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Modal-Based Detection of Bolt Loosening in Steel Structures: EMA vs. OMA Comparison

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Abstract

The loosening of bolted connections within structural elements poses a significant threat to their load-bearing capacity. Early detection of such loosening is paramount to prevent structural failures. However, traditional non-destructive testing methods often struggle to identify bolted connection issues due to the intricate geometry and material disparities present within these connections. In response to this challenge, a vibration-based approach emerges as a promising solution, utilizing changes in the natural frequencies of structures to pinpoint the extent of damage, particularly in bolted connections. This article presents experimental investigations to detect loosening within bolted connections in a lab-scale steel beam using both Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). The results demonstrate the successful detection of the extent of loosened bolted connections during experimental damage assessments. The findings presented herein underscore the efficacy of a vibration-based approach in detecting bolt loosening, contributing to advancing structural health monitoring and mitigating potential catastrophic failures.

Keywords: modal analysis; natural frequencies; structural health monitoring; bolt loosening.

1. Introduction

Operational Modal Analysis (OMA) is critical for understanding structures' dynamic behaviors [1], which provides insights into modal parameters essential for engineering applications. There has been a growing interest in applying OMA to diverse structures, varying from civil engineering infrastructure to aeronautic systems.

The field of OMA has witnessed significant improvement in methodology and application. One Influential example is the study conducted by [2], which focuses on the comparative analysis of ultra-high-voltage transmission towers using the fast Bayesian FFT method for dynamic analysis and uncertainty evaluation. Another research area is the application of Bayesian methods in modal analysis, which uses tuned mass dampers (TMDs) as passive control devices to reduce structural vibrations [3]. One study in the aeronautic field presents an automated system identification method for aeronautic structures [4].

Bolted joints, common in industries like aviation and power distribution for connecting components such as beams, plates, and shells, can be affected by dynamic loads, potentially causing joint loosening and structural issues [5]. This paper explores operational modal analysis to assess bolted joint integrity under dynamic conditions, aiming to improve our ability to detect and prevent joint failure, with a specific focus on how bolt loosening affects vibrational characteristics [6].

Preventing lightning-induced damage to power grids relies on effective lightning rods. Traditionally, lattice structures were used, but modern lightning rods incorporate single-rod steel tubes for better performance in transmission lines. However, adverse weather conditions and strong winds challenge their structural integrity. Large rods can experience significant oscillations and vibrations, leading to the loosening of flange fastening bolts and, in extreme cases, catastrophic collapse [10, 11]. Given the potential economic losses resulting from power grid lightning rod failures, early detection of bolt loosening is crucial [10, 11].

Researchers have explored both direct and indirect methods to address this issue. Direct methods like measuring strain changes offer insights into bolt pre-tightening force. Indirect techniques like electrical impedance and electro-mechanical impedance technologies have gained traction due to their theoretical and experimental feasibility [12–14]. Vision-based and ultrasonic methods have shown promise among these approaches, although their applicability to large lightning rods varies [1, 2, 15, 16].

Additionally, vibration-based methods have emerged as a cost-effective and operationally straightforward means of detecting bolt loosening, mainly through techniques like hand hammer and laser excitation [10, 11]. The paper seeks to contribute valuable insights to structural integrity assessment and early fault detection through rigorous investigation and advanced modeling techniques. Frame structures are prevalent in various industries due to their cost-effective design and robust load-bearing capabilities. These structures find application in diverse sectors, such as building supports, transportation, and towers. Constructed from a combination of L bars and flat bars, frame structures play a vital role in withstanding external loads and preventing collapse [16, 17].

Frame structures rely on connections like welding, riveting, and bolting, with bolted joints being cost-effective and user-friendly [17]. Experimental modal analysis (EMA) is a powerful method for extracting modal parameters and vibration characteristics, including natural frequency, mode shape, and damping ratio. This is achieved through impact hammer or shaker tests, with accelerometers and Fast Fourier Transform (FFT) analyzers capturing output responses via frequency response functions (FRFs) [18, 19]. Prior research has employed EMA to study different materials, including alloys and magnesium, within the context of friction stir welding joints and frame structures, informing structural improvements [20, 21].

