INTELLISWITCH Symposium

Low-complexity Behavioral Model for Predictive Maintenance of Railway Turnouts

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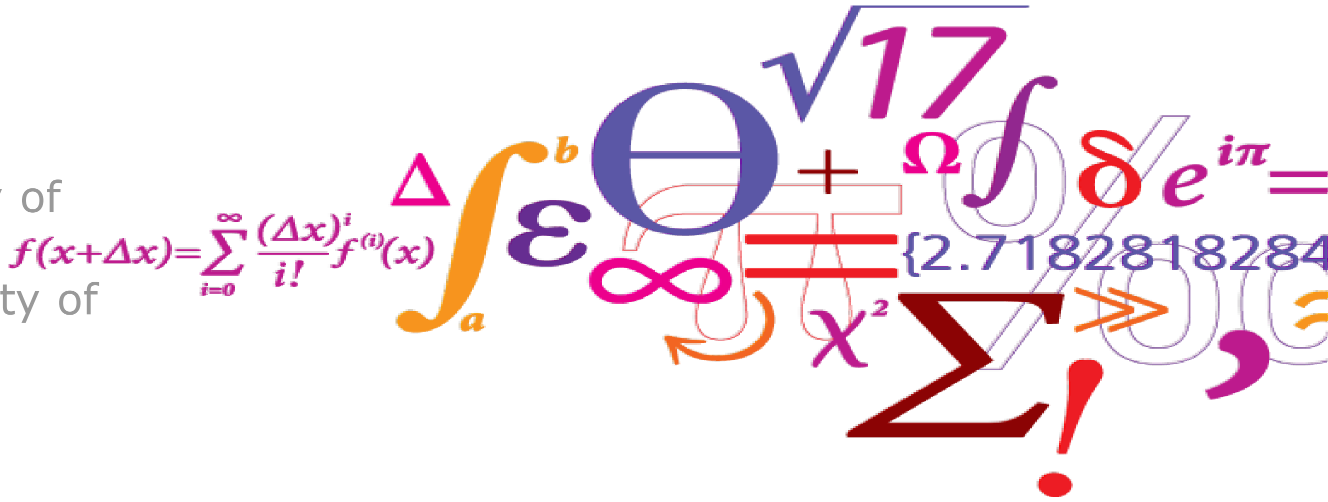
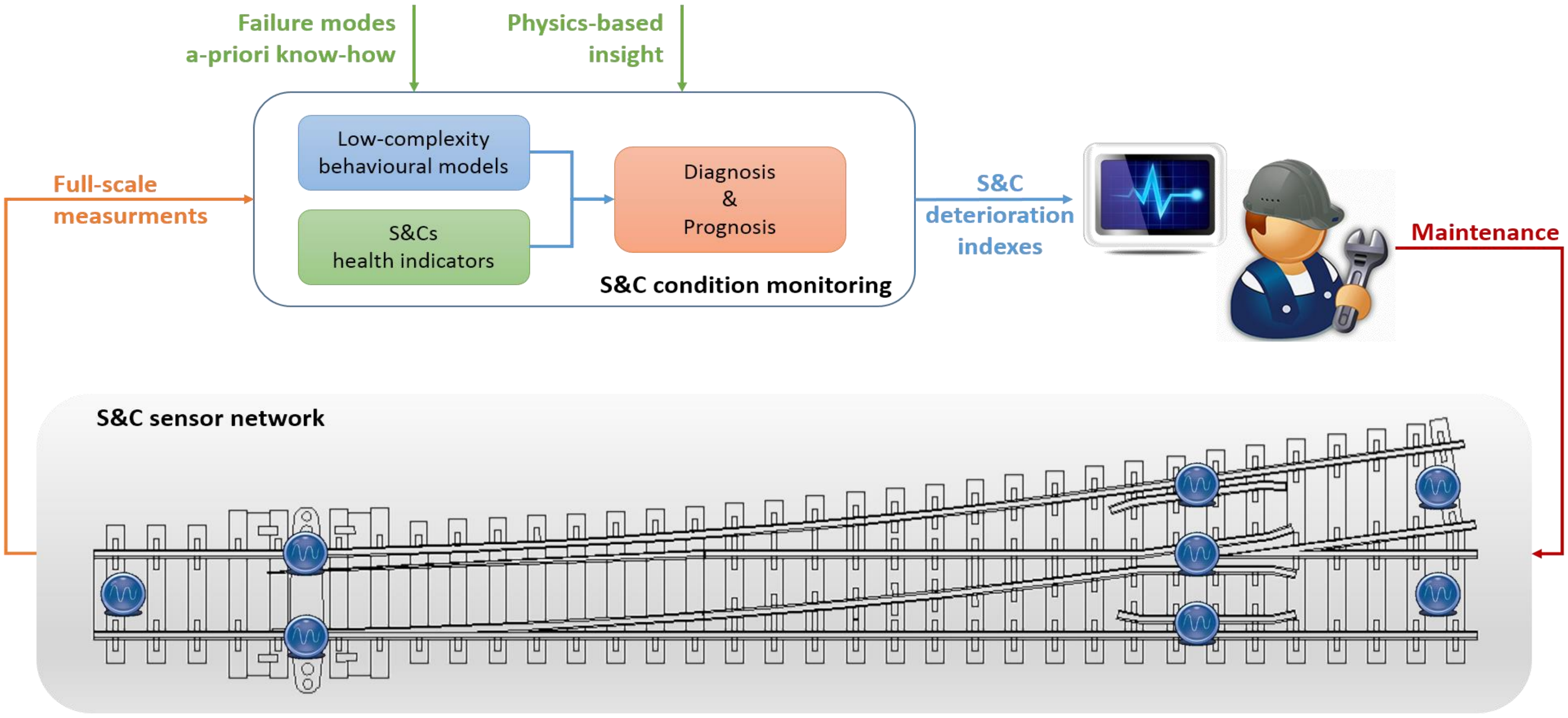
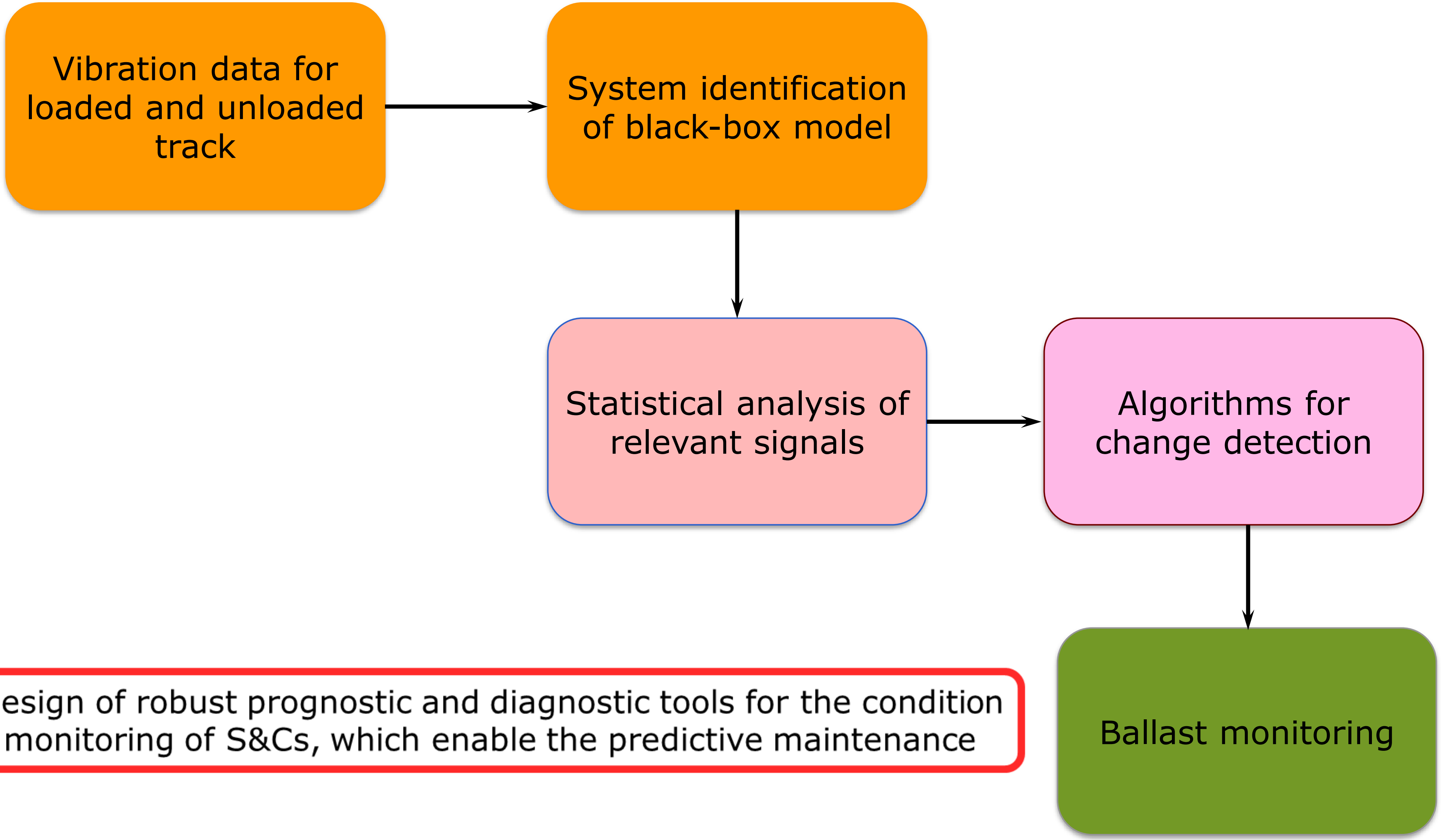


