Finite Element Model Updating for Digital Twin Development using Operational Modal Analysis: the JRC Atmospheric Observatory Tower Case Study *

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Abstract. This paper presents the development of an accurate digital twin of a 100 m-tall steel truss Atmospheric Observatory tower located at the European Commission (EC)'s Joint Research Centre (JRC) in Italy. The study aims to align material properties and, more important, boundary conditions for the structural model. Wireless accelerometers were used for continuous vibration monitoring at different levels of the tower. Operational Modal Analysis (OMA) techniques were applied to identify the tower's dynamic parameters, and a Finite Element Method (FEM) model was developed to provide deeper insights into the structural behavior. Model updating techniques were employed to minimize discrepancies between the FEM model and the measured dynamic parameters. The updated numerical model accurately captures the tower's dynamic behavior, emphasizing the importance of model updating for enhancing the accuracy of digital twins and opening the way to the benefits of digital twins in structural health monitoring and predictive maintenance strategies for complex structures.

Keywords: Finite Element Model Updating · Douglas-Reid Method · Structural Health Monitoring · Optimization Algorithms

1 Introduction

A number of factors play an important role in ensuring the proper functioning of any country's civil structures and infrastructure. Key structures such as skyscrapers, offshore platforms, bridges, and telecommunication towers are vital components of this complex built environment, and their failure can have

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widespread and severe consequences [14]. Due to the limited availability of resources for the maintenance and inspection of these aging structures, in recent years there has been an increasing focus on Structural Health Monitoring (SHM) to assess their safety. SHM represents a valuable tool for engineers to assess the condition of structures and prioritize maintenance, helping to prevent catastrophic failures and extend the lifespan of critical infrastructure. Moreover, the creation of digital twins, which are virtual replicas of physical assets, enables advanced simulations, predictive analytics, and performance forecasting, provided that a precise virtual model of the structure is developed and regularly updated through data-driven synchronization, ensuring consistency between the physical and virtual environments.

However, a detailed Finite Element Method (FEM) model of a complex system requires the identification of numerous physical input parameters whose characteristics are not always known or precisely computable. In building numerical models, different strategies aimed at improving the accuracy of the results can be adopted. One of the most effective strategies is based on Operational Modal Analysis (OMA) and Finite Element Model Updating (FEMU). OMA has been increasingly used since the beginning of the 20$^{\text{th}}$ century due to its capability in providing non-destructive structural assessment [8,16]. It can be adopted to overcome the unavoidable uncertainties of structural systems such as material properties, boundary conditions, masses, etc. allowing to reduce the scatter between the experimental and numerical results of modal properties (i.e. natural frequency and modal shapes). The updated model, can replicate with higher accuracy the dynamic properties under operational loads. [3].

FEMU methods are broadly categorized into two major classes: *direct* methods [15,1] and *iterative* methods [11]. Direct methods involve updating the structure's mass and stiffness matrices based on experimental modal data. The main advantage of direct methods is their ease of implementation. However, they often result in inconsistent mass and stiffness matrices. Additionally, direct methods are generally limited in capturing localized effects. In contrast, iterative methods [1,2] refine the physical and mechanical properties of the structure producing more physically sound mass and stiffness matrices, and are more widely used due to their higher accuracy. In this paper, we study the implementation of the Douglas-Reid method for model updating and its integration with continuous vibration-based SHM systems, for a tall steel trussed structure located at the European Commission (EC)'s Joint Research Centre (JRC) Ispra site.

2 Case Study: Atmospheric Observatory Tower

The *JRC Atmospheric Tower* is a 95 m tall steel truss structure positioned on top of a 5 m tall reinforced concrete base building. The tower comprises 8 hollow-core circular steel columns: 4 *center* vertical columns and 4 *external* ones. The *center* columns span from the tower's base to its top with two different sections: RO 244.5 $\times$ 20 and RO 193.7 $\times$ 12.5 from 5 m to 70 m elevation and 70 m to 100 m elevation, respectively. The external columns, with section RO 298.5 $\times$ 20, are vertical up to the elevation of 25 m and then converge to connect to the core columns. For this inclined portion, a RO 244.5×20 steel hollow section is used. The floors are formed by steel grids supported by $HEA140$ horizontal beams. The interstory height is 5 m. Given the structure's complexity, this is a good case study for FEMU and SHM integration assessment.

