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Deniss Mironovs

DEVELOPMENT OF STRUCTURAL HEALTH MONITORING SYSTEM FOR STRUCTURES IN OPERATIONAL CONDITIONS

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on November 3, 2023 at 14:15, at the Faculty of Civil Engineering of Riga Technical University, 6A Ķīpsalas Street, Room 342.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Deniss Mironovs ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 4 chapters, Conclusions, 54 figures, 7 tables; the total number of pages is 113. The Bibliography contains 123 titles.

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INTRODUCTION

Motivation and scope

Structures are integral part of civil engineering, aviation, energy and transportation. These fields of economy demand structures to be reliable, safe, functional and at the same time cost-efficient. Cost efficiency of production and maintenance drive structures to be less reliable, which in turn creates the necessity to observe structural health during its lifetime, i.e. to perform structural health monitoring.

Planned structural checks can be insufficient to prevent failures. From 2009 to 2012, in China there were 3 major wind turbine component failures, either blades or tower [1]. A recent accident happened in Estonia in 2022 [2], when a 60-meter-tall wind turbine tower collapsed under heavy wind conditions. Another example of a serious accident was the crack and opening in the fuselage of a Boeing 737 during flight. This has caused a rapid depressurization, but fortunately, the plane was landed safely in Yuma, Arizona [3].

Fig. 1. Major structural failures. Left: Saaremaa, Estonia 2022; right: Yuma, Arizona 2011.

Larger wind turbine blades are exposed to larger mechanical stresses, more pronounced aerodynamic effects, structural instability, and more complicated failure mechanisms [4] as compliance increases with blade length. This, in turn, renders the blades more prone to damage. For example, wind turbine blade failures account for 30 % of total failures related to wind turbines [5], while the cost of blade manufacturing accounts for 15–20 % of the cost of a whole wind turbine [6].

The necessity to reduce unnecessary structural checks while improving the overall reliability of structures suggests that constant or at least frequent structural health monitoring (SHM) is needed. The goal of structural health monitoring is to timely detect damage, which allows to plan repairs in an optimal fashion and enables the safety of the structure.

The topic of structural health monitoring is very popular among scholars and practitioners and has been developing rapidly for several last decades. Apart from ongoing academic research in the field, quite a few commercial SHM systems exist on the market, e.g. several systems introduced by HBM [7] and SGS [8]. In these systems, structural health is evaluated by means of non-destructive testing (NDT). Existing NDT techniques are based on measuring different physical phenomena, like strain, electrical resistance of materials, acoustic emission of structure's inhomogeneity, and vibration. Vibration-based structural evaluation methods [9] rely mostly on modal analysis [10] and particularly on operational modal analysis (OMA) [11]. As shown in the Thesis, OMA methods are very promising due to their applicability potential. Some works show OMA-based SHM being used on large static civil structures, like buildings [12] and bridges [13], [14].

Few studies show OMA-based SHM applied on smaller-sized structures (blades, wings), which are part of a moving entity (aircraft). These studies are mostly done in a laboratory environment using high-cost instrumentation [15], [16], which provides high-quality scientific results but can be difficult (not affordable) to implement in real-life structures. In a health monitoring system survey [17], it was concluded that SHM systems for the foundation, tower and blades of a wind turbine are mostly limited to experimental and research installations.

As mentioned, continuous SHM for static civil structures exists, but for moving structures like wind turbine blades or aircraft, there are some significant challenges. The costs of downtime for a wind turbine, or especially an aircraft, are quite high; thus, taking a structure out of operation for SHM testing is not desirable. Continuous SHM during operation can only be realised by having a damage sensing-system installed on the structure. This system should be affordable, and the health assessment process must not be sophisticated.

The affordability of such a system is supposed to be achieved by choosing alternative sensors for OMA. Instead of traditional accelerometers, which can be the most significant part of an SHM system in terms of cost if tens or even hundreds of sensors are implemented, more affordable piezo film sensors are proposed. Piezo film sensors, having negligible weight, small size and very small thickness, are advantageous for application for aerodynamic parts.

Aims of the Thesis

The Thesis aims to develop a vibration-based structural health diagnostics system technology, which would create prerequisites for full structural monitoring system development during regular operation of the surveyed object in its operational conditions. The technology includes important stages of SHM system development – sensors network, data acquisition, data storage and processing, analysis and damage detection. In the presented Thesis, SHM system prototypes are demonstrated, which are affordable, reliable and user-friendly.

Tasks of the Thesis

To achieve the aims of the Thesis, the following tasks were formulated:

1. Perform a scientific literature review in the field of SHM, OMA, vibration sensors, and damage detection algorithms. Implement existing solutions that do not require modification.
2. Formulate SHM system development and usage process.

3. Develop an intermediary damage detection algorithm on the basis of the evaluation of vibration responses without modal parameter estimation. Test the reliability of such an algorithm on actual structure.
4. Formulate an approach for taking into account natural conditions that could influence the precision of damage detection.
5. Validate the application of piezo film sensors as an alternative to accelerometers for OMA and test SHM systems' prototype data processing methods for condition monitoring.

Scientific novelty

The scientific novelty of the Thesis:

1. Experimental application of piezo film sensors for OMA purposes. Previous studies did not show examples of using piezo film sensors for operational modal analysis. Piezo film sensors application has its differences compared to the application of accelerometers – different installation techniques and different vibrational data interpretation. Compared to accelerometer response, piezo films provide a deformation (strain) velocity signal. Even though it does not change the modal characteristics of the structure, it does change the visual representation of mode shapes, which needs to be considered.
2. Development of two new algorithms for damage detection. These algorithms evaluate changes of modal characteristics differently than existing algorithms. The first algorithm can compare structural states without performing modal analysis, which saves time on data analysis. Another algorithm is a tool for comprehensive modal parameters (frequency and mode shape) change analysis. It gives estimates of how modal parameters change compared to a previously set reference.
3. Introduction of a *modal passport* concept. Modal passport is a database of modal parameters expressed as functions of different influence factors like temperature and loads.

Practical significance

The Thesis can be used as guidance for developing SHM systems for various structures. Alternatively, the proposed SHM system prototype can be applied directly on structures. However, one must perform all necessary certifications of the SHM system, especially in the aviation field. The system would require an engineer to operate it, register data, read influence factors values, and check if the damage detection parameter shows any sign of damage. In case it does show a sign of damage, more in-depth analysis is performed primarily using the mode shapes for the potentially damaged structure.

