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Efficient system identification, model updating, and virtual sensing in the Digital-Twin-as-a-Service software platform

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ABSTRACT

The Digital-Twin-as-a-Service is a digital platform designed to ease the building, deploying, using, and sharing of digital twins in a collaborative environment. The platform is a multi-user environment with dedicated virtual workspaces for each user. In addition, the platform provides common services like communication to all users. In this study, the platform is used to create a vibration-based monitoring workflow, where the data from the vibration sensors installed on the physical structures flows to the function blocks, which implement different structural analysis methods. The function blocks run in the private workspace of a user on a remote server. The workflow consists of several branches: (i) the vibration data is used to infer modal parameters through system identification; (ii) the obtained modal parameters are used to update the finite element model of the structure; (iii) the measured vibrations and the mode shapes of the updated model are used to estimate the full-field displacement and strain fields by means of modal expansion-based virtual sensing.

Keywords: Vibration Monitoring, Digital Twin, Digital-Twin-as-a-Service, System Identification, Model Updating, Virtual Sensing

1. INTRODUCTION

The vibration data measured on a mechanical or civil engineering structure often holds important information about the dynamical properties of the structure. If available, this information can be used to detect structural failures, predict the remaining useful lifetime (RUL), improve the performance of the structure, etc. [1]. Typically, the vibration data is collected via dedicated short- or long-term measurement campaigns. During the campaign, the sensors, data acquisition (DAQ) system(s), cables, and controlling computer(s) are installed on the structure, and the vibration data is then collected. After the campaign, the data is processed and a report is issued, which provides the findings, conclusions, and recommendations. After the campaign is over, the measurement equipment is taken off the structure and stored until the next measurement campaign. Typically, measurement campaigns are limited by testing one representative of the fleet of the structures of interest.

In contrast, in a monitoring scenario, the data is collected during the entire lifetime of the structure, being processed in real-time (or almost in real-time), and reported via dashboards. If there is a fleet of structures, all or several structures of the fleet are monitored. For many decades, monitoring was and still is mandatory in a range of industries (e.g., monitoring of power stations), where slowly varying parameters like temperature, pressure, and liquid flow speed are monitored. The key difference of *vibration* monitoring is the amount of data that one needs to collect to extract valuable information. Only recently, the increased availability of vibration sensors, DAQ systems, data handling, and data storage infrastructure has made vibration monitoring technically and economically feasible.

Still, vibration monitoring is a challenging task, due to the following aspects:

1. *Need for a human-in-the-loop:* most of the structural analysis methods assume that an experienced user interacts with the software. Automation of these methods is an active field of research; e.g., automated operational modal analysis (OMA) was reported in [2], [3], and automated mode tracking in [4], [5].
2. *Hardware connectivity:* the vibration sensors and DAQ systems, which can stream big amounts of synchronously sampled vibration data directly to the cloud, are still in their infancy [6], [7].
3. *IT infrastructure:* creating and maintaining an IT infrastructure that enables a scalable, robust, and secure workflow is a challenge, too. The manual handling of data derived from measurement campaigns is not viable for continuous measurement scenarios like vibration monitoring. It requires a dedicated IT infrastructure that provides engineers with a convenient environment to perform automated analysis on the streaming measurement data and thereby help build efficient monitoring applications.

Digital twins (DTs) are used for providing services such as monitoring, decision-making, simulations, and predictions, among many other application scenarios [8]. The DTs are software counterparts of real-world entities named physical twins (PTs). The DTs enhance the value delivered by PTs by performing simulations using physics-based numerical models and real-time data. The simulation results are integrated into services that are built on top of the DT. There is an implicit requirement for automated bi-directional communication between the PT and DT [9]. In some applications, an automated communication from the PT to DT coupled with manual communication from the DT to PT is sufficient. Such a link turns the DT into a digital shadow (DS), which is still very useful for monitoring applications. The present paper focuses on the DT technologies that can help to solve the second and third of the abovementioned problems, namely, hardware connectivity and IT infrastructure. A detailed discussion of the need for a human-in-the-loop is beyond the scope of this paper; we will use known structural analysis methods to illustrate the concept.

