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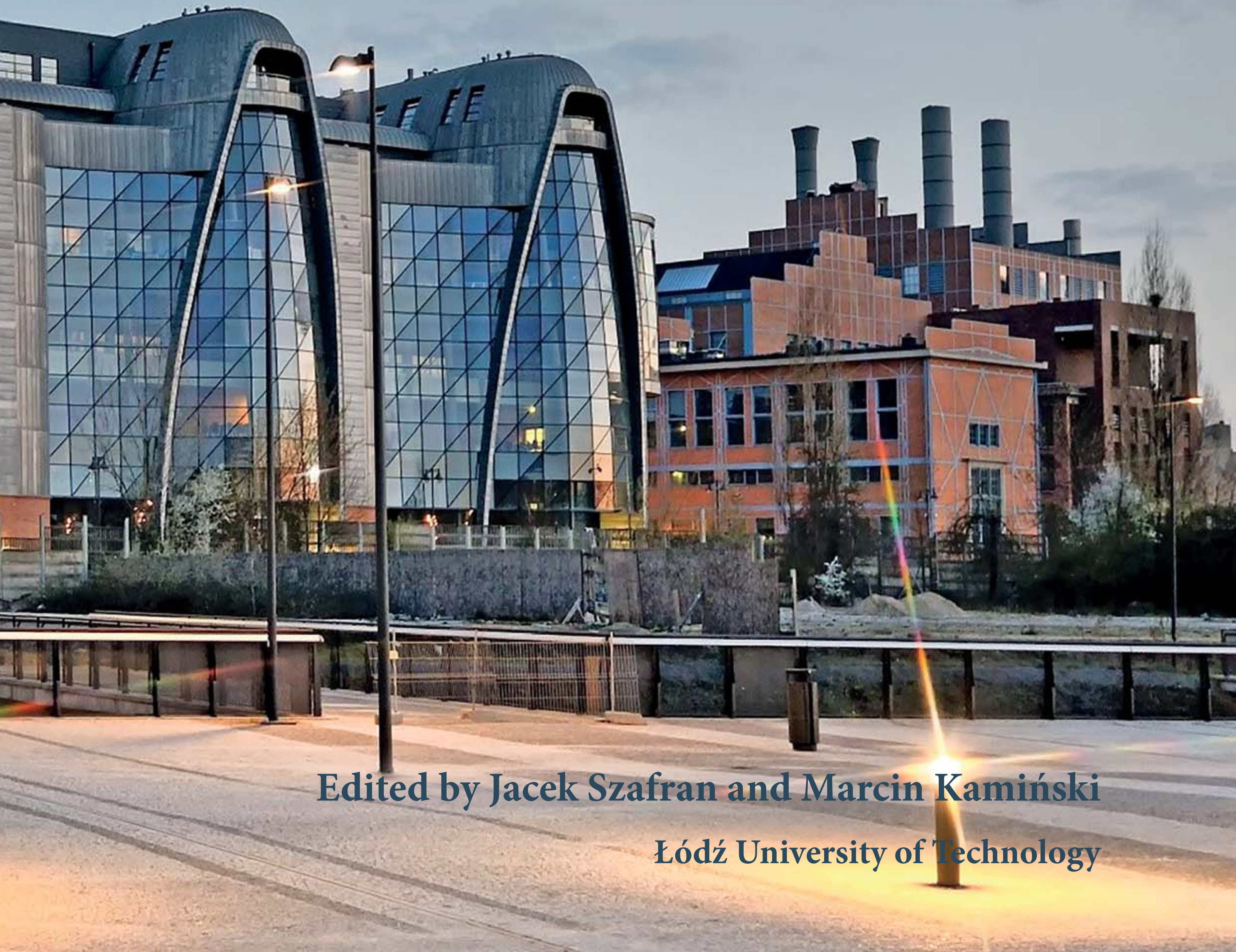
CONTEMPORARY PROBLEMS

Book of Abstracts

2nd-3rd December 2021, Łódź, Poland



Edited by Jacek Szafran and Marcin Kamiński

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PARAMETRIC IDENTIFICATION OF UNCERTAIN BOLTED CONNECTIONS WITH BAYESIAN APPROACH