Methodology of the research

The presented work relies on existing SHM technologies, mainly modal analysis and operational modal analysis testing techniques, commercial hardware and software. Operational modal analysis techniques used in the Thesis include enhanced frequency domain decomposition and stochastic subspace identification.

A novel approach of signal sensing is applied, i.e. using piezo film sensors instead of conventional accelerometers or strain gauges.

Applicability limitations

A widely acknowledged set of features that a fully developed SHM system possesses include the ability to operate without interruptions, mostly automatically and autonomously, as well as the system's robustness against various mechanical and environmental impacts and longevity. The proposed SHM system prototype, however, is not fully automatic and has not yet been tested for robustness. Still, for the purpose of brevity, the proposed SHM system prototype shall be called the SHM system within the scope of this Thesis.

This SHM system prototype is limited to small and medium-scale structures (0.5–20 m) in dimensions, as other structures have not been tested with this prototype. Smaller structures (<0.5 m) will not be enough to accommodate the necessary amount of sensors. For larger structures, it is yet unknown whether deformation sensors could correctly register large-scale deformations for the mode shapes of lower order to be successfully identified. Also, it is unknown how electrical signals in wires would translate between sensors and the data acquisition system's inputs at large distances (>20 m). This might be an issue due to electromagnetic interference and the absence of preamplification in sensors. However, this limitation might be lifted in future studies.

Another limitation is rather technical – to install the system, the structure must be equipped with a sensing system. The installation process can take hours or even days for complex structures. If this process is performed during post-production in a factory, then this is not a serious issue. However, for existing and operating structures, especially wind turbine blades and helicopter blades, it would be necessary to detach those from the machine, apply sensors indoors (to guard against wind and rain), and then attach the blades back.

The proposed SHM system is not a commercial product and lacks an intuitive, all-in-one user interface in application form.

Arguments for the defence of the Thesis

The Thesis shows how, even with limited financial resources, it is possible to develop an SHM system and monitor the condition of a large number of typical structures. One would need a set of cheap piezo film sensors, wiring, a data acquisition module, a PC and software. For in-depth structural condition analysis, one would also need modal parameter estimation software, like *ARTeMIS*.

Newly developed damage detection algorithms have different purposes and different implementations. The modal field comparison method, for example, does not require the use of commercial software and can be realised using code in *Matlab*, *Octave* or *Python.* Modal parameters variation intensity parameter does require modal parameter estimation, but, as an advantage, provides damage localization.

All of the above give operators of structures helpful information about structural conditions, so that repairs can be planned in an optimal manner. This also increases the safety and reliability of structures, which helps to bring costs down. SHM system is an investment that pays off after some time.

Structure

The Thesis consists of several parts.

First, a scientific and commercial literature review is presented, covering topics such as operational modal analysis, including modal parameters identification, vibration sensors, embedded sensors, harmonics extraction and structural damage identification.

Next, the Thesis goes through the steps of SHM system development emphasising technological novelty like the application of piezo film sensors. A formulation for a harmonics extraction algorithm is introduced.

A concept of a modal passport is introduced – a framework for modal parameters assessment between multiple measurements with different operating conditions.

Then, newly developed modal parameters evaluation methods are shown, describing the mathematical background and application. Two methods were developed for this Thesis:

- Modal parameter variation intensity – a method to evaluate the mode shape and modal frequency changes due to the damage with the possibility of comparing the results with healthy states. This method allows to evaluate the intensity of the damage and to perform damage localization.
- Modal field comparison method, also called a singular value change assessment – a method to approach structural state damage detection without prior modal parameters estimation, saving time and computing power.

Lastly, SHM technology application cases are discussed, concluding both challenges and limitations, which surfaced during real-life experiments, and successful examples of damage detection in a beam and helicopter blades. The overall structure of the Thesis is shown in Fig. 2.

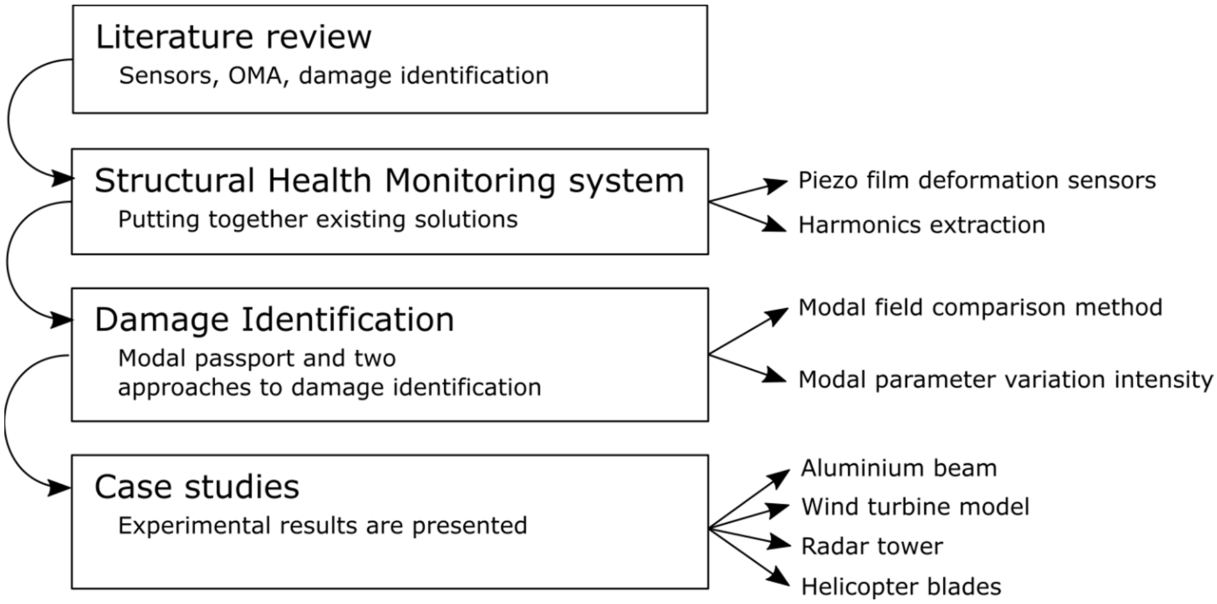


Fig. 2. Thesis structure.