2. STRUCTURAL ANALYSIS METHODS

The structural analysis methods are employed to extract useful information from vibration data. The monitored structure and chosen analysis methods define the requirements for the sensors, DAQ system, and data handling framework.

In this study, we consider two scenarios that generate value for the end user of the monitoring system. The first scenario (light blue branch in Figure 1) starts with modal parameter estimation using OMA and is followed by mode tracking. The obtained modal parameters are used by the model updating method (light green branch, Figure 1), which results in an updated finite element (FE) model of the structure. Since the monitoring is continuous, the FE model constantly reflects the changes in the structure or its boundary conditions. E.g., in the case of an offshore monopole wind turbine, the FE model could reflect the tidal activity, appearance of a scour hole [5], degradation of the transmission piece

[10] [11], etc. The updated FE model can be used for what-if simulations, e.g., for modelling of consequences of severe storms or earthquakes.

In terms of digital twining, this scenario demonstrates how the numerical model, which is an essential part of a DT, constantly follows and reflects the development of the PT.

The second scenario (light pink branch in Figure 1) serves to estimate the structural fatigue and RUL of the structure. For the end user, this is valuable information for making informed business decisions concerning, e.g., prolonging its exploitation, making investments in its repairs/reinforcement, or demolishing it.

This scenario starts by passing the updated FE model to the FE solver, which solves the eigenvalue problem, resulting in numerical eigenfrequencies and eigenvectors (displacement and strain mode shapes). The modal expansion-based virtual sensing method brings together the numerical mode shapes and measured vibration data. Its output is estimated displacements, strains, and stresses at any point of the structure. With this information in hand, one can detect the hot spots, which are subjected to the most fatigue. The fatigue of the hot spots define the fatigue of the entire structure, so it is vital to estimate the RUL at hot spots based on, e.g., rain flow counting algorithms, Palmgren-Miner's rule, and S-N curves.

From the digital twining perspective, in this scenario, the accumulated structural fatigue information supplements the updated FE model thus further enhancing the DT.

The methods mentioned above are well-known in the structural dynamics community. However, they have to be adopted to function without, or with very limited, user interaction. The adopted methods need to be implemented as function blocks to be a part of the flow, as explained in the following sections.

For modal parameter estimation, we used the pyOMA2 implementation of covariance-driven stochastic subspace identification (SSI) [12] combined with the clustering algorithm outlined in [13]. The mode tracking was subsequently performed by pairing clusters from different experiments based on the statistical properties of the modal parameters within each cluster. The modal expansion-based virtual sensing is implemented following [10].

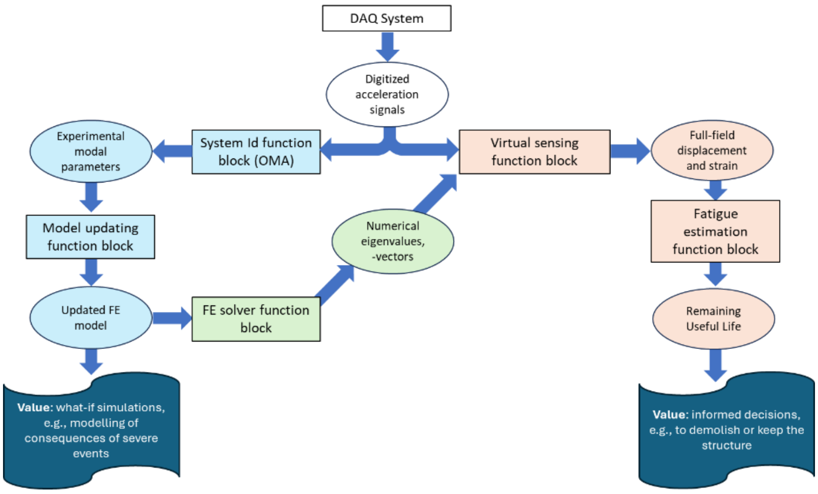


Figure 1. Workflow of the presented monitoring system.