The initial FE model of the tower was developed within the CAST3M software, details about the numerical model are discussed in [6]. The updated numerical model of JRC Atmospheric Tower is built in MIDAS Gen software. The material is assumed to be perfectly elastic and isotropic. The real tower and the final comprehensive numerical model are shown in Figure 1 while the results of the modal analysis of this first model are reported in Table 1 for natural frequencies and Figure 2 for modal shapes.

Table 1: Natural frequencies of FEM

Modes	Natural Frequency $[Hz]$	Mode Shape
1	0.66	X (no sign inversion)
2	0.67	Y (no sign inversion)
3	2.33	X (1 sign inversion)
4	2.36	Y (1 sign inversion)
5	3.10	T (no sign inversion)

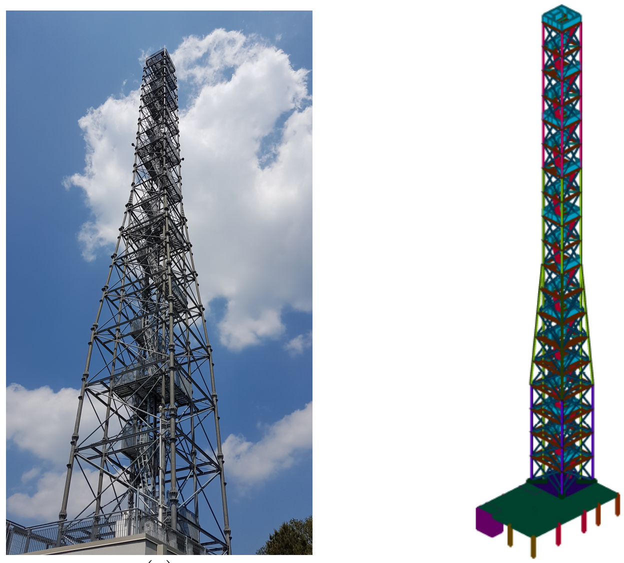
3 Ambient Vibration Testing

Continuously monitored ambient vibration can be used in output-only tests for identifying the dynamic properties of a structure. To this aim the tower is equipped with three wireless accelerometers, placed at different heights (60 m, 80 m and 100 m); they are solar powered triaxial custom *LORD Microstrain G-Link-200 OEM* devices with external antenna, having a clock synchronization with a precision of $\pm 32\,\mu s$ and operating with a sampling frequency of 64 Hz.

3.1 Modal parameter estimation with OMA

OMA focuses on extracting structural modal parameters, like natural frequencies, mode shapes and damping ratios, from field measurements taken under normal operational conditions (ambient excitation). Advanced specialized software packages are used for OMA; notable accessible examples include `PyOMAc`, `KOMAc`, and `PyOMA`, which are open-source solutions specifically developed for OMA tasks. We identified modal frequencies using two well known methods Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI). In EFDD we use the strategy of the Inverse Discrete Fourier Transform (IDFT) which basically converts our Power Spectral Density (PSD)

Figure. 1: **(a)** View of JRC atmospheric tower. **(b)** Finite element model of the tower structure.



(a) (b)

function in the time domain; here, peaks of the system response lie at the resonance frequency of the structure which we get from the zero-crossing times. In SSI method modal properties were computed in the time domain; the main advantage of this method is that we can find the effective state of space for a very complex dynamic system which is under the stochastic excitation directly by taking OMA data. Results obtained by these methods are summarized in Table 2.

Table 2: Comparison between experimental and numerical natural frequencies

Mode	Deformed Shape	Exp. (EFDD) $[Hz]$	Exp. (SSI) $[Hz]$
1	X (no sign inversion)	0.79	0.79
2	Y (no sign inversion)	0.79	0.79
3	X (1 sign inversion)	2.48	2.49
4	Y (1 sign inversion)	2.55	2.58
5	T (no sign inversion)	3.07	3.07

(a) 1^{st} Mode (b) 2^{nd} Mode (c) 3^{rd} Mode (d) 4^{th} Mode (e) 5^{th} Mode

Figure. 2: Global mode shapes of Tower structure.

4 Model Updating

In this work, the discrepancy between the FEM natural frequencies and the experimental ones is reduced using a model updating method. We first performed a manual tuning to get general information on the behavior of the structure and figure out which parameters are most important for accurately representing the system's behavior. Then we carried out a sensitivity analysis on the parameters selected for the updating, to better assess the role of the updating parameters. Finally, we performed the Douglas-Reid semi-automatized model updating method. The complete model update workflow is shown in Figure 3.