Publications

1. Janeliukstis, R., Mironovs, D., Safonovs, A. Statistical Structural Integrity Control of Composite Structures Based on an Automatic Operational Modal Analysis – a Review, (2022), Mechanics of Composite Materials, Volume 58, Issue 2, pp. 181–208. DOI: 10.1007/s11029-022-10026-1 (indexed in Scopus)

2. Mironovs, D., Ručevskis, S., Dzelzītis, K. Prospects of Structural Damage Identification Using Modal Analysis and Anomaly Detection, (2022) Procedia Structural Integrity, Volume 37, pp. 410–-416. DOI: 10.1016/j.prostr.2022.01.103 (indexed in Scopus)

3. Janeliukstis, R., Mironovs, D. Smart Composite Structures with Embedded Sensors for Load and Damage Monitoring – A Review, (2021) Mechanics of Composite Materials, Volume 57, Issue 2, pp. 131–152. DOI: 10.1007/s11029-021-09941-6 (indexed in Scopus)

4. Solovyev, D., Dadunashvili, S., Mironov, A., Doronkin, P., Mironov, D. Mathematical Modeling and Experimental Investigations of a Main Rotor Made from Layered Composite Materials, (2020) *Mechanics of Composite Materials*, 56 (1), pp. 103–110. DOI: 10.1007/s11029-020-09864-8 (indexed in Scopus)

5. Mironov, A., Priklonskiy, A., Mironovs, D., Doronkin, P. Application of Deformation Sensors for Structural Health Monitoring of Transport Vehicles, (2020) *Lecture Notes in Networks and Systems*, 117, pp. 162–175. DOI: 10.1007/978-3-030-44610-9_17 (indexed in Scopus)

6. Mironovs, A., Mironovs, D. Modal Passport of Dynamically Loaded Structures on the Example of Composite Blades. In: Proceedings of 13th International Conference "Modern Building Materials, Structures and Techniques", Lithuania, Vilnius, 16–17 May 2019. Vilnius: VGTU Press, 2019, pp. 1–8. DOI: 10.3846/mbmst.2019.091

7. Mironovs, D., Mironovs, A., Čate, A. Harmonic Components Extraction Influence on Resulting Modal Parameters of Vibrating Structures. In: Proceedings of 13th International Conference "Modern Building Materials, Structures and Techniques", Lithuania, Vilnius, 16–17 May 2019. Vilnius: VGTU Press, 2019, pp. 1–8. DOI: 10.3846/mbmst.2019.012

8. Mironovs, D., Mironov, A. Vibration Based Signal Processing Algorithm for Modal Characteristics Change Assessment, (2018) *AIP Conference Proceedings*, 2029, art. no. 020043, DOI: 10.1063/1.5066505 (indexed in Scopus)

9. Mironov, A., Mironovs, D., Kabashkin, I. Advanced Structural Health Monitoring and Diagnostics of Transport, Industrial and Energy Facilities, (2018) *Lecture Notes in Networks and Systems*, 36, pp. 159–171. DOI: 10.1007/978-3-319-74454-4_15 (indexed in Scopus)

10. Mironovs, D., Mironov, A., Chate, A. Application Case: Prototype of Radar Tower Structural Health Monitoring System, (2018) *Engineering for Rural Development*, 17, pp. 1301–1307. DOI: 10.22616/ERDev2018.17.N106 (indexed in Scopus)

11. Mironov, A., Mironovs, D. Experimental Application of OMA Solutions on the Model of Industrial Structure (2017) *IOP Conference Series: Materials Science and Engineering*, 251 (1). DOI: 10.1088/1757-899X/251/1/012092 (indexed in Scopus)

Participation in conferences

1. 4th International Conference on Structural Integrity, ICSI 2021, Spain, Funchal, Madeira, 30 August – 2 September 2021, online. “Prospects of Structural Damage Identification Using Modal Analysis and Anomaly Detection”, paper presentation and publication in conference proceedings.

2. 19th International Multi-Conference “Reliability and Statistics in Transportation and Communication” (RelStat-2019), Latvia, Riga, 16–19 October 2019. “Application of Deformation Sensors for Structural Health Monitoring of Transport Vehicles”, paper presentation and publication as a book chapter.

3. 13th International Conference "Modern Building Materials, Structures and Techniques", Lithuania, Vilnius, 16–17 May 2019. “Harmonic Components Extraction Influence on Resulting Modal Parameters of Vibrating Structures”, paper presentation and publication in conference proceedings.

4. 14th International Conference “Mechatronic Systems and Materials”, MSM 2018, Poland, Zakopane, 4–6 June 2018. “Vibration Based Signal Processing Algorithm for

Modal Characteristics Change Assessment", paper presentation and publication in conference proceedings.

5. 18th International Multi-Conference "Reliability and Statistics in Transportation and Communication" (RelStat-2018), Latvia, Riga, 17–20 October 2018. "Condition Monitoring of Helicopter Main Gearbox Planetary Stage", paper presentation and publication in conference proceedings.

6. 17th International Scientific Conference Engineering for Rural Development, Latvia, Jelgava, May 23–25, 2018. "Application Case: Prototype of Radar Tower Structural Health Monitoring System", paper presentation and publication in conference proceedings.

7. 17th International Multi-Conference "Reliability and Statistics in Transportation and Communication" (RelStat-2017), Latvia, Riga, 18–21 October 2018. "Advanced Structural Health Monitoring and Diagnostics of Transport, Industrial and Energy Facilities", paper presentation and publication in conference proceedings.

8. 3rd International Conference "Innovative Materials, Structures and Technologies" (IMST 2017), Latvia, Riga, 27–29 September 2017. "Experimental Application of OMA Solutions on the Model of Industrial Structure", paper presentation and publication in conference proceedings.

9. Riga Technical University 61st International Scientific Conference, 22 October 2020, Riga, Latvia, Online. Presentation of the ongoing research.

10. Riga Technical University 62nd International Scientific Conference, 28 October 2021, Riga, Latvia, Online.

1. VIBRATION-BASED STRUCTURAL HEALTH MONITORING

1.1. Operational Modal Analysis

The main concept behind vibration-based SHM methods is that damage-induced structural changes are reflected in modifications of mass, stiffness and damping of the structure [10]. Any structure is a dynamic multi-degree of freedom system, which can be described with an equation of motion:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t), \tag{1.1}$$

where

M – mass matrix, kg;

C – damping matrix;

K – stiffness matrix;

$x(t)$ – response vector, $\dot{x}(t)$ and $\ddot{x}(t)$ are the first and the second time derivatives of the response;

$f(t)$ – applied force vector, N.