3. DAQ SYSTEM CONNECTIVITY

3.1. Requirements for DAQ system

The structural analysis methods (Section 2) and the monitored structure set the requirements for the vibration data and DAQ system. E.g., the requirements for OMA can be found in [14]. The sampling rate can vary from 50 samples per second (Sa/s) for civil structures like bridges and buildings to 4 kSa/s for mechanisms like pumps and compressors. All the mentioned methods require that the data be sampled synchronously. The phase between the vibration at different points of the structure provides dynamic displacement patterns, which hold important information about mode shapes, operational mode shapes, and fatigue. Another important characteristic is the dynamic range of the sensing system. The structures in question may operate under very different conditions; e.g., an offshore wind turbine foundation can experience a wide range of response levels (e.g., during calms and storms). To ensure the usefulness of the data, the sensing system must provide a dynamic range of at least 16 bits per sample (~90 dB). The number and type of sensors (e.g., mono- and multiaxial sensors) can vary from structure to structure, but one to twelve vibration measurement channels can be considered as a reasonable estimate.

It must be noted that the considered vibration monitoring scenarios do not require real-time data processing. We do not include the cases where the measured data is used in control schemes. This significantly relaxes the requirements for the latency of the system.

The abovementioned properties of the DAQ system define the requirements for hardware connectivity: the DAQ system must be able to stream the data to the cloud, where the data analysis algorithms typically reside. Edge computing can be instrumental in reducing the amount of data that needs to be transferred to the cloud. E.g., in [15], it was demonstrated that even heavy algorithms such as SSI-based OMA can run on the edge, on a single board computer (Raspberry PI), which is located close to the sensors and DAQ. However, in many cases, the customers require that the raw time domain data be archived in their databases. In these cases, transmitting a large amount of data via the Internet is unavoidable.

Exemplifying the data transmission speed needed to satisfy the abovementioned vibration monitoring scenarios, it might require a capacity ranging from 800 bit/s (= 1 ch. x 50 Sa/s x 16 bit/Sa) to 1.2 Mbit/s (= 12 ch. x 4000 Sa/s x 24 bit/Sa) per monitored structure.

3.2. MQTT protocol

From the data transmission speed viewpoint, the vibration monitoring scenario is more demanding than those typically considered in Industry 4.0 (Industrial Internet of Things, IIoT). E.g., the UPC UA protocol, which is a de facto standard in IIoT/Industry 4.0, does not satisfy the requirements for vibration monitoring. We use the Message Queuing Telemetry Transport (MQTT) protocol for data transmission from vibration sensors to the function blocks which then support the monitoring applications. The MQTT is a simple protocol developed for resource-constrained Internet of Things (IoT) sensors but can also be used with feature-rich DAQ systems. The protocol was chosen as it is lightweight and fast, capable of transferring sufficient amounts of data [16]. It was designed to account for slow and unstable Internet connection and it has extensive support from the IoT/IIoT communities. The protocol is based on the client-server architecture, where the clients can publish and/or subscribe to the data; the data exchange happens via an intermediary, which is called an MQTT broker. There is support for delivering messages at different quality of service levels, security – both transport layer security, user authentication and authorization [17].

In the presented application, the DAQ system is the client that publishes the vibration data. The analysis methods, implemented as function blocks, are clients that subscribe to the data. After processing the data, the function blocks can either publish the output using the same protocol, to be used as an input to the next function blocks, save the results in a database, and/or visualize them in a dashboard (Figure 2).

Following the protocol, the clients exchange data via MQTT messages. The data is packed in MQTT payloads. Each payload is accompanied by a specially formatted text string called MQTT topic. The MQTT clients provide the topic when publishing data or subscribing to the data. For the latter, the topic can contain wildcards, which allows designing a flexible data flow. The downside of the flexibility, however, is the difficult interoperability: MQTT does not provide any standard for the topics and payload formatting, which makes it difficult for two or more parties to agree upon the communication. The recently developed Sparkplug protocol [18] addresses the interoperability issues, though the protocol has not yet reached widespread popularity.