Condition monitoring for switches and crossings (S&Cs)

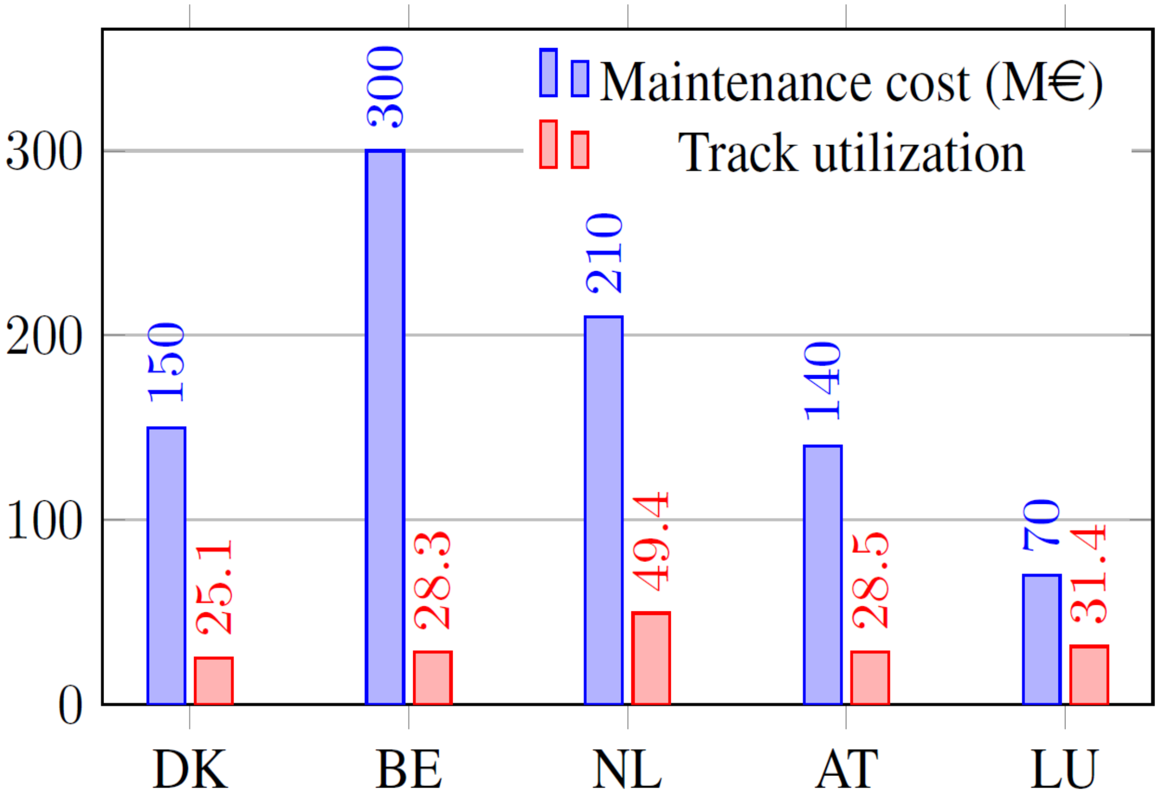


Towards diagnosis of S&Cs



Design of robust prognostic and diagnostic tools for the condition monitoring of S&Cs, which enable the predictive maintenance

Motivation



Maintenance cost for European countries (2012 data)

Banedanmark [1]

- Each year 1/3 of the total track maintenance cost is spent on turnouts (2012).