The response vector is typically displacement of a structural point, thus the first time derivative is velocity, and the second time derivative is acceleration. In frequency ω domain, the equation of motion can be shown as

$$(-M\omega^2 + j\omega C + K)x(\omega) = f(\omega). \tag{1.2}$$

The matrix of frequency response functions (FRF) of a system is defined as

$$H(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{(-M\omega^2 + j\omega C + K)}. \tag{1.3}$$

Equation (1.3) shows how FRF of a structure depends on mass, damping and stiffness, and how one can obtain FRF by measuring applied force f and registering the vibrational response x. Using FRF from multiple points on the structure it is possible to estimate modal parameters of a structure by applying the following equation:

$$H_{pq}(\omega) = \sum_{m=1}^{M} \frac{A_{pqm}}{j\omega - \lambda_m} + \frac{A_{pqm}^*}{j\omega - \lambda_m^*}, \tag{1.4}$$

where

p – index for input location where force is applied;

q – index for output location where response is measured;

m – index for mode number;

M – total number of natural modes;

λ_m – system's pole for mode m;

A_{pqm} – residue.

In a unique case, when $M = 1$, this is a single degree of freedom system.

The system's poles contain natural frequencies f and damping ratios ζ:

$$f_m = \frac{\mathrm{Im}(\lambda_r)}{2\pi}, \quad \zeta_m = -\frac{\mathrm{Re}(\lambda_r)}{|\lambda_r|} \tag{1.5}$$

The system's residue contains information about the mode shape ψ of the structure's vibration, as well as scaling factor Q – the amount of particular mode shape's participation in the total response, related to the excitation force, and is shown as

$$A_{pqm} = Q_{pqm}\psi_{pqm}\psi_{pqm}^{\mathrm{T}}. \tag{1.6}$$

The Thesis considers an output-only method, called operational modal analysis (OMA). As forces are not measured in OMA and thus are unknown, it is assumed that forces are evenly distributed in space across the structure and in frequency domain [18]. Natural excitation forces should be random in time and have sufficient energy to excite necessary modes. Examples of such excitation are wind, rain, earthquakes, a significant number of moving vehicles, etc.

Violation of the OMA assumption can lead to erroneous estimation of modal parameters, for example, the presence of periodic components in the measured vibrational signal due to rotating parts close to the measured structure. The Thesis offers utilization of time synchronous averaging (TSA) [19] with an advanced feature for suppression/extraction of the periodic component.

OMA advantages:

- The tested structure can remain in operation without disrupting the object's normal exploitation.
- No excitation mechanisms are needed, which saves costs and time.

OMA disadvantages:

- OMA results depend on the excitation and environmental conditions.
- The scaling of mode shapes is necessary for a meaningful comparison between measurements.

Modal parameters estimation

OMA modal parameter estimation techniques are divided into two categories – time domain and frequency domain techniques [20]. The techniques differ in their mathematical complexity, computational efficiency, and identification accuracy. The frequency domain techniques are peak picking (PP), frequency domain decomposition (FDD), enhanced frequency domain decomposition (EFDD), and others. Examples of time-domain techniques are two stochastic subspace identification (SSI) sub-techniques – data-driven SSI and covariance driven SSI.

The frequency domain techniques rely heavily on singular value decomposition (SVD), a matrix factorization into singular vectors and singular values, proportional to the system's eigenvectors and eigenvalues. SVD of a power spectra matrix is given as

$$G_{xx}(\omega) = U(\omega)S(\omega)U(\omega)^H, \tag{1.7}$$

where

U – a singular vector matrix;

S – singular value's diagonal matrix;

U^H – conjugate transpose (Hermitian transpose).

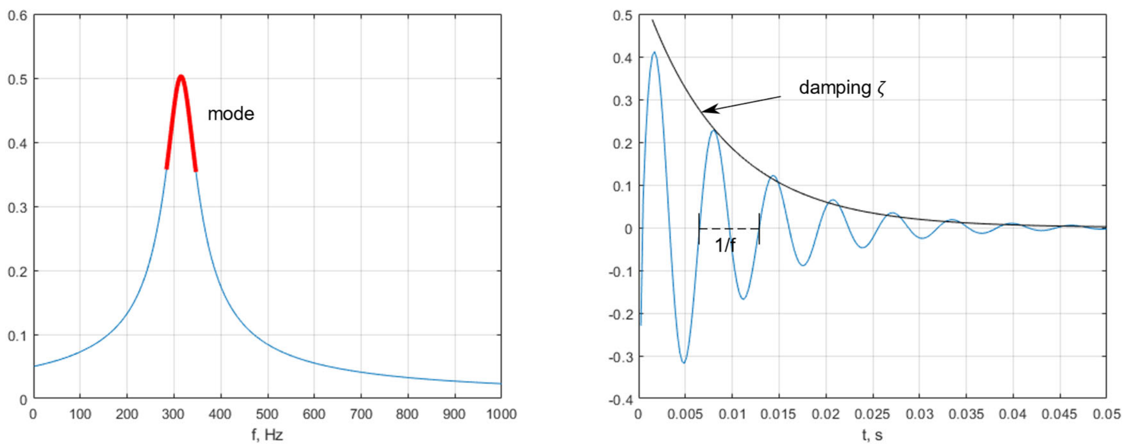


Fig. 1.1. a) SVD plot of an SDOF system; b) inverse FFT of the SVD plot.

Enhanced FDD considers each mode to represent a SDOF system (Fig. 1.1(a)). The singular value $s(\omega)$ corresponding to the singular vector $u(\omega_r)$ is the auto power spectral density (PSD) function of the corresponding single degree of freedom system. This PSD function is identified around the peak by comparing the mode shape estimate $\hat{\psi}_r$ with singular vectors for the frequency lines around the peak. Singular values form the auto PSD function, as long as corresponding singular vectors have high modal assurance criterion (MAC, see Section 1.3) value with $\hat{\psi}_r$. When auto PSD is formed, it is processed using inverse FFT, and a time impulse decay function is obtained (Fig. 1.1(b)), from which frequency f_r is estimated from crossing times, and damping ζ_r is estimated from the decay.

Multi-patch OMA

It is possible to significantly reduce the cost of an SHM system if one uses a multi-patch OMA. In this OMA approach, the vibration is measured consequently by dividing sensors into small groups, called patches, at a time. This allows to reduce the number of required input channels. Each group includes two types of channels: reference channels, which are not moved, and moving or roving channels. After all patches are separately measured, signal processing algorithms combine those patches for further modal parameter estimation.