Detecting and preventing structural damage are crucial for maintaining industrial structure integrity. Changes in modal parameters, especially natural frequencies, often signal damage [22]. Vibration techniques have become valuable tools for damage detection, including monitoring frequency changes, mode curvature alterations [23], and employing methods like frequency shifting and amplitude changes [24]. Extracting natural frequencies from Frequency Response Functions (FRFs) has effectively identified changes in structural characteristics [25, 26].

In line with this context, this paper aims to investigate the differences between experimental and operational modal analysis results between tightened and loosened bolt joints in frame structures. Focusing on natural frequency and mode shape, this study has demonstrated a decrease in the structure's natural frequencies when the bolt is loosened, and the experimental results of both methods are in accordance with each other. Through this investigation, the paper seeks to enhance our understanding of the effects of bolted joint loosening on the modal characteristics of frame structures.

2. Theory

Experimental Modal Analysis (EMA) is a traditional method for identifying modal parameters of a system, including natural frequencies, damping ratios, and mode shapes, by measuring both the system's inputs (excitations) and outputs (responses). However, applying this method to large structures, such as bridges and buildings, or addressing differences between laboratory and real-world conditions can pose limitations.

These limitations have led to the adoption of Output-Only Modal Analysis (OMA) in modal identification. In OMA, system identification is achieved solely using the system's output data obtained under operational conditions [27]. While valuable, OMA has drawbacks, including substantial computational costs due to bias errors that need to be mitigated for unbiased results. Additionally, this method does not provide mode shape scaling due to limited input information.

In essence, OMA's primary concept involves estimating either the correlation function or spectral density function and utilizing these functions to extract modal parameters. Typically, random responses follow a Gaussian distribution, concentrating all the necessary information within the signal's second-order properties for extracting system characteristics [28].

Estimating the correlation function directly comes with significant computational costs. As a common practice, alternative methods like the Welch method are employed to estimate the correlation function. However, this approach introduces leakage bias errors due to the non-periodic nature of the data. These errors can be mitigated by applying windowing functions, which force the endpoints of each signal sample to be zero. Various windowing functions are available, but employing a Hanning window with a 50 percent overlap is advisable, as it is a practical approach for data processing [29].

EMA and OMA offer several identification techniques [30-32], categorized into two main types: time-domain and frequency-domain. In this article, we employ Frequency Domain Decomposition (FDD), a frequency-domain identification method based on the Singular Value Decomposition (SVD) of the spectral density matrix derived from the output data. FDD is widely favored for its user-friendly nature. Let's consider the output signal y(t), to express it as a linear combination of normal modes and modal coordinates, as follows:

$$y(t) = a_1 q_1 + a_2 q_2 + \cdots = \boldsymbol{Aq}(\boldsymbol{t}) \tag{1}$$

A represents the mode shape matrix, and q(t) is the modal vector. Building upon the definition of the correlation function matrix and equation (1), we arrive at the following conclusion:

$$R_y(\tau) = E[y(t)y^T(t+\tau)] \ = \boldsymbol{A}E[q(t)q^T(t+\tau)]\boldsymbol{A^T} = \boldsymbol{A}R_q(\boldsymbol{\tau})\boldsymbol{A^T} \tag{2}$$

To further our analysis, we apply the Fourier transform to both sides of equation (2), resulting in:

$$G_y(f) = \boldsymbol{A}G_q(f)\boldsymbol{A^T} \tag{3}$$

Frequency Domain Decomposition (FDD) provides an approximate solution; within this technique, two primary approaches are commonly used. The first approach assumes that modal coordinates are uncorrelated, resulting in $G_q(f)$ being a diagonal and positive matrix due to the Parseval theorem. This allows us to use the Singular Value Decomposition (SVD) of the spectral density matrix to obtain auto-spectral densities of $G_q(f)$.