RSSB [2]

- 31% of the track-related derailments are due to S&Cs malfunctioning in Great Britain (2009-2014).

Failure data recorded in the UK (2009) [3]

- Ballast degradation is the 3rd most important component affecting the turnouts performance with a failing frequency of 7.9%.

Presentation overview

- Problem definition and review of methodologies
- Receptance test
- Eigensystem realization algorithm method (ERA)
- Low-complexity behavioral model
    - Model validation
- Future works

Problem definition

Railway infrastructure
(Rail, sleepers and ballast)

Damaged ballast

Methodologies for ballast monitoring

Instrumental Methodologies

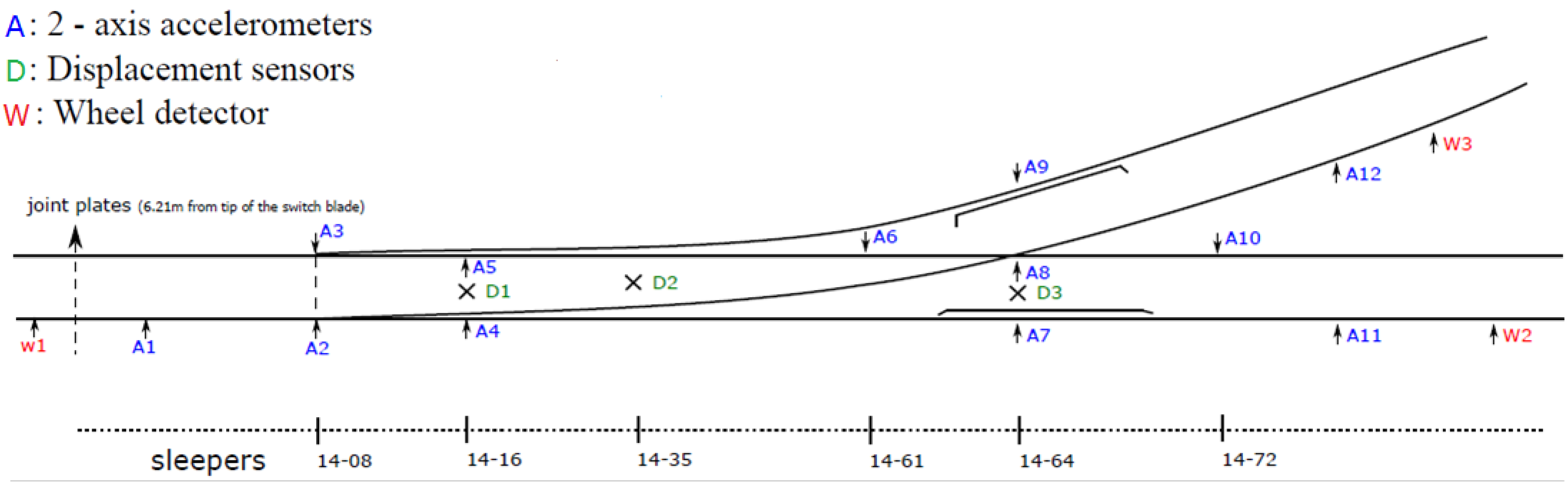
Ballast monitoring

- **Cone penetration test (CPT)**
  - Destructive test
  - Time consuming
  - Affects train operation
- **Ground penetrating radar (GPR)**
  - Locating ballast damage, frequency range electromagnetic waves
- **Visual inspection**
  - effective in detecting surface damages

Model-based methodologies

- **Finite element methods (FEM)**
- **Multibody simulation (MBS)**
- **Complex mathematical models**