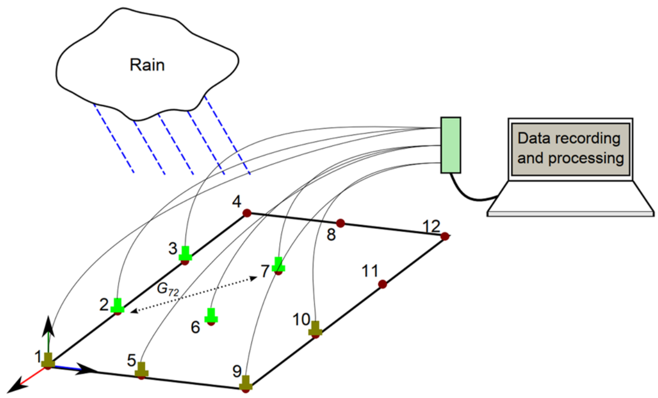


Fig. 1.2. Schematic of a multi-patch OMA measurement with 2 patches, Sensors 2, 3, 6 and 7 are reference sensors [21].

1.2. Vibration sensors

A common type of vibration sensors utilized in OMA applications is piezoelectric, including conventional accelerometers. The Thesis introduces another type of piezoelectric vibration transducer as a sensor for OMA application. This piezoelectric film deformation sensor (Fig. 1.3) is made of a polarized semi-crystalline fluoride polymer called polyvinylidene fluoride (PVDF). The films are very thin (0.23 mm) and can be glued to the testing surface with conventional adhesives or double-sided tapes.

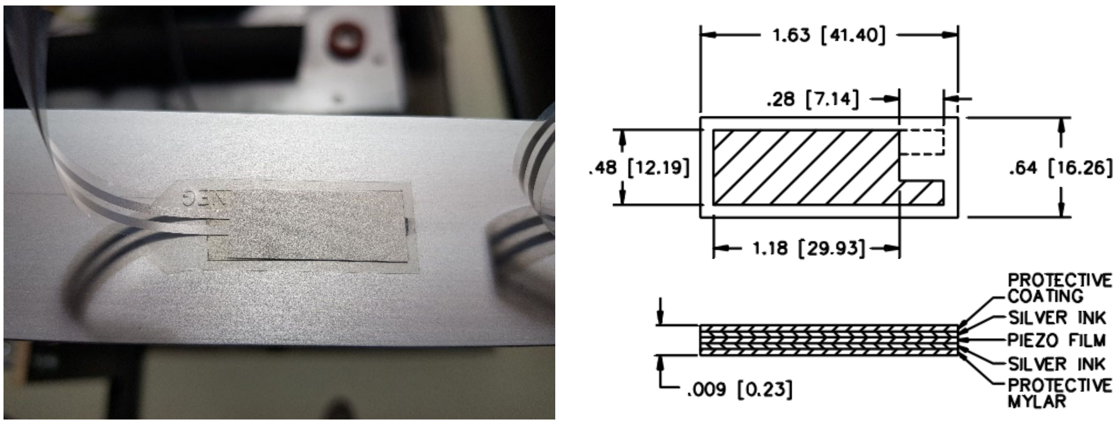


Fig. 1.3. Piezoelectric PVDF film transducer for vibration measurements [22].

PVDF material is superior to materials of other sensor types in numerous ways:

- Wide frequency bandwidth (10^{-3} to 10^{9} Hz).
- Large dynamic range (6.9×10^{-4} to 6.9×10^{10} Pa).
- High elasticity (2–4 GPa compared to 43 GPa for PZT).
- Low density (1780 kg/m^3 compared to 7500 kg/m^3 for PZT).
- High dielectric toughness – can withstand strong electric fields (75 V/µm) where most of the piezoelectric ceramic materials become depolarized.
- High mechanical toughness and impact resistance (10^{9} Pa to 10^{10} Pa).

- High chemical stability – resistance against humidity (<0.02 % moisture absorption), most of the chemical substances, oxidizers and intensive UV radiation.

Sensing based on piezo-film sensors is a cost-effective SHM solution. They are much cheaper (about 10–15 euros/piece) than accelerometers, which, for industrial applications, can cost hundreds of euros [23]. Accelerometers typically also induce mass loading to the structure and have a non-negligible size, thus affecting the structure's modal and aerodynamic properties.

Piezo film sensors do not require balancing circuits, like Wheatstone bridge, for strain gauges. Compared to acceleration measurements, dynamic strain measurements are proven sensitive to minor local damage [24], [25], [26].

PVDF film sensors, however, have some disadvantages, one of them being sensitivity to electromagnetic interference. These sensors have a considerable sensitivity spread of around 20 % [27], which does not allow for directly comparing modal shapes between different structures. It does allow the comparison of mode shapes for an individual structure, however, assuming that the sensitivity of the sensors does not significantly change with time.

1.3. Structural damage identification

The most common set of damage-sensitive features in vibration-based SHM are modal parameters – frequency, damping ratio, and mode shape. A good quality mode shape identification requires a dense sensor network, which is possible to realize with PVDF sensors.

A useful tool for comparing the mode shapes to reveal any changes in the structural state is the *modal assurance criterion* (MAC). It is calculated as

$$\mathrm{MAC}\big(\{\phi_i\},\{\phi_j\}\big)=\frac{\left|\{\phi_i^T\}\{\phi_j\}^*\right|^2}{\left(\{\phi_i^T\}\{\phi_i^*\}\right)\left(\{\phi_j^T\}\{\phi_j^*\}\right)}, \quad (1.8)$$

where $\{\phi_i\}$ and $\{\phi_j\}$ are different mode shape vectors [27]. Usually, MAC is plotted as a matrix where the mode shapes from one set are compared to the same mode shapes from another set. The correlation values close to unity indicate that the mode shapes are similar.

It is one of the tasks of the Thesis to introduce an alternative DSF, which is modal-based and allows fast structural state analysis (without modal parameter estimation) and in-depth analysis of estimated modal parameters. These approaches are presented further in the Thesis.

2. STRUCTURAL HEALTH MONITORING SYSTEM

2.1. SHM related problems

External factors

The damage detection of an OMA-based SHM system is based on the change of modal properties of a structure. But modal properties are influenced not only by the change in stiffness, mass or damping (internal factors) but also by loads, temperature and other external factors. This can create false positive alarms, thus degrading SHM effectiveness. For example, the change in rotation velocity of a wind turbine also changes the modal parameter of a blade due to the resulting difference in centrifugal force.

Skilled personnel requirement

After measurements and data processing, any trial OMA-based system gives a set of modal parameters for some amount of modes. When dealing with structures which are more complicated than simple structures (beam or plate), the amount of detected modes can be quite large. For analysis and interpretation of such modes, highly skilled and experienced personnel is required. Mass application of OMA-based system is complicated due to the need for subjective interpretation of results.