The second approach involves assuming a white noise input, leading to the following equation (4):

$$G_y = \sum\left(\frac{a_n\psi_n^T}{-i\omega-\lambda_n} + \frac{a_n^*\psi_n^H}{-i\omega-\lambda_n^*} + \frac{\psi_n a_n^T}{i\omega-\lambda_n} + \frac{\psi_n^* a_n^H}{i\omega-\lambda_n^*}\right) \tag{4}$$

In this equation, a_n represents the mode shapes, ψ_n stands for the modal participation vectors, and λ_n corresponds to the poles associated with the system's modes. The fundamental idea underlying the white noise input assumption is that the input signal x(t) is uncorrelated with x(t+τ) except at τ=0 [28].

In real-world applications, the choice of the most suitable OMA method, whether based on the assumption of uncorrelated modal coordinates or white noise input, relies on the specific characteristics of the data and the particular system being studied.

3. Experimental Setup

A precise experimental setup was used to investigate bolt loosening, employing two steel beams (240×40×4 mm) connected by a single M5 '8.8' grade bolt. The '8.8' designation indicates the bolt's grade, placing it in the category of high-strength hexagonal head bolts, well-suited for construction and industrial applications. Notably, the bolt tightening torque was varied, with one instance at 5.5 N.m. and another at 8 N.m. representing different degrees of bolt fastening. The experimental setup involved precisely assembling the two steel beams through a single bolted joint, replicating real-world scenarios. To emulate typical structural conditions, each beam was securely clamped at one end, establishing a dual-end restraint configuration, a common configuration encountered in structural systems. The significance of this investigation cannot be overstated, as the failure to detect bolt loosening in complex structures could lead to catastrophic and irreparable consequences. **Figure 1** illustrates the structure employed in this experimental investigation. Central to this study was the Modal Test, a powerful technique employed to delve into the intricate dynamics of the structural system. Specifically, the Experimental Modal Analysis (EMA) method unveiled the system's natural frequencies, providing invaluable insights into its vibrational characteristics. Subsequently, both modal tests, EMA and OMA, are compared. Upon validation of this method under operational conditions, it can be readily applied to detect bolt loosening in large-scale structures by simply attaching sensors and collecting data. This streamlined approach offers a practical and efficient means of bolt-loosening detection in real-world structural applications.

Experimental Modal Analysis is a sophisticated methodology that affords a deep understanding of a structure's dynamic behavior. It operates by exciting the system with controlled mechanical input, typically accomplished using a modal hammer. These impulses prompt the structure to vibrate, inducing a meticulously captured response by strategically placed accelerometers. In this test, an AP Tech AU02 Modal Impulse Hammer model was used, and piezoelectric accelerometers of the same AP Tech model were attached to the structure. All data were collected using a Crystal Instruments Spider-80X data acquisition card and then processed using the Experimental Data Management (EDM) software (**Figure 1**).