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ABSTRACT: The paper presents the parametric identification of structural connections characterised by highly uncertain stiffness. Such uncertainties often appear in structural bolted connections. One of the common problems in parametric identification with the use of modal data is the problem of the mode matching. In this work the model updating method based on the Bayesian approach was used to identify the unknown parameters. Due to the probabilistic framework it allows to avoid the problem of the mode matching. A laboratory-scale frame structure is considered in this research, however this structure contains bolted connections common also in large-scale light-weight structures. The problem of parametric identification has been decomposed into the following tasks: (a) selection of the finite element model, (b) evaluation of the identifiability of the parameters, and (c) updating the finite element model with the use of available measurement data.

Keywords: Bayesian approach, mode matching, system identification, model updating, bolted connections.

1. INTRODUCTION AND MOTIVATION

The present study is devoted to parametric identification of bolted connections characterised by highly uncertain stiffness parameters. Such connections are common in many frame structures. Thus, the parametric identification of bolted connections is applicable in a variety of fields, especially in structural health monitoring but also in development of simulation models.

Recently in literature many approaches for modelling of highly nonlinear bolted connections are concentrated on both stiffness and damping (Segalman 2006). In this work the attention is paid to identification of the stiffness parameters for modal analysis purposes. Gutkowski and Błachowski (2010) indicated that local parameters of the bolted connections have significant influence on the dynamics of the whole structure. It often causes the need of updating of the finite element (FE) model. Model updating is widely accepted as method of parametric identification (An et al. 2019).

Classical methods for model updating are based on the concept of modal sensitivity. These methods require comparison of modal parameters calculated from FE model with these ones extracted from the measurement. However, not always all the modes can be measured and furthermore their order can be inconsistent with those obtained numerically. Another difficulty characteristic for classical model updating methods is so-called mode switching. (Friswell and Mottershead 1995).

In this work parametric identification based on Bayesian approach is applied for stiffness identification in the bolted joints of a certain frame structure. Contrary to the classical methods, in the Bayesian apprach it is not postulated that the numerical modal parameters should be equal to the experimental ones. Instead, the most probable values of unknown parameters are sought. It allows to overcome the mode matching problem. A frame structure equipped with semi-actively lockable joints, namely: lockable joints, mounted through the bolted connections is considered. During measurements the lockable joints were locked, hence they are considered as rigid connections. More details about the lockable joints can be found in works of Ostrowski et al. (2021) and Popławski et al. (2021).

2. STRUCTURE WITH UNKNOWN STIFFNESS PARAMETERS

2.1. Structure under consideration

The lockable joint connected with structural members (steel profiles) through the bolted connections, namely: beam-joint connections, and FE model of the structure are shown in Figure 1a and b, respectively. The structure is equipped with six lockable joints. Due to the assembly inaccuracies the stiffness parameters of these connections are characterised by high uncertainties. It results in asymmetry in the mode shapes (see Fig. 3).

a) b)

Fig. 1. a) Semi-actively lockable joint with visible beam-joint connections of the laboratory-scale frame structure and b) mesh of FE model with its dimensions and parametrization of each beam-joint connection.

2.2. Model class selection

A class of FE models $(\mathbf{M},\ \mathbf{K}(\boldsymbol{\theta}))\in$ is considered, where $\mathbf{M}$ is constant mass matrix and $\mathbf{K}(\boldsymbol{\theta})$ $\mathbf{K}(\boldsymbol{\theta})=\mathbf{K}(\theta_1,\theta_2,\ldots,\theta_{Nt})=\mathbf{K}_0+\sum_{t=1}^{N_t}\mathbf{K}_t$ is stiffness matrix depending on vector of unknown parameters $\boldsymbol{\theta}=[\theta_1\ \cdots\ \theta_{Nt}]^T$, where $\mathbf{K}_0$ is stiffness-matrix component corresponding with steel profiles characterised by well-known stiffness, matrix components $\mathbf{K}_t=k_r\mathbf{L}_t^T\mathbf{L}_t$ multiplied by parameters θ_t describe sought stiffnesses of the beam-joint connections. Each of such connections is represented by stiffness between two rotational degrees of freedom (DOFs) k_r (see Fig. 1b, zoomed joint) and $\mathbf{L}_t$ is Boolean matrix choosing rotational DOFs involved in tth beam-joint connection. The beam joint-connections are parametrized independently on each other. The lockable joints are treated as rigid bodies. Dynamics of the lockable joints is represented by lumped masses and mass-inertia moments, whereas displacements are represented by offsets in FE mesh.