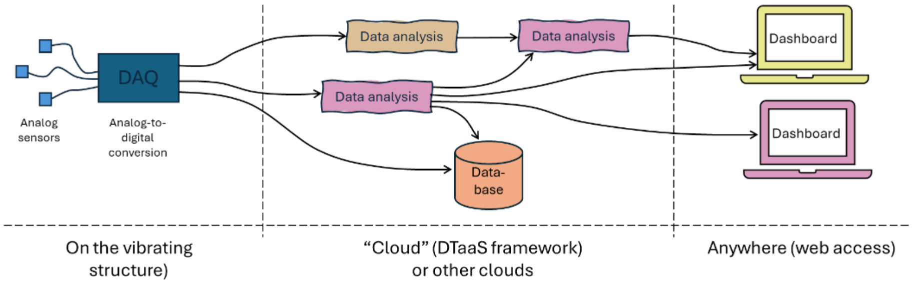


Figure 2. Data flow from the sensors to the function blocks to the dashboards

4. IT INFRASTRUCTURE: DTAAS

To facilitate the data flow from the DAQ system to the function blocks, one needs a secure, robust, and scalable IT infrastructure, which supports collaborative development. The presented study employs the Digital-Twin-as-a-Service platform (DTaaS), developed and maintained by Aarhus University [19]. The DTaaS has previously been adopted for structural monitoring applications [20].

The structural monitoring is a collaborative effort between users with different expertise. These users come from engineering, operations, and managerial domains. Thus, it is pertinent to have a cloud-based, collaborative DT platform that facilitates the creation, configuration, execution, and usage of multiple DTs in an isolated manner. The DTs made from the composition of reusable assets (elements of each DT) reduce the expertise required of DT users [21]. The DTaaS fulfills these requirements. The users of the DTaaS have private workspace and controlled access to common services. A user view of the platform is shown in Figure 3. The users can build reusable elements, i.e., numerical models and function blocks, in their private workspaces. The function blocks can be combined to form data processing chains. A user can create a workflow by configuring these reusable elements and share them with other users if needed. This workflow can be used one or more times by all users of the platform.

The function blocks of an instantiated workflow use the DTaaS platform services to receive the data from the sensors and DAQ system installed on the PT. These platform services are available to all users and workflows running in user workspaces. DTaaS provides the MQTT message broker as a platform service. The DTaaS platform also provides access to databases, dashboards, and virtual monitors as platform services. The results of workflow can be published on dashboards for the perusal of non-technical experts.

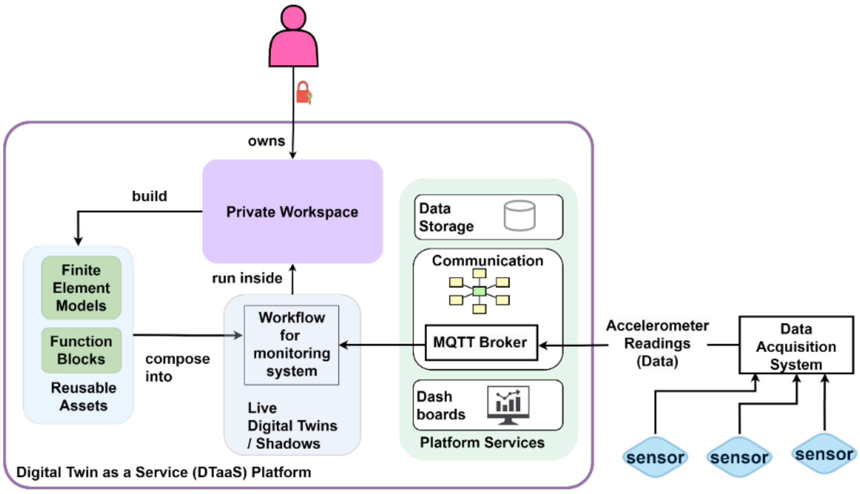


Figure 3. A user view of the DTaaS platform. The data flow from the sensors to monitoring workflow is facilitated by the platform services.

5. DEMONSTRATION

We monitor the vibrations of two similar beams (Figure 4) with the purpose of demonstrating the workflow shown in Figure 1 implemented in the DTaaS environment.