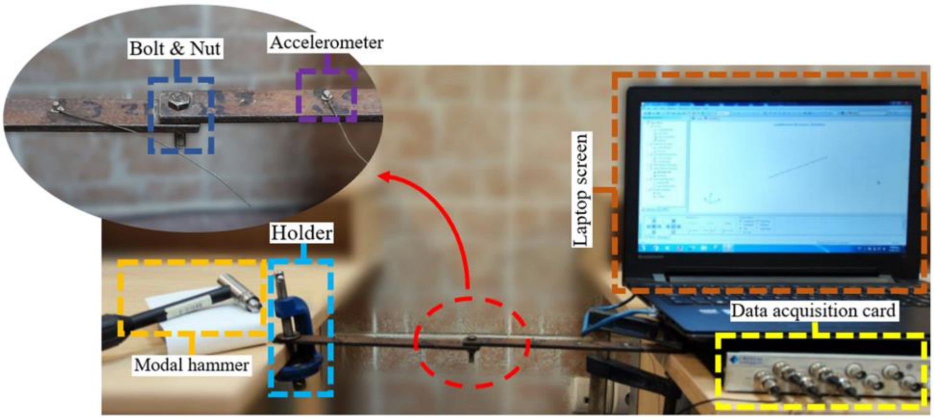

Figure 1. Experimental setup

The advanced equipment and meticulous tool selection ensured precise structural response measurement and nuanced analysis, pivotal for detecting and quantifying bolt loosening in structural health monitoring. Accelerometers, strategically placed, capture intricate vibrational patterns induced by excitation. This data reveals the structure's natural frequencies, representing its inherent oscillation rates under external forces.

4. Results and Conclusion

The process begins with an initial modal test, usually using Experimental Modal Analysis (EMA). Controlled mechanical impulses from a modal impulse hammer induce vibrations in the structure while strategically placed accelerometers record these vibrations. Subsequent analysis unveils the undisturbed system's natural frequencies and mode shapes as a baseline measurement for understanding pristine structural dynamics. The preliminary results of the modal test for tightened and loosened bolts are presented in Figure 2 and Figure 3, respectively.