Three numerical FEM models, of increasing fidelity, were created for this purpose in MIDAS. The first model (`FEM1`) is the initial basic model reported in Section 2, which has fixed constraints at the base of the building. The second model (`FEM2`) includes the effects of the base actual restraint through three-dimensional elastic spring supports, located at the base foundation, with different stiffness levels. The last model (`FEM3`) explores, additionally, the effects of the joints stiffness for the beams, columns and vertical bracing.

4.1 Manual tuning

In model updating, manual tuning entails manually updating the parameters, understanding the behaviour of the structure and determining the approximated base value of the updating parameter. The boundary conditions of the numerical model have the highest influence on defining the dynamic behavior of the structure [5]; as the base of the building lies on the ground, whose stiffness properties are largely unknown, considering the base completely fixed may not be correctly representative of the real conditions. In this light, a preliminary model with uniform spring stiffness for the whole foundation has been set; subsequently, the foundation stiffness has been modified in a predefined 1-10 range [10]. Figure 4 shows the error behaviour for this variation of spring stiffness.

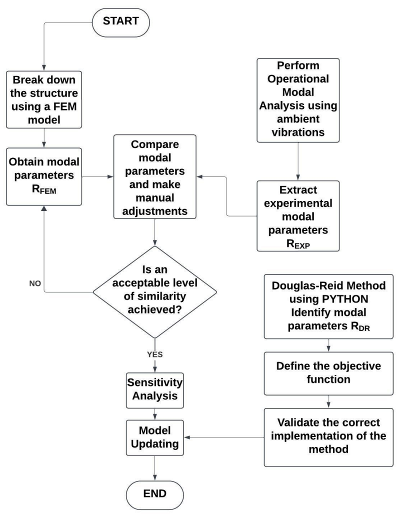


Figure. 3: Workflow for model updating process

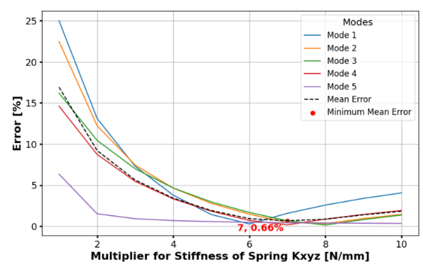


Figure. 4: Frequency error analysis with varying stiffness in elastic spring supports

After manual tuning, an optimal multiplier value of 7 was obtained for the stiffness of the foundation springs, with a minimum error 0.66 % and a corresponding value of 8050 kN/mm in all directions, which was used in further models and analyses. As a further refinement, spatially variable foundation springs could be introduced, according to specified patterns.

4.2 Sensitivity Analysis

The sensitivity analysis is required to evaluate the effect, on structural response, of the parameters selected for updating. For each parameter, the $S_{i,j}$ sensitivity coefficients are computed according to Equation (1). These coefficients show the influence on the structure's modal response of each specific variable. In the present work, we have changed each updating parameter by 5 % to compute its sensitivity coefficient. Table 3 shows the parameters considered (Young's modulus, density, boundary condition considered equivalent to an elastic foundation).

Only those parameters which have the highest sensitivity on the initial frequency of the lower modes are considered. In the last column of Table 3 the sensitivity coefficients are reported. It can be observed how the E_3 steel Young's modulus (internal plus inclined columns) and the E_5 one (vertical truss elements) have the highest influence (20 and 20.8 % respectively) in defining the dynamic behavior of the structure. The least influencing update parameters, with a value of 0.9 %, are E_1 and E_6 (the Young's modulus of the floor beams of the tower and of the columns of the base building, respectively). The remaining other parameters have a comparatively intermediate influence on the structure. Note that in the initial stage a larger number of parameters were considered, but their influence was negligible so that they have not been reported here, and will not be considered as updating parameters for the subsequent analysis. After discarding the non-relevant parameters, the ones included in the procedure are the elastic moduli, stiffness and densities reported in Table 3.

$$S_{i,j} = 100 \cdot \frac{X_j}{R_i^{\mathrm{FEM}}} \cdot \frac{\Delta R_i^{\mathrm{FEM}}}{\Delta X_j}, \quad i = 1, \ldots, M \quad , \quad j = 1, \ldots, N \tag{1}$$