Methodologies for quantitative evaluation of integral modal parameters of the entire structure and healthy state boundaries definition do exist, but few practical applications were demonstrated.

Sensors' costs and sizes

Common type of sensors used in OMA are accelerometers, which are robust and precise. However, they are quite expensive (100–1000 $); in some applications they require thread fixation, their size and weight (including shielded coaxial cables) can influence modal characteristics of a structure and operations of a facility by disrupting aerodynamics of a blade, for example. Another type of sensors, deformation sensors, do not have most of the mentioned limitations – they are cheap, can be applied on the surface of a structure, are plain and light, together with connecting wires they can be covered with a protective layer, creating an integral element with the measured structure. Two types of deformation sensors can be used – strain gauges and piezo film sensors. Strain gauges are very useful for testing structures in laboratory conditions, but they are hard to apply for OMA. These sensors require bridge connection and balancing, so each sensor needs a single dedicated channel in a specific data acquisition system. A large number of data acquisition channels increases SHM system costs. Utilization of accelerometers and strain gauges limits SHM system development and application diversity.

All mentioned problems have a cumulative effect, which results in high costs of production and application of SHM systems, not to mention the size and weight of sensors. The high cost of an SHM system reduces interest from the commercial sector and consequently does not allow mass usage of SHM systems. The sensor's size and weight are also crucial for aerodynamic applications.

2.2.SHM problem solutions

The Thesis proposes an overall approach to the SHM system development process. This process can be divided into the following tasks:

1. Choosing the structure to be monitored and acquiring its dimensions and functional properties.

2. Selection and application of a sensor's network.
3. Acquisition of healthy state vibrational data with influence factors, formation of a healthy state data base embedded in *modal passport* (discussed further).
4. Periodic acquisition of unknown state vibrational data during the structure's life cycle (monitoring), comparison of newly acquired data to the healthy state data.

Above, the term *modal passport* is introduced. It is a complex of methodological, algorithmic and software solutions, which includes a modal description method of typical monitoring objects' structure, primarily internal and external factors' influence functions on the structure's modal properties. Another feature of a modal passport is a universal method for monitoring an individual object using typical modal properties and influence functions, which allows:

- integrated estimation of structural condition as a result of a measurement;
- definition of healthy (reference) state boundaries of the structural condition;
- fault detection.

As a solution to the skilled personnel requirement and to reducing the complexity of the SHM system data processing steps, a modal field comparison method is introduced in Section 3.3. This method processes the vibrational responses based on the singular value decomposition without modal parameter estimation.

The solution to the high cost of sensors is the application of piezo film deformation sensors, which are described in detail in Section 1.2. These sensors lack the disadvantages that are identified for accelerometers and strain gauges and are widely used for industrial purposes, mainly for alarms, signalization and other security solutions. Just like strain gauges, piezo film sensors are cheap, light, and can be integrated into a structure. Piezo films do not require bridge connection and balancing. The size of a piezo film sensor used in current studies is 16 x 45 mm and 28 μm thick, although other sizes are available. The weight of a single sensor is smaller than 0.1 g. The application of piezo films also allows using the same data acquisition systems (DAQ) as for accelerometers. The wiring between piezo film sensors and DAQ can be done using the multiplexing approach, which reduces the number of input channels and brings costs further down. Multiplexing is achieved by using switches or patch bays to connect the signals from sensors to DAQ input in patches, making measurements for different zones of the structures sequentially.

The implementation of said solutions will allow to bring the SHM system's costs down and simplify its application.

2.3.SHM system's development steps

The proposed SHM system's technology would ensure the development, serial production and application of a monitoring system for the technical state of various structures for typical equipment (objects) operating under different operational conditions.

SHM system is designed to detect damage in an individual structure from a set of measurements of this structure. Damage detection in a structure from a set of monitored structures is not pursued here, as early studies showed that the large scatter of damage-sensitive parameters due to changes in mass, geometry and other material properties significantly reduces the reliability of the SHM system.

In order to successfully monitor the structural condition, each structure must have a built-in SHM system, which reads the vibration data and sends it to the workstation (computer). Next, the operator performs the operational modal analysis (OMA), evaluating the modal parameters of each structure's sample. The resulting modal parameters, together with the recorded external influence factors such as static loads or rotational velocity (blades), shall be entered by the operator into the database. This database provides an application of the modal passport technique (see Section 3.1), storing the results of previous measurements of these structures. Such a database also stores the reference modal parameters of an intact structure and the influence functions that are typical for such structures. A special damaged sample recognition algorithm later analyses the database and recognizes the measurements (data samples) that show sufficiently different modal parameters at given external factors compared to the reference. This stage is called damage identification. Next, the operator will be able to perform an in-depth analysis of the modal parameters of a particular damaged sample in order to decide on the significance of the damage and possibly localize the damage from the analysis of mode shapes. This allows to plan further actions with the given structure – repair, replace, or perform no action if the defect is not significant.

Based on the above description, two components can be defined for the SHM system:

- A measuring system, which in turn consists of:
    - sensors and cables on the structure,
    - data transmission system to the computer.
- Data processing and analysis part:
    - OMA software,
    - modal passport with reference state data and influence functions.

The modal passport formation for typical structures consists of the following steps:

1. Build an FE model of a structure.
2. Calculate modal parameters for the FE model taking into account the real-world boundary conditions, loads, temperature regimes, and other factors. The FE calculation results are required to optimize the sensor network and select the test settings and for modal identification.
3. Create a sensor network based on the results of the FE modelling. Optionally, use an optimization algorithm for sensor placement [28].
4. The real structure is to be equipped with the developed sensor network.
5. Prepare a measuring system, including cables, connectors, a data acquisition device with a computer, and sensors for load, temperature, and other factors.
6. Perform operational modal analysis of the structure and record the obtained modal parameters and external factor indicators in one database (modal passport). Where possible, these measurements shall be carried out in a controlled environment, gradually changing the external influence factors.

7. Obtain damaged state data with a modelling approach. Damage modelling allows to foresee modifications in modal parameters due to possible future damages:
    a. A random test situation shall be repeated on the FE model, and it shall be verified that the FE model and test results are similar. In case the results do not match, necessary adjustments shall be made to the FE model.
    b. Introduce structure-specific damage into the FE model, perform calculations and save the obtained parameter sets, including modal parameters and external factors.

For further process, the operator takes the estimated modal parameters from the new measurements of the same structure or other structures of the same type and, using the modal passport, performs an evaluation of the structural condition. The measurement results are compared to the modal passport data using the damage detection algorithm (modal parameter variation) or alternatively using the raw data by the algorithm from Section 3.3. The result of the evaluation is usually a prediction of whether the structure is healthy or damaged.