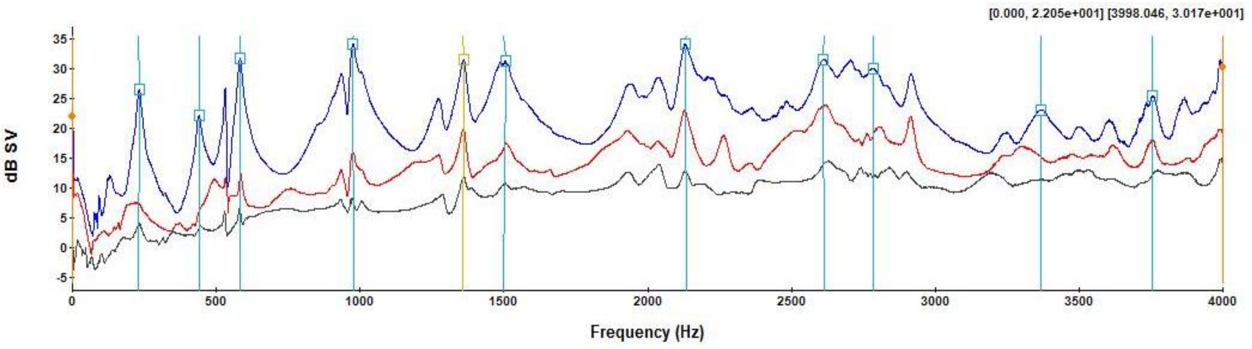

Figure 2. MIF of EMA test for tightened bolt

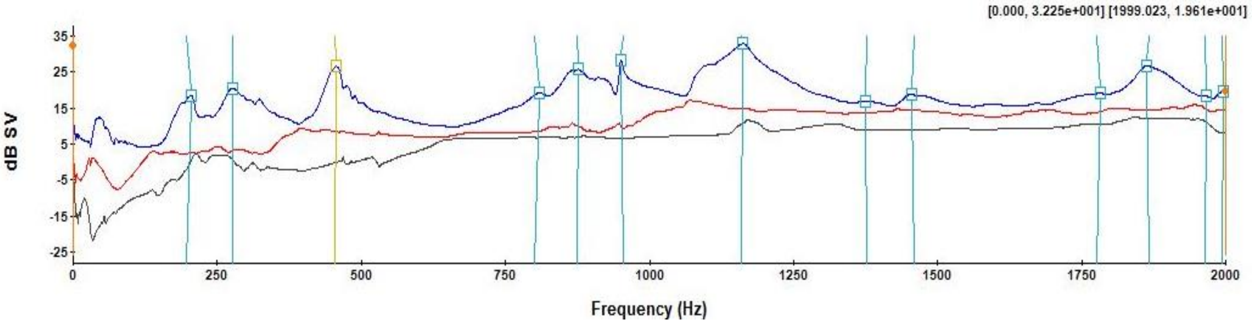

Figure 3. MIF of EMA test for loosened bolt

Intentional loosening of the bolt connection is introduced to simulate real-world scenarios where structural components may degrade over time. At first, the setup was fastened with 8N.m. torque and after that, the same EMA and OMA tests were done for the state where the bolt was fastened with 5.5N.m. torque. A repeated modal test is conducted, and the vibrational responses are again recorded and analyzed. Changes in the natural frequencies and mode shapes are carefully observed and quantified during this phase.

The key to identifying bolt loosening lies in the discernible alterations detected in the structural behavior. As the bolt connection loosens, the structural stiffness is reduced, leading to shifts in natural frequencies and changes in mode shapes. These changes manifest as deviations from the baseline measurements obtained during the initial test. The degree of frequency reduction and mode shape distortion directly correlates with the extent of bolt loosening. It is important to note that this procedure is repeated twice, once using the EMA method and subsequently with the Operational Modal Analysis (OMA) method, ensuring robustness and reliability in the assessment.

4.1 EMA and OMA Results Comparison

In the first method, the Experimental Modal Analysis (EMA) test, the output of the accelerometers should ideally exhibit a decay-free response. Upon completing the experiment, the Frequency Response Functions (FRFs) from the accelerometer outputs are saved in UFF file format. The N-Modal software, a product of OROS, was utilized to examine the stored data, modal analysis, and the generation of Modal Impedance Function (MIF) plots. This software enabled a comprehensive analysis of the experimental data, facilitating the visualization of critical insights into the structural behavior.

After conducting all tests and validating the data using the mentioned method, the results of EMA and OMA tests are presented in Table 1. The results are nearly identical for the fully tightened condition, achieved using an 8N.m. torque. Table 2 also reports the percentage difference error between these two methods. As observable, the relative error of the two methods is below 10 percent, which is an acceptable value. Now, we need to address the main objective of the project, which is to investigate the percentage decrease in natural frequencies in the loosened state compared to the tightened state. The results are presented in Table 3.

Table 1. Results of modal tests

Test type - Torque (N.m.)	1st Natural Frequency	2nd Natural Frequency	3rd Natural Frequency
EMA – 5.5	196.03	275.73	453.72
OMA – 5.5	200.76	296.41	464.39
EMA – 8	214.8	420.01	548.59
OMA – 8	230.31	440.26	582.34

Critically evaluating the findings in Table 2, we can confidently assert that operational modal analysis (OMA) emerges as a valuable tool for detecting bolt loosening in large-scale structures. This capacity carries profound implications, as it has the potential to avert catastrophic events arising from connection failures. To appreciate the significance of this capability, let us delve into the methodology employed. The key mechanism for identifying bolt loosening lies in tracking the variations in the system's natural frequencies. Table 3 is pivotal in comprehensively depicting the percentage decrease in these natural frequencies. In practice, this approach equips engineers and analysts with a powerful means of structural health monitoring. By leveraging OMA and closely monitoring the system's natural frequencies, they can preemptively detect and address bolt loosening issues, ensuring critical infrastructure safety and integrity.

Table 2. The percentage error of operational modal analysis compared to experimental results

Torque (N.m.)	1st Natural Frequency	2nd Natural Frequency	3rd Natural Frequency
5.5	2.41	7.50	2.35
8	6.73	4.60	5.80

In addition to analyzing the results through changes in natural frequency, alterations in mode shapes are also evident. Figure 4 depicts the mode shapes of the system in both the tight and loose bolt conditions in the EMA test, and Figure 5 compares the mode shapes in the OMA test. It is clear that after the bolt loosening and decreased system stiffness, the mode shapes undergo noticeable changes, losing their original order. Consequently, bolt loosening in the structure can be effectively detected by employing both methods of identifying natural frequencies and system mode shapes.