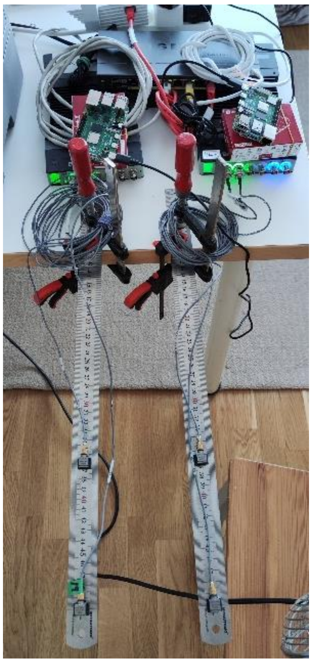
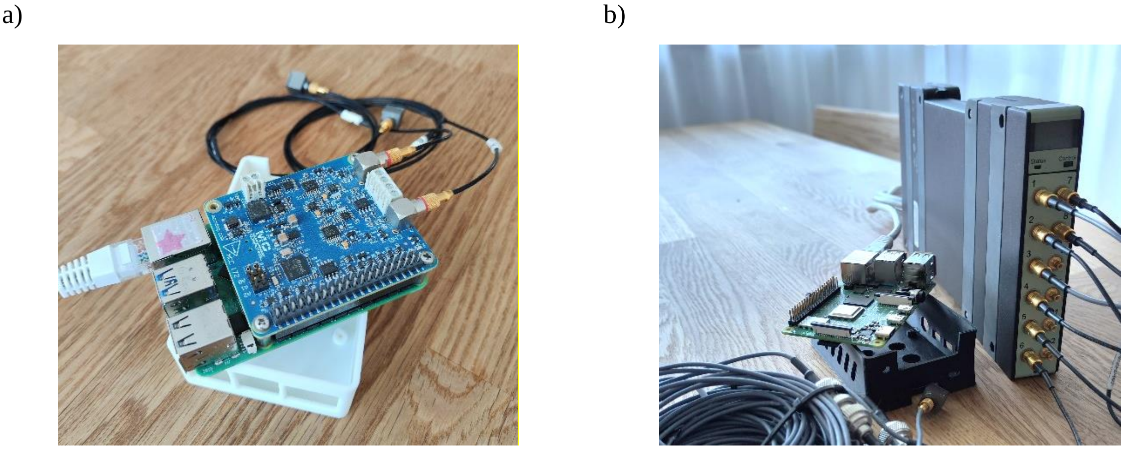


Figure 4. Monitored structures used for the demonstration.

The beams are made of steel and have dimensions 430x29x1 mm^3; they are clamped to a desk. Each beam is instrumented by two Bruel and Kjaer (B&K) monoaxial accelerometers Type 4507 B 005, with a nominal sensitivity of 1000 mV/g. The sensors are located at 265 and 400 mm from the clamped end.

Two prototype DAQ systems are employed for the demonstration; both are based on a Raspberry Pi single-board computer [22]. The first example (Figure 5a) employs the MCC172 DAQ system [23]. This is an entry-level 24 bit/Sa, 2 to 8 channels IEPE/CCLD-enabled DAQ board that can be mounted on top of Raspberry PI (so-called Hardware Attached on Top, HAT). The Raspberry PI controls the DAQ using the Application Program Interface (API). The second example (Figure 5b) employs a professional-grade DAQ system from B&K [24]. It is a LAN-Xi DAQ module (either Type 3160, Type 3050, or Type 3053; 4, 6, and 12 channels, respectively). The Raspberry PI computer controls the module via OpenAPI from HBK [25].



a)

b)

Figure 5. Left: 2 channels MCC172-based DAQ mounted on top of Raspberry PI 5; Right: 12 channels B&K LAN-Xi-based DAQ and Raspberry PI 4.

Both DAQ systems provide sample-synchronous data acquisition. In both cases, Raspberry PI uses the dedicated API provided by the DAQ manufacturer to query the vibration data from the DAQ; then it packs the data to MQTT payloads, provides the MQTT topic, and publishes it to the remote MQTT broker. The systems sample the vibrations at 256 Sa/s and stream the data (32 bit/Sa) to DTaaS using the MQTT protocol.