Table 3: Sensitivity Analysis for Various Tower Parameters

Name	Parameter	Initial value	Sensitivity coefficient ($S_{i,j}$)
Floor Beams of Tower	E_1 $[MPa]$	210000	0.9%
Internal Column+Inclined Column of Tower	E_3 $[MPa]$	210000	20%
Internal Column last 6 Floors of Tower	E_4 $[MPa]$	210000	3%
Vertical Bracing of Tower	E_5 $[MPa]$	210000	20.8%
Columns of Base Building	E_6 $[MPa]$	33000	0.9%
Elastic Foundation at base	K $[kN/mm]$	1150	4.2%
Floor Beams of Tower	ρ_1 $[kg/m^3]$	7860	10.2%
Internal Column+Inclined Column of Tower	ρ_2 $[kg/m^3]$	7860	11.5%
Internal Column last 6 Floors of Tower	ρ_3 $[kg/m^3]$	7860	8.3%
External Shaft of Tower	ρ_4 $[kg/m^3]$	7860	1.4%
Vertical Bracing of Tower	ρ_5 $[kg/m^3]$	7860	10.7%

It must be observed that the elastic moduli here considered must be intended as fictitious variables, taking the overall stiffness of the element into account, which is affected by a number of phenomena, mainly related to the joints behaviour. A similar comment applies to densities, whose value fictitiously incorporates the effect of additional masses.

4.3 Douglas-Reid Model Updating

The Douglas-Reid (DR) method [9] was introduced in 1982 and it belongs to the class of iterative model updating procedures. This method has received increasing consideration in research and operative analyses, where numerical models need to precisely match the response of monitored real structures. The DR model updating uses a second-order quadratic interpolation technique. It has been effectively used to update complex models of large structures, such as bridges [7,12] and historical buildings [17], where its simplicity and lower computational requirements are particularly beneficial.

In our application of DR method to the *JRC Atmospheric Tower*, the update parameters were chosen to better represent the structure's mechanical and physical characteristics. This usually involves the refinement of both natural frequencies [17,13] and mode shapes [4]. In this study, we only work on natural frequencies as, in the case here considered, the updating parameters have a negligible influence on the mode shapes [17]; nonetheless, if needed, the method can also be implemented to directly address the mode shapes as well [4] by following the same procedure.

The first step in the DR method is to identify the experimental f_i^{exp} and FEM f_i^{FEM} natural frequency for M modes, refer to Equation (2).

$$f_i^{\text{exp}} \quad (i = 1, \dots, M), \quad f_i^{\text{FEM}} = f_i^{\text{FEM}}(x_1, x_2, x_3, \dots, x_k, \dots, x_N) \tag{2}$$

The DR method uses second-order approximation of the natural frequency f_i^{DR} reported in Equation (3), which has $2N + 1$ unknowns. To find these unknowns, the nominal value x_k^B of each updating parameter and its upper x_k^U and lower x_k^L range are initially defined and normalized by the nominal value.

$$f_i^{\text{DR}} = C_i + \sum_{k=1}^{N} \left(A_{i,k} x_k + B_{i,k} x_k^2 \right), \quad \frac{x_k^L}{x_k^B} \leq \frac{x_k^B}{x_k^B} \leq \frac{x_k^U}{x_k^B} \tag{3}$$

To get the unknowns, we first create the $2N + 1$ equations system shown in Equation (4), varying one updating parameter at a time (within its upper and lower bound), while keeping fixed the nominal values for the others and equating with frequencies obtained from Equation (3).

$$\begin{aligned}
f_i^{\text{DR}}(x_1^B, \dots, x_k^B, \dots, x_N^B) &= f_i^{\text{FEM}}(x_1^B, \dots, x_k^B, \dots, x_N^B) \\
f_i^{\text{DR}}(x_1^U, \dots, x_k^B, \dots, x_N^B) &= f_i^{\text{FEM}}(x_1^U, \dots, x_k^B, \dots, x_N^B) \\
f_i^{\text{DR}}(x_1^L, \dots, x_k^B, \dots, x_N^B) &= f_i^{\text{FEM}}(x_1^L, \dots, x_k^B, \dots, x_N^B) \\
f_i^{\text{DR}}(x_1^B, \dots, x_k^U, \dots, x_N^B) &= f_i^{\text{FEM}}(x_1^B, \dots, x_k^U, \dots, x_N^B) \\
f_i^{\text{DR}}(x_1^B, \dots, x_k^L, \dots, x_N^B) &= f_i^{\text{FEM}}(x_1^B, \dots, x_k^L, \dots, x_N^B) \\
f_i^{\text{DR}}(x_1^B, \dots, x_k^B, \dots, x_N^U) &= f_i^{\text{FEM}}(x_1^B, \dots, x_k^B, \dots, x_N^U) \\
f_i^{\text{DR}}(x_1^B, \dots, x_k^B, \dots, x_N^L) &= f_i^{\text{FEM}}(x_1^B, \dots, x_k^B, \dots, x_N^L)
\end{aligned} \tag{4}$$