Table 3. Percentage of natural frequency drop ratio in the loosened state compared to the tightened state

Test type	1st Frequency drop	2nd Frequency drop	3rd Frequency drop
EMA	14.88	37.37	22.09
OMA	6.54	29.43	15.35

Loosened Tightened

Figure 4. Second mode shapes in two different types of EMA test

Loosened Tightened

Figure 5. First mode shapes in two different types of OMA test

Upon reviewing the results of natural frequencies and system mode shapes, it can be confidently concluded that in large structures with diverse applications, whether connected through bolted joints or other types of connections, it is feasible to detect the weakening of these connections under operational conditions without the need for structural excitation. This detection can be accomplished solely by identifying changes in mode shapes and natural frequencies, thereby mitigating potential failures.

REFERENCES

1. Rahman, A. G. A., Z. C. Ong & Z. Ismail (2011). "Enhancement of coherence functions using time signals in Modal Analysis." Measurement 44(10): 2112–2123.\S. Mallat, *A Wavelet Tour of Signal Processing*, Academic Press, New York, 1998.
2. Zhu, Y. M. (2023). "Operational modal analysis of two typical UHV transmission towers: A comparative study by fast Bayesian FFT method." Engineering Structures 277: 115425.
3. Wang, X., Z. Zhu and S.-K. Au (2023). "Bayesian operational modal analysis of structures with tuned mass damper." Mechanical Systems and Signal Processing 182: 109511.
4. Volkmar, R., et al. (2023). "Experimental and operational modal analysis: Automated system identification for safety-critical applications." Mechanical Systems and Signal Processing 183: 109658.
5. Orlowitz, E. and A. Brandt (2017). "Comparison of experimental and operational modal analysis on a laboratory test plate." Measurement 102: 121-130.
6. Chen T., Yao C., Wang X., Yu Q. Study on vibration damping design of single-steel-pole lightning rod. Building Structure, Vol. 48, 2018, p. 20-25.
7. Chen D., Huo L., Li H., Song G. A fiber bragg grating (FBG)-enabled smart washer for bolt pre-load measurement: design, analysis, calibration, and experimental validation. Sensors, Vol. 18, Issue 8, 2018, p. 2586.
8. Jin W. Q., Han S. S., Fei J. D., Shi Z. L., Chen W. B., Bao W. M., Yang J., Gong W., Su J. Z., Lv Y. G., Xie Y., Sun J. On-line bolt-loosening detection method of key components of running trains using binocular vision. Proceedings of SPIE – The International Society for Optical Engineering, Vol. 10605, 2017, p. 1060513.
9. Zhao Y. S., Yang C., Cai L. G., Shi W. M., Liu Z. F. Surface contact stress-based nonlinear virtual material method for dynamic analysis of bolted joint of machine tool. Precision Engineering, Vol. 43, 2016, p. 230-240.
10. Buijsen M J D 2011 Dynamic Space Frame Structures