At the moment of writing, the two monitoring systems were up and running for about 30 days. During this time, some parts of the systems were restarted several times, while the other parts were kept running. The restarts stopped the data flow for a while; however, after the function block started again, the entire workflow became up and running again. The demonstration confirmed that the stability of the entire DTaaS-based monitoring system ensures high data availability.

At the moment of writing, the model updating branch and fatigue/RUL estimation (Figure 1) were not implemented as a chain of DTaaS function blocks. Figure 6 shows the dashboard illustrating the development of natural frequencies over several days and demonstrates (as an almost real-time animation) the full-field displacement and strain experienced by the beams.

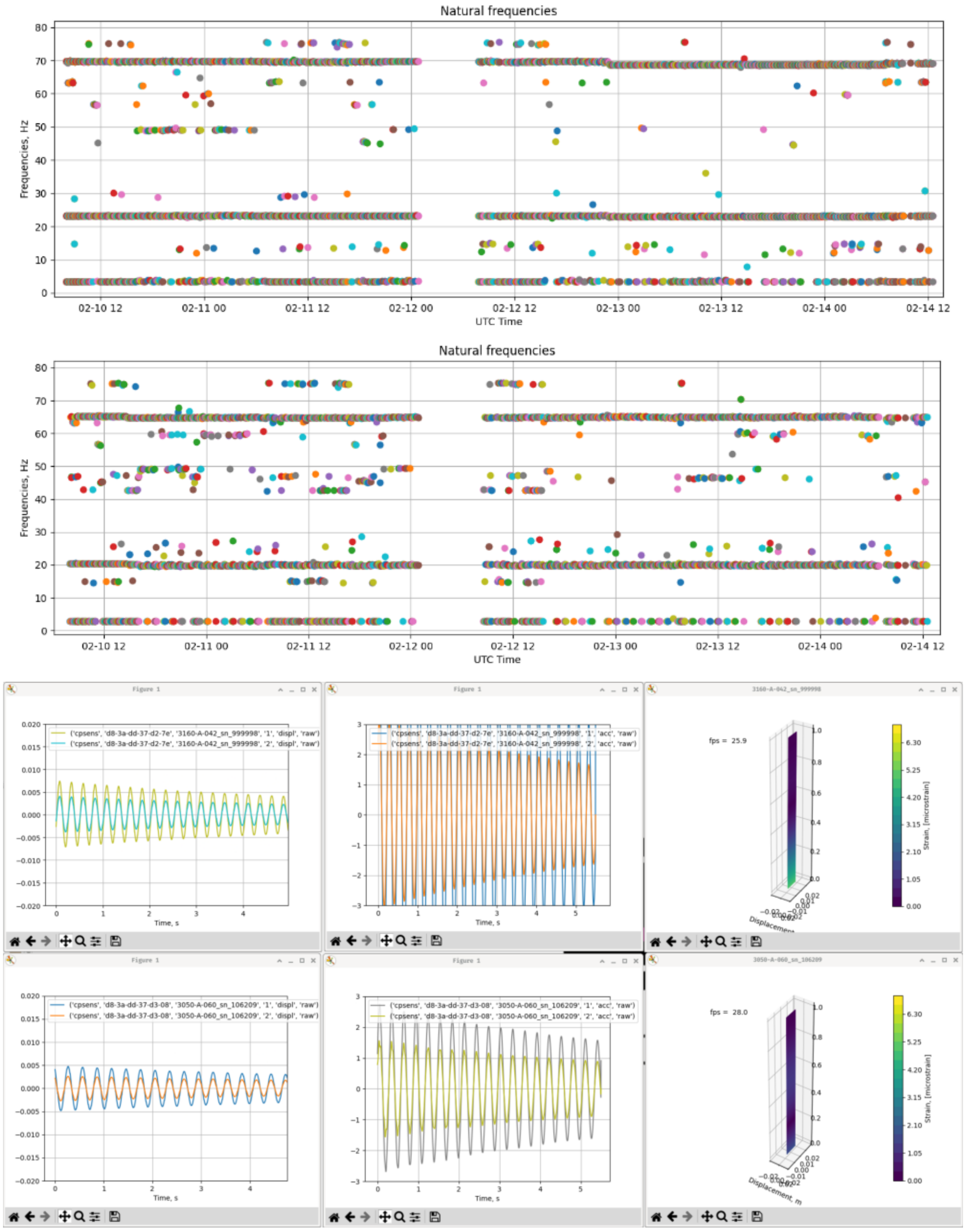


Figure 6. Top: Dashboard showing the development of the natural frequencies over time; Bottom: Current time histories and (animated) view of the deformed structures; the color matches the estimated strain.

