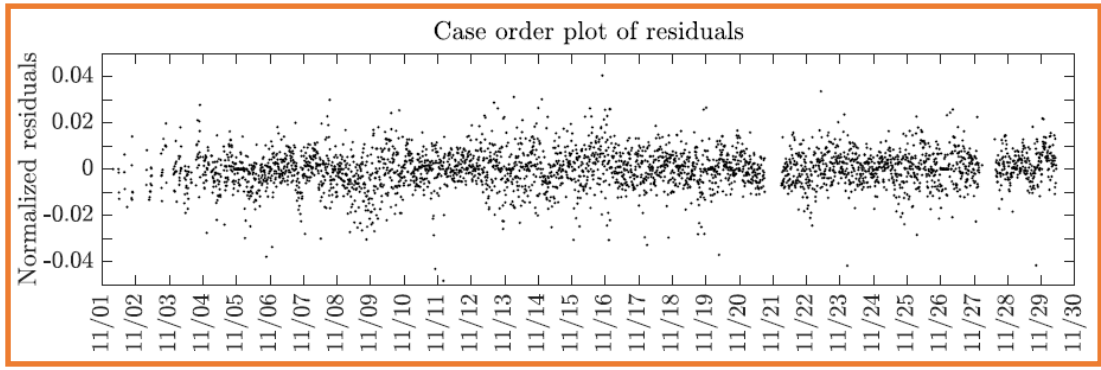
- Multiple linear regression (0.47 Hz mode)



0.47Hz mode

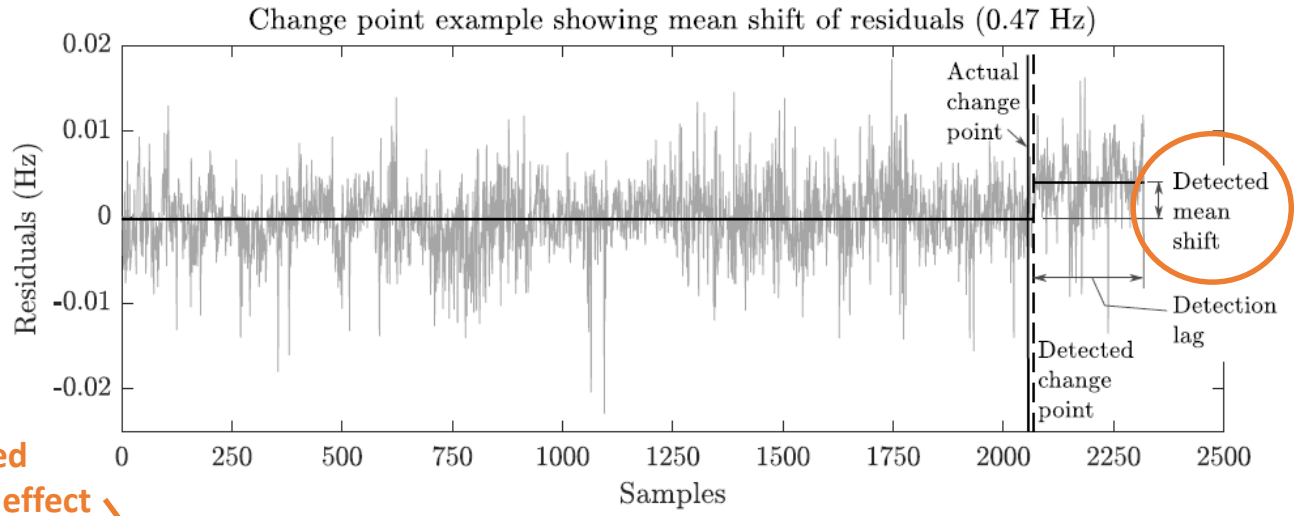
Model statistics :
R-squared: 0.468, Adjusted R-Squared 0.446
F-statistic vs. constant model: 21.1, p-value = 0
RMSE = 0.00454, Standard deviation of residuals = 0.00445
Top coefficients : ModeIdent., WindSpeed





Condition assessment by statistical analysis of OMA estimates

- Residual Analysis and change point detection for damage identification



Simulated damage effect

Simulated damage effect

Sensitivity analysis :

Mode	Imposed shift in mean (%)	Change point accuracy (number of samples) Avg.	σ	Detection lag (number of samples) Avg.	σ	Detected mean shift (%) Avg.	σ
0.47Hz	0.4	60.0	87.6	358.8	112.8	0.55	4.03×10^{-2}
	0.6	16.6	29.3	276.6	77.0	0.75	4.40×10^{-2}
	0.8	10.3	20.0	224.0	46.0	0.95	4.31×10^{-2}
	1.0	5.3	14.3	152.7	32.4	1.15	4.95×10^{-2}
	1.2	2.7	7.7	105.9	22.9	1.36	7.18×10^{-2}
	1.4	1.7	2.7	80.0	16.7	1.55	6.55×10^{-2}
	1.6	1.4	1.9	61.3	12.2	1.75	5.86×10^{-2}

Conclusions

Major challenge to VBSHM : uncertainty and noise –> variability of identified modal parameters

Possible solution : reduce measurement and computational uncertainties combined with large scale collection and processing of operational response data to increase accuracy of modal parameter estimates and establish trends with known environmental and operational processes

Means : Long-term continuous monitoring of an in-service civil structure

Implications : instrumentation renewals, multi-state and multi-scale data, proper tools for database management, system diagnostics, metadata extraction, robust automated on-line and off-line processing and analysis .

Recent advances :

- Identified and minimized causes of variability in all data collection and processing operations
- Redevelopment of data processing and analysis tools (SPPLASH 3)
- Novel AI-FSI technique for automated OMA and mode tracking
- Processed large amounts of current and historical data (database)
- Applied established and novel statistical methods to analyze modal parameters in the time domain
- Novel damage detection by residual analysis and change point detection.

Thank You!

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