Sensor placement

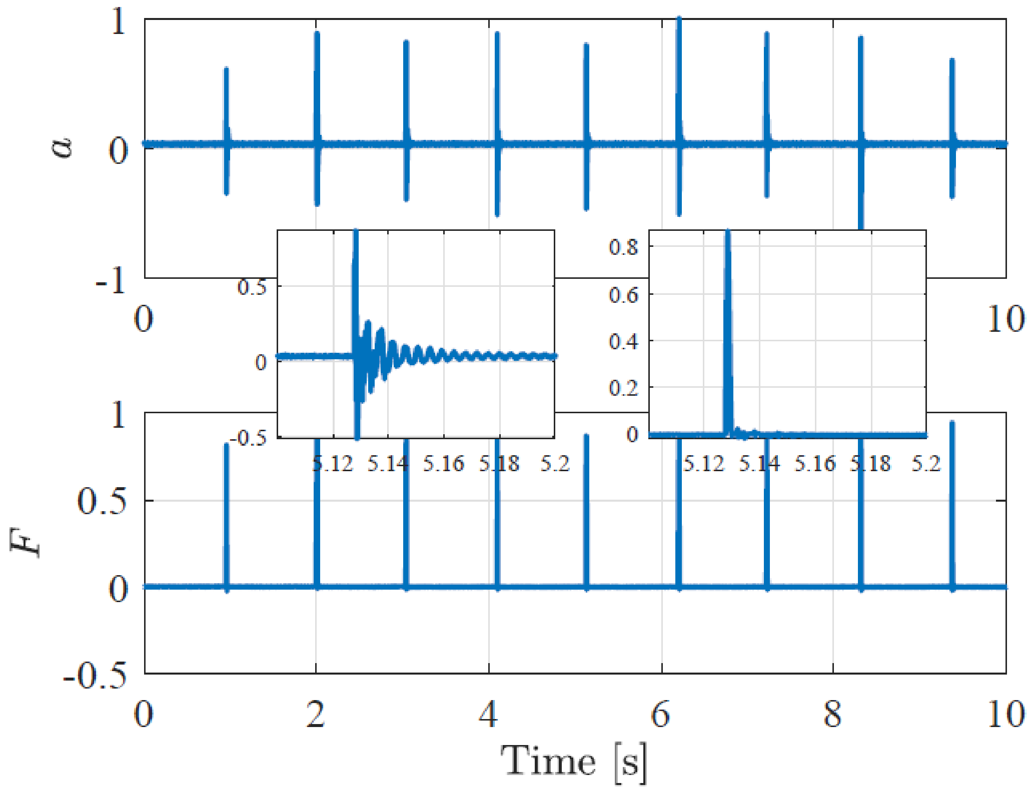


Receptance test

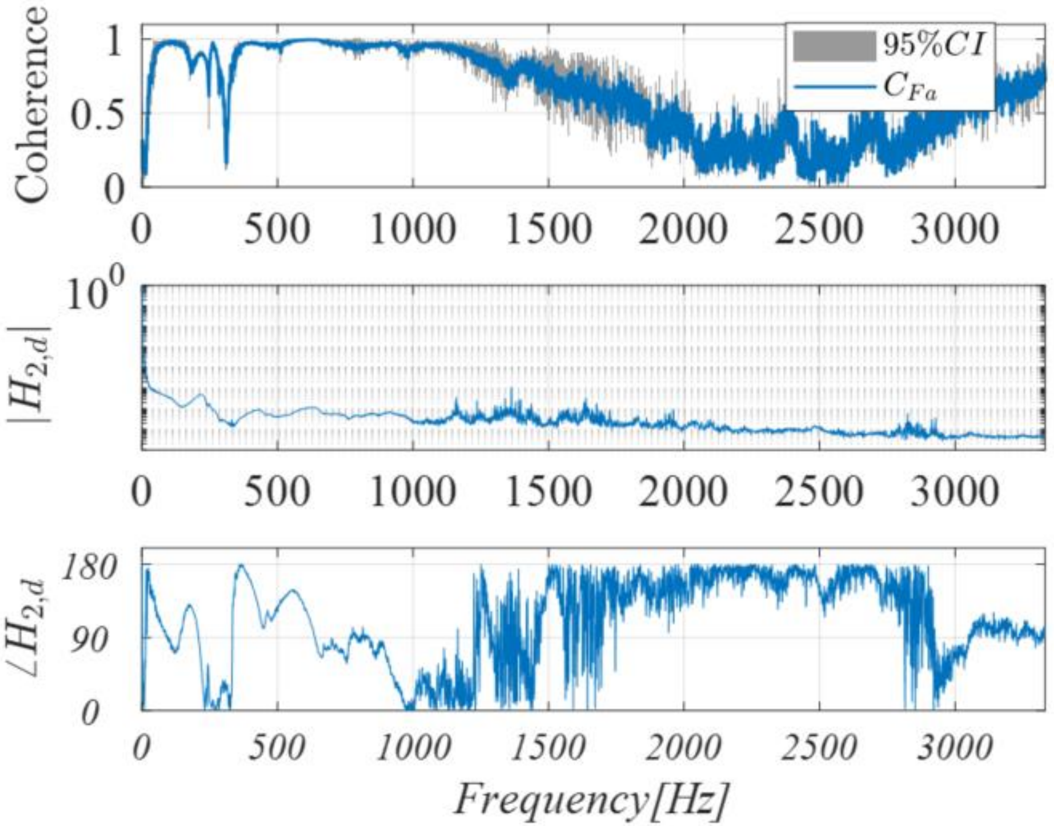
Overview of the turnout at Tommerup station