6. CONCLUSIONS

The study demonstrated how the DTaaS platform facilitates vibration monitoring. This includes acceleration measurement using MQTT-enabled DAQ systems, streaming the data to the remote platform, and application of different analysis techniques to the data. The data analysis includes modal parameter estimation via SSI-based OMA, followed by mode tracking and modal expansion-based virtual sensing.

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REFERENCES

[1] C. A. Brebbia, G. B. Warburton, R. R. Wilson, H. Tottenham, and J. M. Wilson, *Vibrations of Engineering Structures*, vol. 10. Berlin, Heidelberg: Springer Berlin Heidelberg, 1985. doi: 10.1007/978-3-642-82390-9.

[2] C. Devriendt, F. Magalhães, W. Weijtjens, G. De Sitter, Á. Cunha, and P. Guillaume, “Structural health monitoring of offshore wind turbines using automated operational modal analysis,” *Struct Health Monit*, vol. 13, no. 6, pp. 644–659, Nov. 2014, doi: 10.1177/1475921714556568.

[3] M. Tarpø, T. Friis, P. Olsen, M. Juul, C. Georgakis, and R. Brincker, “Automated reduction of statistical errors in the estimated correlation function matrix for operational modal analysis,” *Mech Syst Signal Process*, vol. 132, pp. 790–805, Oct. 2019, doi: 10.1016/j.ymssp.2019.07.024.

[4] A. Tavares *et al.*, “An industrial benchmark study of Automated Modal Analysis using density-based clustering techniques,” in *Proceedings of ISMA 2024 - International Conference on Noise and Vibration Engineering and USD 2024 - International Conference on Uncertainty in Structural Dynamics*, W. Desmet, B. Pluymers, D. Moens, and J. del F. Zarza, Eds., Leuven: KU Leuven, Departement Werktuigkunde, Sep. 2024.

[5] M. Weil, C. Sastre Jurado, W. Weijtjens, and C. Devriendt, “Machine learning and uncertainty quantification to track and monitor natural frequencies in vibration-based SHM applied to offshore wind turbines,” *Data-Centric Engineering*, vol. 6, Jan. 2025, doi: 10.1017/dce.2024.60.

[6] C. R. Soto-Ocampo, J. M. Mera, J. D. Cano-Moreno, and J. L. Garcia-Bernardo, “Low-cost, high-frequency, data acquisition system for condition monitoring of rotating machinery through vibration analysis-case study,” *Sensors (Switzerland)*, vol. 20, no. 12, pp. 1–19, Jun. 2020, doi: 10.3390/s20123493.

[7] T. Collins, “Open-Source, Reusable Software Stack Enables Real-Time Processing and Algorithm Development for CbM,” Aug. 2021. Accessed: Feb. 26, 2025. [Online]. Available: https://www.analog.com/en/resources/technical-articles/open-source-reusable-software-stack.html

[8] S. Mihai *et al.*, “Digital Twins: A Survey on Enabling Technologies, Challenges, Trends and Future Prospects,” *IEEE Communications Surveys & Tutorials*, vol. 24, no. 4, pp. 2255–2291, 2022, doi: 10.1109/COMST.2022.3208773.

[9] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, “Digital Twin in manufacturing: A categorical literature review and classification,” *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1016–1022, 2018, doi: 10.1016/j.ifacol.2018.08.474.

[10] A. Iliopoulos, R. Shirzadeh, W. Weijtjens, P. Guillaume, D. Van Hemelrijck, and C. Devriendt, “A modal decomposition and expansion approach for prediction of dynamic

responses on a monopile offshore wind turbine using a limited number of vibration sensors," *Mech Syst Signal Process*, vol. 68–69, pp. 84–104, Feb. 2016, doi: 10.1016/J.YMSSP.2015.07.016.