The system in Equation (4) can be expressed in matrix form as:

$$\{f_i^{\text{FEM}}\} = [C]\{K_i\} \tag{5}$$

Solving this system delivers the values of the unknown interpolation constants, listed in the vector K_i. So, the DR model natural frequencies (3) can be used in place of the numerical frequencies f_i^{FEM} in the minimization procedure of the objective function: this delivers the optimal values of the updating parameters.

$$[C] = \begin{bmatrix} 1 & x_1^B & (x_1^B)^2 & \dots & x_N^B & (x_N^B)^2 \\ 1 & x_1^U & (x_1^U)^2 & \dots & x_N^B & (x_N^B)^2 \\ 1 & x_1^L & (x_1^L)^2 & \dots & x_N^B & (x_N^B)^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 1 & x_1^B & (x_1^B)^2 & \dots & x_N^U & (x_N^U)^2 \\ 1 & x_1^B & (x_1^B)^2 & \dots & x_N^L & (x_N^L)^2 \end{bmatrix} \qquad \{K_i\} = \begin{Bmatrix} C_i \\ A_{i,1} \\ B_{i,1} \\ \vdots \\ A_{i,N} \\ B_{i,N} \end{Bmatrix} \tag{6}$$

The objective functions considered in this work are reported in (7), where PMR_i is the participation mass ratio for each mode that acts as a weighting function.

$$J_f'' = \frac{100}{M} \sum_{i=1}^{M} \left(\frac{f_i^{\text{FEM}} - f_i^{\text{exp}}}{f_i^{\text{exp}}} \right)^2 \cdot \text{PMR}_i \tag{7}$$

5 Model Updating Results

Table 4 report the values of the updated parameters, as well as their variations obtained after performing the model updating of the basic FEM model (`FEM1`). Similarly, the variation of the updating parameters for the advanced FEM model (`FEM2`), in which the effect of elastic springs at the base was incorporated. It can be observed how the second model, being intrinsically more capable of capturing the structural response, generally requires much more limited variations in the parameters. Finally, the error for the initial model (`FEM1`) and the more refined model (`FEM2`) are reported in Table 5, again showing the significantly better performance of the second model; the advanced model (`FEM2`) shows an error smaller than 2% for all the five lower modes. The updated structural parameter values are reported in Table 4.

Finally, as a further improvement the model (`FEM3`) was set, which evaluates, based on a sensitivity analysis, whether connections are perfectly rigid or not (maybe as a consequence of bolts loosening); this accounts for the effects of the joints flexibility by changing the bending stiffness of the joint sections within the modified mesh shown in Figure 5 for a typical tower segment. The advanced model (`FEM2`) is used for analysing the structure's response: seven distinct cases were considered with a 0 %, 5 %, 10 %, 15 %, 20 %, 25 % and 30 % reduction of the joints stiffness. The computed numerical modal frequencies are compared with the experimental natural frequencies in Figure 6 for each reduction case.

The results of the model updating due to a variation of element stiffness are shown in Figure 7 where the colour indicates the amount of stiffness variation of each structural component. The most accurate `FEM` model is associated to the 15 % reduction in joint stiffness. This can be regarded as the most accurate model obtained from the overall model updating process.

Table 4: Updating parameter values after model updating in FEM1 and FEM2

Parameter	Initial value	FEM1		FEM2	
		Updated Value	Variation(%)	Updated Value	Variation(%)
E_1 $[MPa]$	210000	315000	50.0	302400	44
E_2 $[MPa]$	210000	329700	57.0	350700	67
E_3 $[MPa]$	210000	285600	36.0	247800	18
E_4 $[MPa]$	210000	197400	-6.0	201600	-4.0
E_5 $[MPa]$	210000	138600	-34.0	180600	-14.0
E_6 $[MPa]$	33000	23760	-28.0	27720	-16.0
ρ_1 [kg/m^3]	7860	7860	0.0	7702.80	-2.0
ρ_2 [kg/m^3]	7860	8410.2	7.0	8410.20	7.0
ρ_3 [kg/m^3]	7860	6523.8	-17.0	8960.40	14.0
ρ_4 [kg/m^3]	7860	8253	5.0	4951.8	-37.0
ρ_5 [kg/m^3]	7860	6547.38	-16.7	6547.38	-16.7
K $[kN/mm]$	1150	-	-	8050	-