Setup for the receptance test including hammer and accelerometers

Receptance test

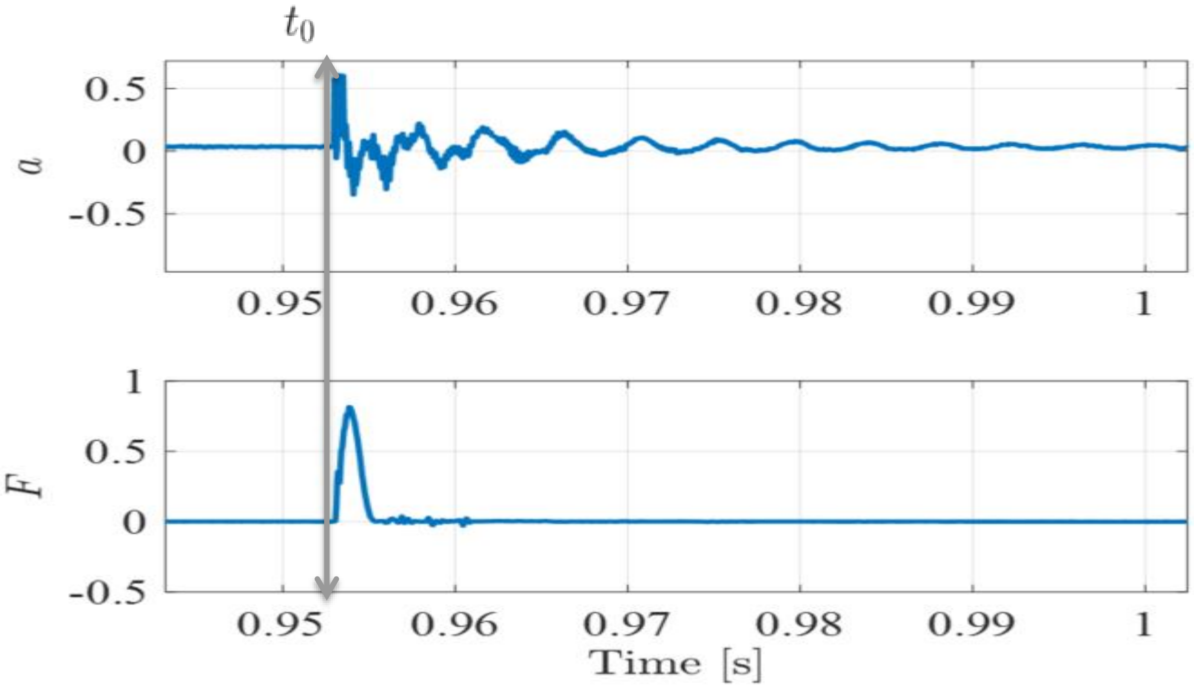


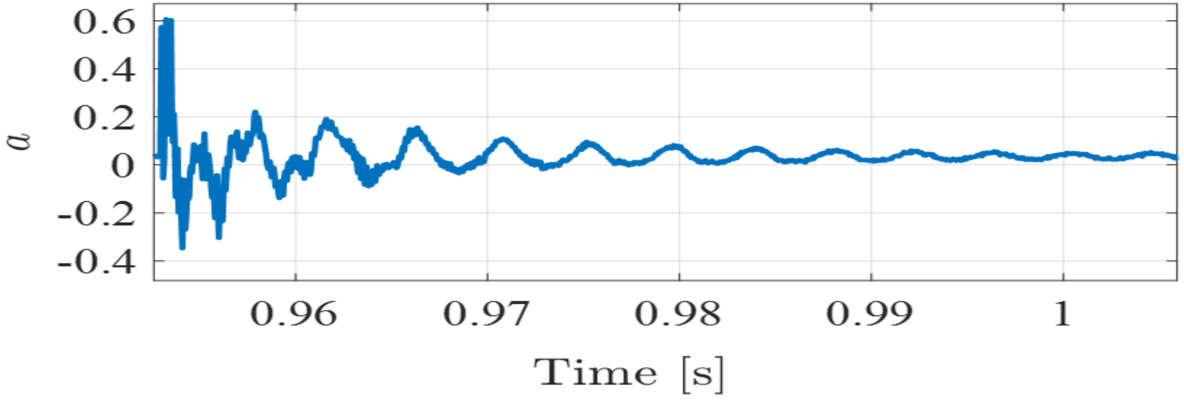
$$C_{Fa}^{\text{avg}}(\omega) = \frac{1}{M}\sum_{i=1}^{M} C_{Fa,i}(\omega)$$



$$H_{2,a}(\omega) = \frac{G_{aa}(\omega)}{G_{Fa}(\omega)} \qquad H_{2,d}(\omega) = \frac{H_{2,a}(\omega)}{-\omega^2}$$

Model identification approach





$$y_i = \mathbf{c}\mathbf{A}^{i-1}\mathbf{b}$$

$$y_i = \mathbf{c}\mathbf{A}^{i}\mathbf{x}_0$$

ERA Method

$$\begin{cases} \mathbf{x}_{i+1} = \mathbf{A}\mathbf{x}_i + \mathbf{b}u_i \\ y_i = \mathbf{c}\mathbf{x}_i \end{cases}$$

$$y_i = \mathbf{c}\mathbf{A}^{i-1}\mathbf{b}$$

$$y_i = \mathbf{c}\mathbf{A}^{i}\mathbf{x}_0$$

$$\mathbf{H}_0 = \begin{bmatrix} y_1 & y_2 & \cdots & y_n \\ y_2 & y_3 & \cdots & y_{n+1} \\ \vdots & \vdots & \ddots & \vdots \\ y_n & y_{n+1} & \cdots & y_{2n-1} \end{bmatrix}$$

$$\mathbf{H}_1 = \begin{bmatrix} y_2 & y_3 & \cdots & y_{n+1} \\ y_3 & y_4 & \cdots & y_{n+2} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n+1} & y_{n+2} & \cdots & y_{2n} \end{bmatrix}$$

$$\mathbf{H}_0 = \begin{bmatrix} \mathbf{c} \\ \mathbf{c}\mathbf{A} \\ \vdots \\ \mathbf{c}\mathbf{A}^{n-1} \end{bmatrix} \begin{bmatrix} \mathbf{b} & \mathbf{A}\mathbf{b} & \ldots & \mathbf{A}^{n-1}\mathbf{b} \end{bmatrix} = \mathbf{\Phi}_o \mathbf{\Phi}_c$$

ERA Method

$$\mathbf{H}_0 = \mathbf{U}\mathbf{\Sigma}^2\mathbf{V}^T = (\mathbf{U}\mathbf{\Sigma})(\mathbf{\Sigma}\mathbf{V}^T) = \mathbf{P}\mathbf{Q}$$