2.4. Application of deformation sensors for OMA

Available OMA applications, which determine the modal parameters of the operating object, deal with acceleration signals but not deformation or strain. It is well known that acceleration is the second derivative of displacement. To use the deformation sensor data, it is necessary to justify the relationship between the displacement and deformation parameters. The piezo film sensors are attached to the surface of the structure, so the measured signal is the deformation of the structure's surface. The displacement of any surface point of the bending beam is determined by the curvature of the so-called elastic or neutral line of this beam. This curvature depends on the longitudinal deformation of the surface layers. The relationship between the deformation of the surface layer of the beam and its displacement

$$\varepsilon_s = y_s'' \cdot \frac{h}{2}, \tag{2.1}$$

where h is the thickness of the beam and $h/2$ is the distance from the neutral axis of the beam to the surface layer.

This relationship is applicable to the static bending deformation for a beam. However, with certain assumptions, this equation also is valid for dynamic deformations.

For bending mode identification, the strain of tension or compression measured on the surface of the oscillating beam is determined by the second derivative of the distribution function of the transverse displacements of the neutral line of the beam and the distance from it to the surface layer. If the thickness of the structure is negligible compared to other dimensions, then deformations are directly proportional to the second derivative of displacements.

Modal parameter estimation results in mode shapes which do not show acceleration (although acceleration is the measured signal) but displacement. So, the obtained mode shapes using deformation signals from piezo film sensors would be simply 180° out-of-phase compared to the displacement shapes.

2.5.Measuring system

The measuring system is a part of the SHM system, which is individually and permanently installed on the structure to be tested throughout its life. The measuring system consists of deformation transducers, wires, connectors, and a data reading device with a computer and software.

The type of sensor used for the proposed SHM system is a polyvinylidene fluoride (PVDF) sensor, described in detail in Section 1.2. These films are elastic, light and have piezoelectric properties. Thanks to these properties, the deformation of the film leads to a change in voltage. Piezo film is located between two printed silver electrodes, forming a capacitor-like structure. Due to this design, the sensor cannot measure static deformations, but this is not an issue for SHM. The particular sensor, shown in Fig. 2.1, is 40 mm long, 16 mm wide and only 28 μm thick.

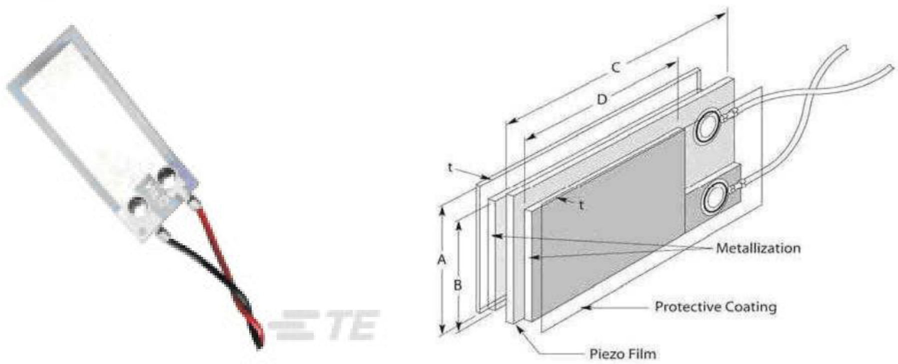


Fig. 2.1. PVDF film deformation sensor from TE connectivity [23].

The sensors are glued with the help of a double flexible adhesive tape (Fig. 2.2 a)). Other types of adhesives are suitable as long as the adhesive is elastic after curing. The size of the piece of adhesive tape must coincide with the size of the transducer surface to ensure full adhesion to the surface of the structure.

Wires used for the SHM system are small diameter (0.25 mm or similar) enamelled copper wires (Fig. 2.2 b)). Wires are glued to the transducers using special two-component epoxy glue. The wires are applied to the surface of the structure using a narrow double-sided elastic adhesive tape and are soldered to a wire hub at the boundary of the structure (Fig. 2.4).

Piezo film sensor has a positive and a negative voltage output. The positive output is considered to be a signal output; the negative one is connected to the ground. All negative outputs are thus joined. The cable hub can also be realised as a cable connector, for example, the D-SUB type.

a) b)

Fig. 2.2. a) Adhesive double-sided tape; b) enamelled copper wire.

a) b)

Fig. 2.3. a) Piezo film sensor with attached wires; b) two-component epoxy glue.

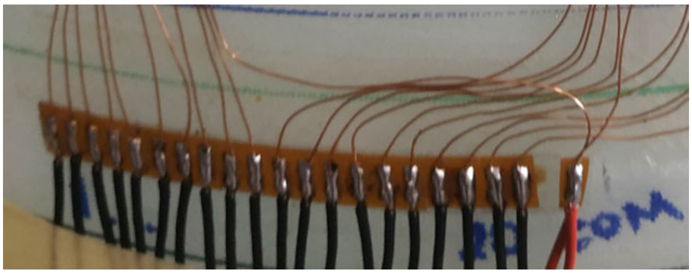


Fig. 2.4. Wiring hub at the boundary of a structure.

The primary role of a DAQ device is to perform analog-digital (AD) conversion of deformation signals. Most commonly, before the AD conversion, there is also a conditioning step – signal amplification and frequency filtering. *Brüel & Kjær's LAN-XI Type 3053* or a similar type of *LAN-XI* module can be used as a DAQ device. The number of modules depends on the number of sensors. For example, with four *Type 3053* modules, it is possible to measure 48 channels simultaneously. Other manufacturers, like *National Instruments*, *Siemens*, etc., also offer DAQ systems.

2.6. Periodic component suppression

A measured data post-processing tool to suppress or extract harmonics before performing the analysis of vibrational data has been developed.

In the frequency domain, the measured signal $X(\omega)$ is determined by the system's frequency response $H(\omega)$ and the forces $F(\omega)$ acting on the system. Ideally, for OMA, forces are even and random, so their spectrum can be regarded as unity. With periodic excitation there is a periodic deterministic component $D_n(\omega)$ to the impact forces. The measured signal is presented as

$$X(\omega) = H(\omega)\big(F(\omega) + D_n(\omega)\big). \tag{2.2}$$

Assuming there are some experimentally obtained $D_{na}(\omega) \approx D_n(\omega)$. Extracting $D_{na}(\omega)$ from (3) will result in

$$X_p(\omega) \approx H(\omega)F(\omega) \tag{2.3}$$

and

$$x_p(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X_p(\omega)\, \mathrm{e}^{\mathrm{j}\omega t} \mathrm{d}\omega, \tag{2.4}$$

where index *p* means "processed". Note that $X_p(\omega) \neq X(\omega)$, since the structure is responding to the forced periodical excitation, and this response remains in the signal. Hence, when one is referencing to the extraction of a periodic component, this means suppression of the said component with sufficient efficiency.