3. IDENTIFICATION OF THE SYSTEM PARAMETERS WITH BAYESIAN APPROACH

3.1. Identifiability of the unknown parameters

In order to check whether the class of models C is correctly selected the identifiability of the unknown parameters should be assessed. Yuen (2010) shown that if likelihood $L(\boldsymbol{\theta})$ function has only one maximum over some search space the parameters are identifiable in such a defined region. $L(\boldsymbol{\theta})$ can be written as follows: $L(\boldsymbol{\theta}) = KK_{\phi}\hat{p}(D_{\phi}|\boldsymbol{\theta},C)K_{\lambda}\hat{p}(D_{\lambda}|\boldsymbol{\theta},C) = KL_{\phi}(\boldsymbol{\theta})L_{\lambda}(\boldsymbol{\theta})$, where $\hat{p}(\cdot)$ is prior probability density function, set D_{ϕ} contains measured mode shapes, set D_{λ} contains measured natural frequencies, $L_{\phi}(\boldsymbol{\theta})$ is likelihood function corresponding with mode shapes, whereas $L_{\lambda}(\boldsymbol{\theta})$ with natural frequencies, coefficients K, K_{λ} and K_{ϕ} are factors normalising functions $L(\boldsymbol{\theta})$, $L_{\lambda}(\boldsymbol{\theta})$ and $L_{\phi}(\boldsymbol{\theta})$ to ones at their maximums, respectively. Inspection of the above equation shows that identifiability depends not only on chosen class of model but also on measurement data available.

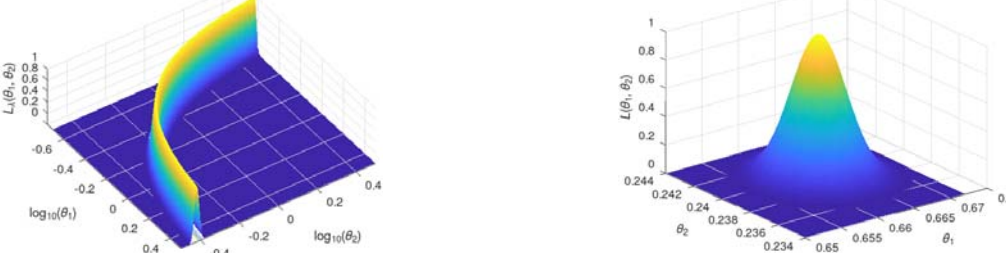
3.2. Bayesian approach-based probabilistic framework of model updating

In Bayesian approach a minimized penalty function J corresponds to prior probability density function: $J(\boldsymbol{\lambda},\boldsymbol{\phi},\boldsymbol{\theta}) = -2\ln p(\boldsymbol{\lambda},\boldsymbol{\phi},\boldsymbol{\theta}|\boldsymbol{\lambda}_{\text{exp}},\boldsymbol{\phi}_{\text{exp}})$, where: $\boldsymbol{\lambda}_{\text{exp}} = \begin{bmatrix}\omega_1^2 & \omega_2^2 & \ldots & \omega_{N_m}^2\end{bmatrix}^{\text{T}}$, ω_m^2 is m^{th} measured natural frequency, $\boldsymbol{\phi}_{\text{exp}}^{(m)}$ is m^{th} measured mode shape $\boldsymbol{\phi}_{\text{exp}} = \begin{bmatrix}\boldsymbol{\phi}_{\text{exp}}^{(1)\,\text{T}} & \boldsymbol{\phi}_{\text{exp}}^{(2)\,\text{T}} & \ldots & \boldsymbol{\phi}_{\text{exp}}^{(N_m)\,\text{T}}\end{bmatrix}^{\text{T}}$. Since both measurement as well as FE model are subjected to certain errors, $\boldsymbol{\lambda}$ and $\boldsymbol{\phi}$ that minimize function J represent the most probable modal parameters of the system, whereas vector $\boldsymbol{\theta}$ contains the most probable parameters of the FE model. Efficient algorithm minimizing function J has been described by Yuen et al. (2006).