$$\mathbf{H}_1 = \mathbf{\Phi}_o \mathbf{A} \mathbf{\Phi}_c$$

$$\mathbf{A} = \mathbf{\Phi}_o^{-1} \mathbf{H}_1 \mathbf{\Phi}_c^{-1}$$

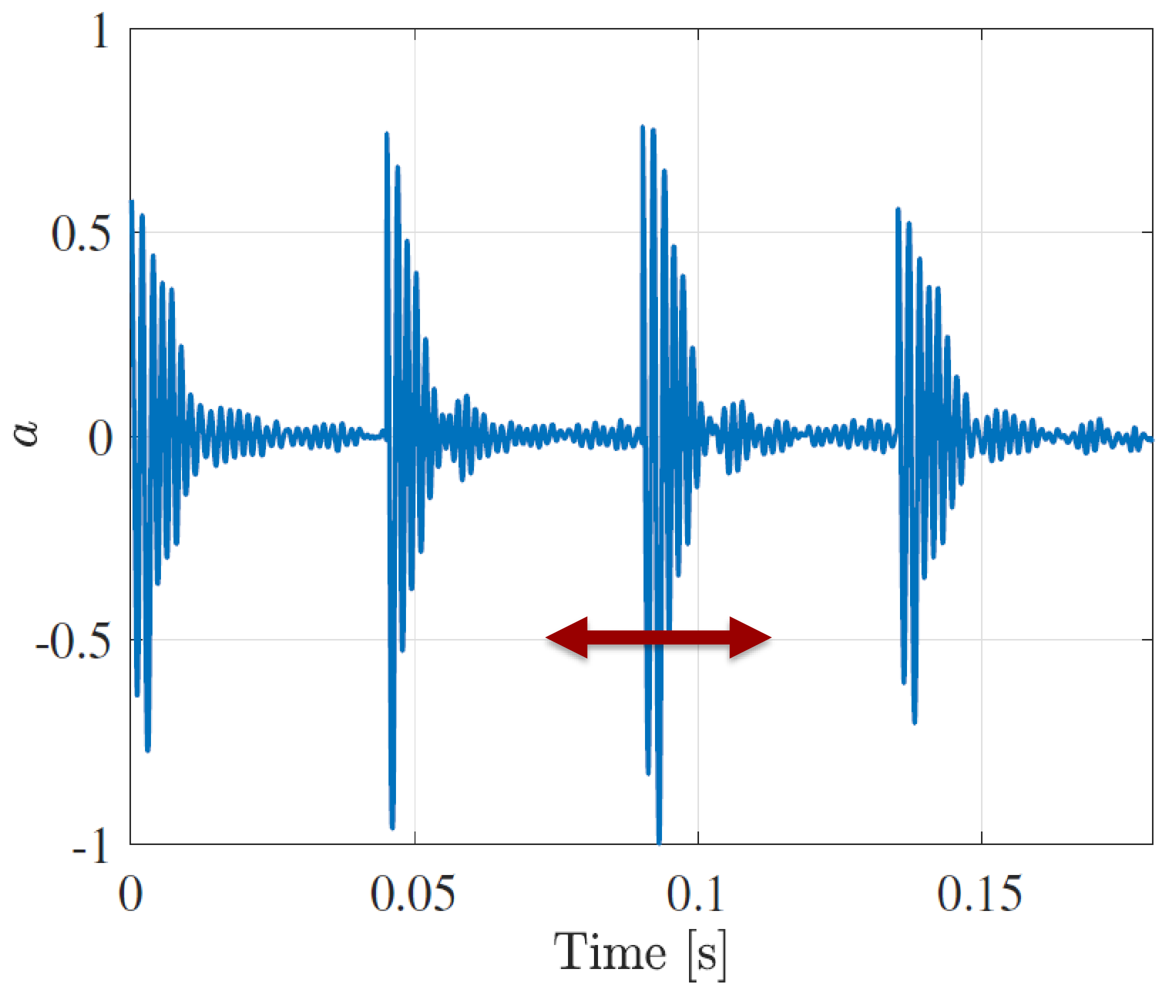
$$\hat{\mathbf{A}} = \mathbf{P}^{-1} \mathbf{H}_1 \mathbf{Q}^{-1}$$

$$\omega_{nk} = \frac{|\ln(\lambda_k(\hat{\mathbf{A}}))|}{2\pi T_s}$$

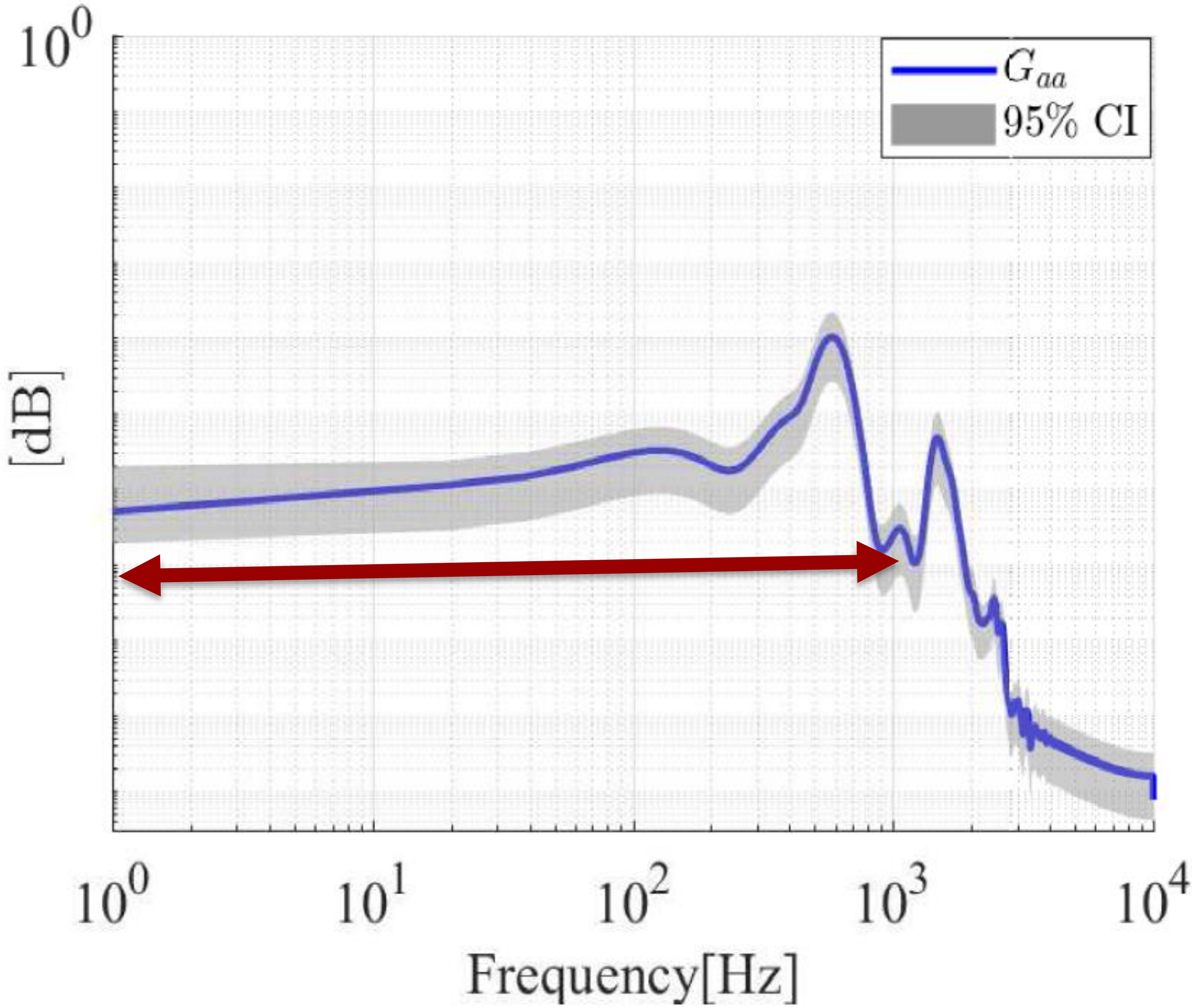
$$\zeta_k = \frac{-\mathrm{Re}(\ln(\lambda_k(\hat{\mathbf{A}}))/T_s)}{|\ln(\lambda_k(\hat{\mathbf{A}}))|}$$