Table 5: Comparison between experimental and numerical natural frequencies of FEM1 and FEM2

Mode	Experimental		FEM1			FEM2		
	EFDD	SSI	Numerical	Error(EFDD)	Error(SSI)	Numerical	Error(EFDD)	Error(SSI)
1	0.79	0.79	0.7685	2.792%	2.792%	0.8013	1.41%	1.41%
2	0.79	0.79	0.7751	2.532%	2.532%	0.8078	2.20%	2.20%
3	2.48	2.49	2.4842	3.874%	3.143%	2.5197	1.57%	1.17%
4	2.55	2.58	2.4885	2.685%	4.136%	2.5580	0.31%	0.86%
5	3.07	3.07	3.2757	8.073%	8.073%	3.1115	1.33%	1.33%

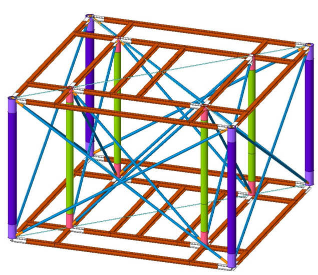


Figure. 5: End section in FEM for vertical truss, columns, and beams for typical floor.

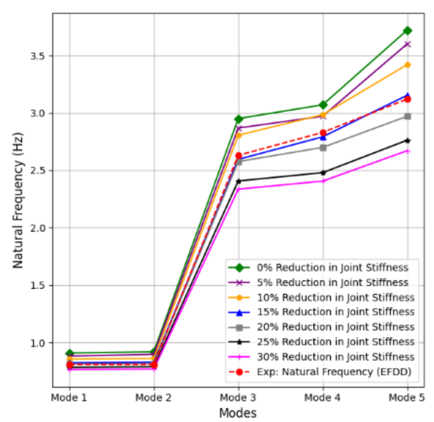


Figure. 6: Effect of joint stiffness reduction on natural frequency.

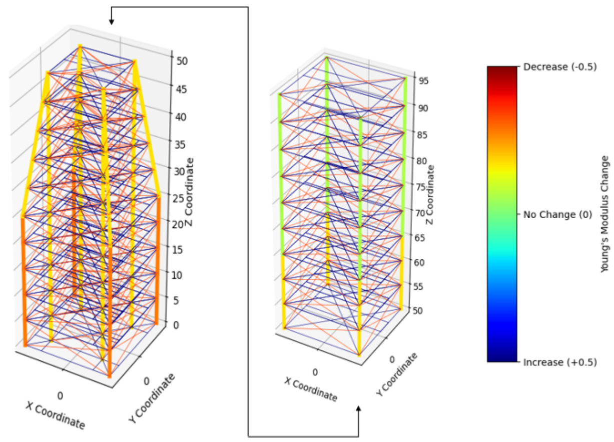


Figure. 7: Variation of Young's modulus in each member of steel truss tower.

6 Conclusion

The goal of this research was to evaluate the effectiveness of combined OMA and FEMU methods to achieve accurate FEM models in support to digital twins development. A FEM model of the *JRC Atmospheric Tower* was created and the dynamic properties of the structure were identified with OMA techniques based on wireless sensor monitoring at different levels of the structure. FEMU is then performed using the semi-optimized approach DR method, updating parameters are then optimized and the updated value is computed based on reducing the objective function.

In our work, three different FEM models `FEM1`, `FEM2` and `FEM3` were considered. In `FEM1`, we update the model by keeping the boundary condition at the base fixed. In `FEM2`, the boundary condition related to the foundation is replaced with a 3-dimensional spring model. In the last model `FEM3`, the effect of different reductions in joint stiffness is considered to achieve a further improvement of the updated `FEM2` model. The numerical response of this final model, compared to the experimental results, seems to produce a reasonable agreement to the real structural behaviour.

When updating real structures, the choice of regularization parameters should be made heuristically. Thus, understanding the impact of these parameters on the updating results is a crucial area for future research. Ideally, this work could offer guidelines for selecting suitable values for regularization parameters.

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