4. RESULTS

4.1. Assessment of parameter identifiability

In order to check the number of maximums of the function $L(\boldsymbol{\theta})$ in the preselected search space the full review method has been employed. Such calculations for full set of parameters, as shown in Fig. 1b, require tremendous computational effort. Thus, for identifiability assessment only two parameters, $\tilde{\boldsymbol{\theta}} = \begin{bmatrix}\tilde{\theta}_1 & \tilde{\theta}_2\end{bmatrix}^{\text{T}}$, have been used, where $\tilde{\theta}_1$ and $\tilde{\theta}_2$ relate to all vertical beam-joint connections and all horizontal ones, respectively, $k_r = 10^4$ for all the beam-joint connections. Identifiability was evaluated in the search space $(\tilde{\theta}_1,\tilde{\theta}_2) \in [10^{-1},10^2]\times[10^{-2},10^2]$. Measurements were performed with aid of three-axes accelerometers placed evenly per each 75 mm on the structure. To show how identifiability depends on available measurement data two cases have been considered. The first, only natural frequency of the first mode has been measured ($L(\boldsymbol{\theta}) = L_{\lambda}(\boldsymbol{\theta})$) and, the second, first five measured natural frequencies and mode shapes are available. In the first case there is no any distinguished maximum of the likelihood function, so parameters $\tilde{\theta}_1$ and $\tilde{\theta}_2$ are not identifiable. In the second case function has only one maximum, so parameters $\tilde{\theta}_1$ and $\tilde{\theta}_2$ are identifiable, moreover likelihood function $L(\tilde{\boldsymbol{\theta}})$ has significant values only in a small neighbourhood of optimal parameters. $\tilde{\theta}_1$ and $\tilde{\theta}_2$ are precisely estimated.



a) b)

Fig. 2. Likelihood function: (a) for measured the first natural frequency only and (b) around neighborhood of optimal parameter values for measured first five natural frequencies and mode shapes.

4.2. Model updating

Model updating performed by minimization penalty function J has been performed. Comparison between numerical and experimental mode shapes is shown in Figure 3. Here full set of $N_t = 16$ parameters has been used to parametrise each beam-joint connection independently on each other. It allows to fit the model into asymmetric mode shapes and accurately reconstruct stiffnesses discrepancies. Table 1 contain final values of parameters $\boldsymbol{\theta}_t$, frequency errors and MAC values for the modal data of the updated FE model.

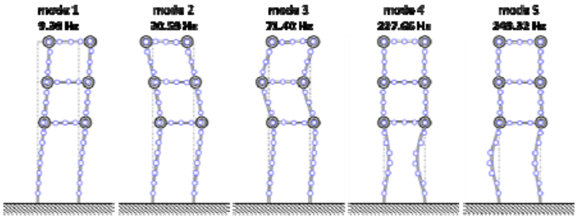


Fig. 3. Comparison between mode shapes of the updated FE model (gray lines) and measured displacements (blue points), natural frequencies in the figure are taken from the measurement.

Table 3. Final values of the parameters $\boldsymbol{\theta}$ relative frequency errors and MAC for updated model

Final values of the unknown parameters							
θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8
0.46	0.90	1.06	1.06	1.08	0.17	0.77	0.28
θ_9	θ_{10}	θ_{11}	θ_{12}	θ_{13}	θ_{14}	θ_{15}	θ_{16}
1.12	1.20	0.32	0.40	0.39	0.24	0.23	0.35

Final relative frequency errors and MAC values					
mode [–]	1	2	3	4	5
$\frac{f_m^{\exp} - f_m(\boldsymbol{\theta})}{f_m^{\exp}}$ [%]	9.90	–5.88	–0.12	–1.67	1.76
MAC [–]	0.97	0.97	0.97	0.89	0.91

5. CONCLUSIONS

Parametric identification of bolted connections can be related to many frame-like structures. For the present study the structure equipped with semi-actively lockable joints has been adopted as an example. In this case Bayesian approach-based parametric identification of the stiffnesses of the beam-joint connections allows for further precise reconstruction dynamics of the structure under investigation including structural asymmetry.

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