$$\mathbf{Y} = \mathbf{P}\hat{\mathbf{x}}$$

Low-complexity behavioral model



Selected identification data set



Power spectrum based on the average of all measured responses

Low-complexity behavioral model

$$\mathcal{M}_l : \begin{cases} \hat{\mathbf{A}}_l = \begin{bmatrix} 0.9701 \pm 0.0018 & -0.05308 \pm 0.0007 \\ 0.05308 \pm 0.0007 & 1.0031 \pm 0.009 \end{bmatrix} \\ \hat{\mathbf{C}}_l = \begin{bmatrix} -0.7995 \pm 0.0062 & -0.0208 \pm 0.0002 \end{bmatrix} \end{cases}$$

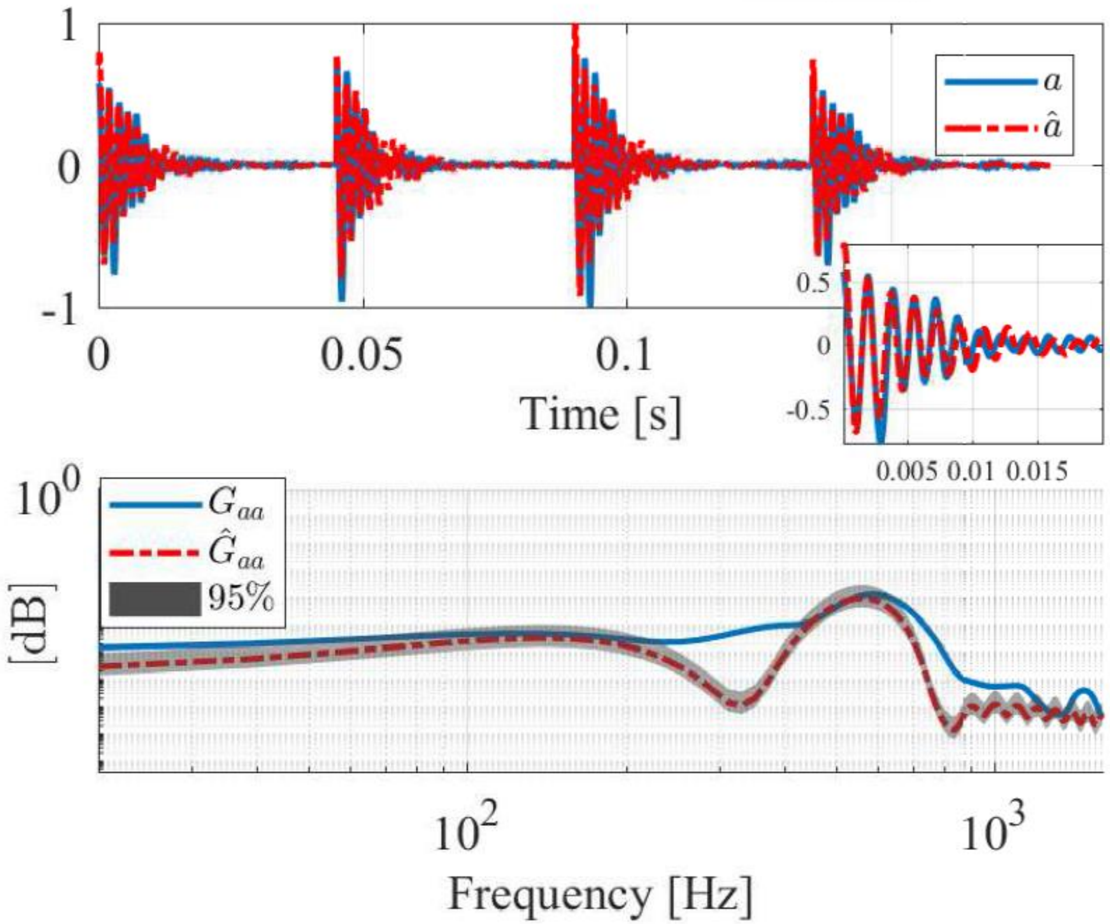
$$\mathcal{M}_h : \begin{cases} \hat{\mathbf{A}}_h = \begin{bmatrix} 0.9342 \pm 0.0298 & 0.1759 \pm 0.0049 \\ -0.1759 \pm 0.0049 & 1.0210 \pm 0.025 \end{bmatrix} \\ \hat{\mathbf{C}}_h = \begin{bmatrix} -1.9931 \pm 0.007 & -0.1689 \pm 0.005 \end{bmatrix} \end{cases}$$

$$\mathcal{M} : \begin{cases} \hat{\mathbf{A}} = \begin{bmatrix} \hat{\mathbf{A}}_l & \mathbf{0} \\ \mathbf{0} & \hat{\mathbf{A}}_h \end{bmatrix} \\ \hat{\mathbf{C}} = \begin{bmatrix} \hat{\mathbf{C}}_l & \hat{\mathbf{C}}_h \end{bmatrix} \end{cases}$$