11. Tien T L 1999 Space Frame Structures
12. Avitabile P J S and vibration 2001 Experimental modal analysis 35 20-31
13. Larbi N, Lardies J J M S and Processing S 2000 Experimental modal analysis of a structure excited by a random force 14 181-92
14. [14] Nazri N A, Sani M S M, Mansor M N and Zahari S N 2018 Model Updating of Friction Stir Welding for Aluminium and Magnesium Plate Structure. In: MATEC Web of Conferences: EDP Sciences) p 04004
15. Pandey A, Biswas M, Samman M J J o s and vibration 1991 Damage detection from changes in curvature mode shapes 145 321-32
16. Z. Qin, Q. Han, F. Chu, Bolt loosening at rotating joint interface and its influence on rotor dynamics, Eng. Fail. Anal. 59 (2016) 456–466.
17. M. Ghaderi, H. Ghaffarzadeh, V.A. Maleki, Investigation of vibration and stability of cracked columns under axial load, Earthq. Struct. 9 (6) (2015) 1181–1192.
18. A. Rostamijavanani, M.R. Ebrahimi, S. Jahedi, Thermal post-buckling analysis of laminated composite plates embedded with shape memory alloy fibers using semianalytical finite strip method, J. Fail. Anal. Prev. 21 (1) (2021) 290–301.
19. A. Alijani, M. Kh, J. Abadi, A.J. Razzaghi, Numerical analysis of natural frequency and stress intensity factor in Euler-Bernoulli cracked beam, Acta Mech. 230 (2019) 4391–4415.
20. F. Mottaghian, A. Darvizeh, A. Alijani, A novel finite element model for large deformation analysis of cracked beams using classical and continuum-based approaches, Arch. Appl. Mech. 89 (2) (2019) 195–230.
21. T.N. Nguyen, C.H. Thai, A.-T. Luu, H. Nguyen-Xuan, J. Lee, NURBS-based postbuckling analysis of functionally graded carbon nanotube-reinforced composite shells, Comput. Methods Appl. Mech. Eng. 347 (2019) 983–1003.
22. W.S. Na, Bolt loosening detection using impedance based non-destructive method and probabilistic neural network technique with minimal training data, Eng.

    Struct. 226 (2021) 111–134
23. W.S. Na, A portable bolt-loosening detection system with piezoelectric-based nondestructive method and artificial neural networks, Struct. Health Monitor. 134(2021) 12–34.
24. V.A. Maleki, N. Mohammadi, Buckling analysis of cracked functionally graded material column with piezoelectric patches, Smart Mater. Struct. 26 (3) (2017) 23-45.
25. F. Du, C. Xu, H. Ren, C. Yan, Structural Health Monitoring of Bolted Joints Using Guided Waves: A Review, Struct. Health Monitor. Sens. Process. 163 (2018) 45–67.
26. Zhang, L., & Brincker, R. (2005). An Overview of Operational Modal Analysis: Major Development and Issues. In R. Brincker, & N. Møller (Eds.), Proceedings of the 1st International Operational Modal Analysis Conference, April 26-27, 2005, Copenhagen, Denmark (pp. 179-190). Aalborg Universiteit.
27. R. Brincker and C. E. Ventura, *Introduction to Operational Modal Analysis.* John Wiley & Sons, Ltd, (2015).
28. M. D. A. Hasan, Z. A. B. Ahmad, M. S. Leong, and L. M. Hee, "Enhanced frequency domain decomposition algorithm: A review of a recent development for unbiased damping ratio estimates," *Vibroengineering*. 2018.
29. Brownjohn, J.M.W., Magalhaes, F., Caetano, E., Cunha, A. (2010) Ambient vibration re-testing and operational modal analysis of the Humber Bridge, Engineering Structures, 32 (8), pp. 2003-2018.
30. Di. Matteo, A., Masnata, C., Russotto, S., Bilello, C., & Pirrotta, A. (2020). A novel identification procedure from ambient vibration data. A Novel Identification Procedure from Ambient Vibration Data for Buildings of the Cultural Heritage, 56(4), 797–812.
31. N. Mohammadi and M. Nasirshoaibi, “Modal parameter identification of a three-storey structure using frequency domain techniques FDD and EFDD and time domain technique SSI: experimental studies and simulations,” *Journal of Vibroengineering*, Vol. 19, No. 4, pp. 2759–2776, Jun. 2017.
32. Al Rumaithi, Ayad, "Characterization of Dynamic Structures Using Parametric and Non-parametric System Identification Methods" (2014). Electronic Theses and Dissertations, 2004-2019. 1325. https://stars.library.ucf.edu/etd/1325.