[11] M. Henkel, W. Weijtjens, and C. Devriendt, "Fatigue Stress Estimation for Submerged and Sub-Soil Welds of Offshore Wind Turbines on Monopiles Using Modal Expansion," *Energies (Basel)*, vol. 14, no. 22, p. 7576, Nov. 2021, doi: 10.3390/en14227576.

[12] D. P. Pasca, D. F. Margoni, M. M. Rosso, and A. Aloisio, "PyOMA2: An Open-Source Python Software for Operational Modal Analysis," 2024, pp. 423–434. doi: 10.1007/978-3-031-61421-7_42.

[13] J. Priou, S. Greś, A. Mendler, M. Perrault, L. Guerineau, and M. Döhler, "Automated Uncertainty-Based Clustering and Tracking of Modal Parameters Under Strong Variations," in *Proceedings of the 10th International Operational Modal Analysis Conference, IOMAC 2024 - Volume 1*, Carlo Rainieri, Carmelo Gentile, and Manuel Aenlle López, Eds., Leuven, 2024, pp. 581–588.

[14] Carlo Rainieri (editor), "Guidelines for OMA in Civil Engineering," https://www.iomac.info/_files/ugd/c19177_5e1572a8baca4889a0bfa8f3b742865c.pdf.

[15] K. Soal, R. Volkmar, C. Thiem, J. Schwochow, Y. Govers, and M. Böswald, "Identification of the Flutter Boundary During Flight Testing Using Operational Modal Analysis," 2024, pp. 516–524. doi: 10.1007/978-3-031-61421-7_50.

[16] N. Naik, "Choice of effective messaging protocols for IoT systems: MQTT, CoAP, AMQP and HTTP," in *2017 IEEE International Systems Engineering Symposium (ISSE)*, IEEE, Oct. 2017, pp. 1–7. doi: 10.1109/SysEng.2017.8088251.

[17] R. J. Cohn and R. J. Coppen, "MQTT Version 3.1.1, OASIS Standard," Oct. 2014. Accessed: Feb. 26, 2025. [Online]. Available: https://docs.oasis-open.org/mqtt/mqtt/v3.1.1/os/mqtt-v3.1.1-os.html

[18] Eclipse Sparkplug Contributors, "Sparkplug 3.0.0 Sparkplug Specification," Nov. 2022. Accessed: Feb. 26, 2025. [Online]. Available: https://sparkplug.eclipse.org/specification/version/3.0/documents/sparkplug-specification-3.0.0.pdf

[19] P. Talasila *et al.*, "Composable digital twins on Digital Twin as a Service platform," *Simulation*, Dec. 2024, doi: 10.1177/00375497241298653.

[20] A. M. D. Jensen *et al.*, "Digital twin as a service for damage prognosis of offshore wind turbine foundations," in *Proceedings of ISMA 2024 - International Conference on Noise and Vibration Engineering and USD 2024 - International Conference on Uncertainty in Structural Dynamics*, W. Desmet, B. Pluymers, D. Moens, and J. del Fresno Zarza, Eds., Leuven, Belgium: KU Leuven, Departement Werktuigkunde, Sep. 2024, pp. 4127–4141.

[21] P. van Schalkwyk and D. Isaacs, "Achieving Scale Through Composable and Lean Digital Twins," in *The Digital Twin*, Cham: Springer International Publishing, 2023, pp. 153–180. doi: 10.1007/978-3-031-21343-4_6.

[22] "Raspberry Pi official webpage," https://www.raspberrypi.com/.

[23] "MCC 172 Hardware overview," https://mccdaq.github.io/daqhats/overview.html#mcc-172.

[24] "HBK DAQ modules," https://www.hbkworld.com/en/products/instruments/daq-systems/lan-xi/measurement-modules.

[25] HBK, "LAN-XI Open API: An Open Ecosystem," https://www.hbkworld.com/en/knowledge/resource-center/articles/open-api-for-lan-xi.