Low-complexity behavioral model

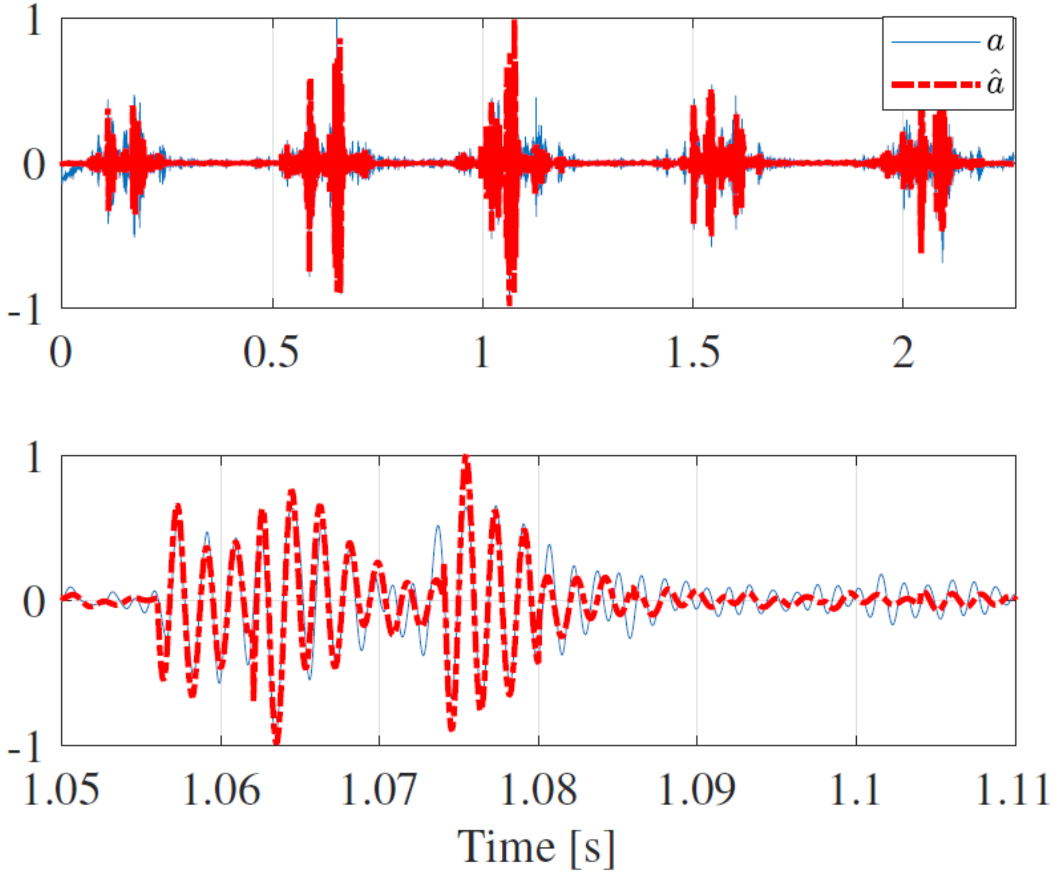
Model	$\lambda\,[-]$	ω_n [Hz]	$\zeta\,[-]$
$\mathcal{M}_l$	$0.988 \pm 0.0509i$	167.59	0.201
$\mathcal{M}_h$	$0.978 \pm 0.1704i$	549.96	0.044

Identified models characteristics

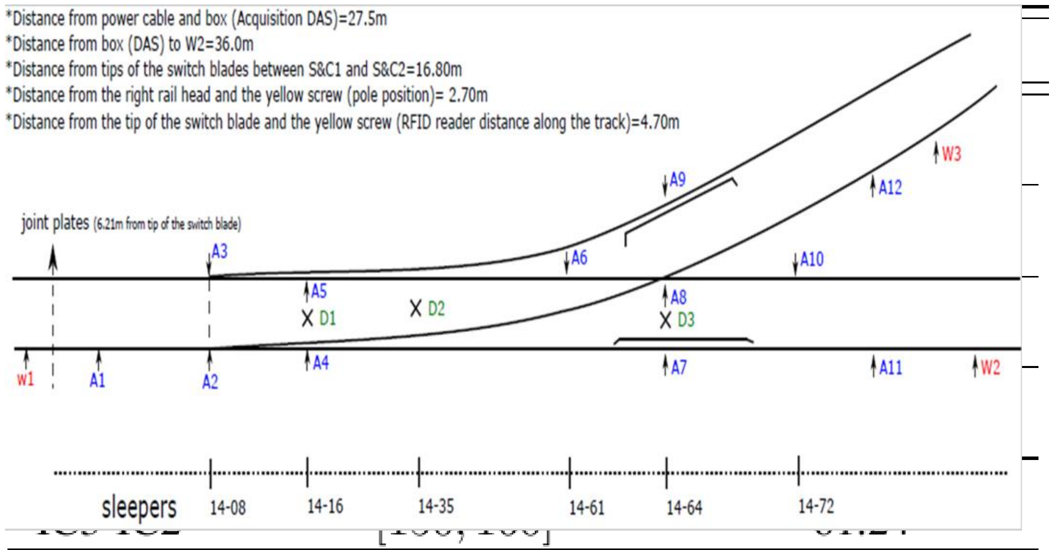


validation data compared with the identified model

Model validation



IC4 train, 110km/h



IC3	[110, 120]	59.87
IR4	[110, 120]	56.48
IC3	[150, 160]	55.68
IC3	[50, 60]	52.35
IR4	[150, 160]	51.50

Conclusion

- 4-th order model has been identified representing the vertical track dynamics
- Eigenmodes of track components (railpad & ballast) were found
- Less computational time compared to FEM and MBS, reduced number of parameters, portable tool (P&P)
- The identified model was validated
- The dominant behavior of the track response to train excitation was estimated
- The robustness of the identified model was validated by comparing the identified model with a pool of ten different passenger trains

Future works

- ✓ Using the proposed identification method for the track response to different train passages, no need to do the receptance test.

- ✓ Long- term monitoring (recursive estimation) of the model natural frequencies and damping ratio provides valuable insights into ballast layer deterioration.

- ✓ The identification of the 4-th order model opens opportunities for the development of a condition monitoring system to supervise the occurrence of degradation affecting the ballast layer and the railpads.

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References

[1]-Juul Andersen, K. (2012). Årsrapport 2012 (Tech. Rep. No.13-00144). banedanmark.

[2]-Clinton, A. (2014). Annual Safety Performance Report 2013/14 (Tech. Rep.). Railway Safety and Standards Board.

[3]-Hassankiadeh, S. (2011). Failure analysis of railway switches and crossings for the purpose of preventive maintenance(MSc Thesis). Royal Institute of Technology.