2.7.Data processing and analysis

As it was previously mentioned, the life cycle of the SHM system for a series of structures is divided into two parts:

- formation of modal passport,
- monitoring.

Formation of a modal passport means creating a modal passport for a typical structure – a set of stable modal parameters for different operational conditions. Monitoring assumes performing regular OMA on individual structures and comparing the resulting modal parameters to the modal passport values for damage assessment. The recorded vibrational responses are processed using OMA-designated software, for example, *ARTeMIS* from *Structural Vibration Solutions*. The processing includes the selection of modal parameter estimation methods, such as EFDD or SSI methods.

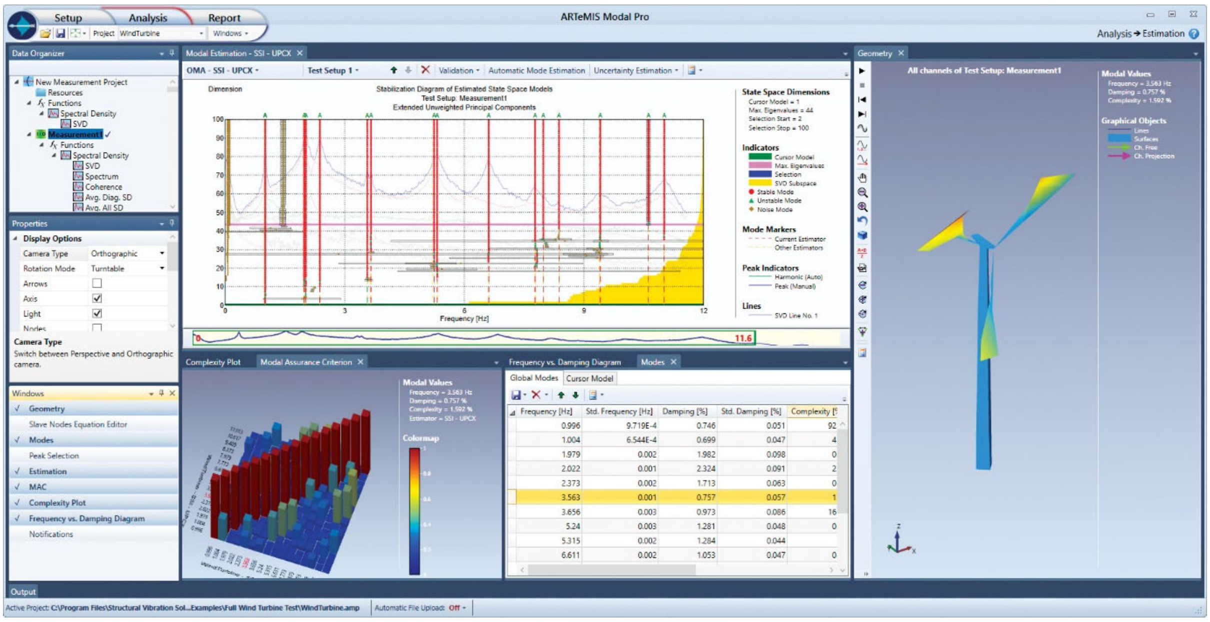


Fig. 2.5. *ARTeMIS Modal* software screenshot.

As a result, the engineer acquires the modal frequencies and shapes of recognized modes. These modal parameters are exported as a matrix in a text file. Frequencies are recorded as separate values, shapes are recorded as vectors with curvature/deformation values at each position of the transducer.

3. DAMAGE DETECTION AND EVALUATION ALGORITHMS

This chapter introduces the theoretical and mathematical basis for damage detection and evaluation algorithms of the SHM system prototype. The description starts with the modal passport architecture and implementation steps. Next, the modal parameter change assessment is shown. This is an assessment method that allows to compare combination of different modal parameters (frequencies and shapes together and separately) vividly and conveniently between different measurements, aiding the engineers in analysing the structural condition. Finally, the so-called modal field comparison method is shown, which evaluates the structural states without modal parameter estimation techniques.

3.1.Modal passport

Modal passport is a combination of measurement technique, modal data storage and processing methods in order to perform structural health monitoring. MP considers an application for a series of structures of the same type, e.g. wind turbine blades or towers.

Modes which are typical for a series of structures of the same type are selected to form a *typical modal passport*. The description of a typical modal passport includes the matrices of modal parameters: frequency, damping and shape over different operating factors. The referred values of modal parameters are the expected means (i.e. average values) of modal parameters for structures of the same type. In addition to averaged values, a typical modal passport also contains confidence intervals, which show the variance of modal parameters around the mean value.

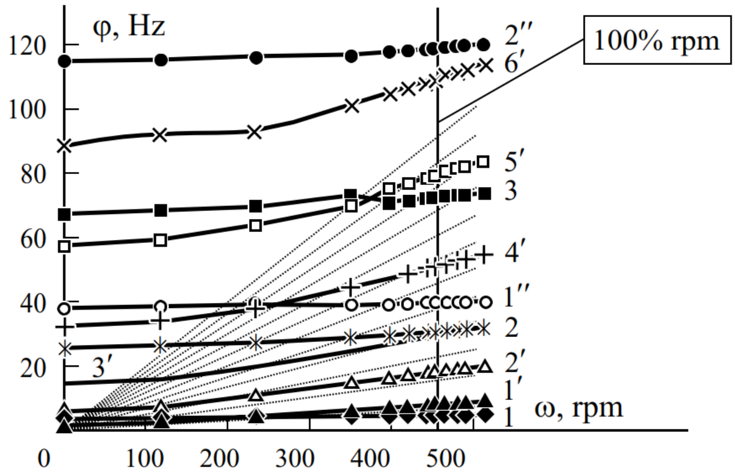


Fig. 3.1. Different modal frequencies as a function of rotational speed (revolutions per minute, rpm) for a composite helicopter blade. Numbers at curves denote the mode type: 1–3 – bending in the rotation plane; 1'–6' – bending in the thrust plane; 1" and 2"– torsional [29].

Operational factors like loading, rotation speed for rotating structures like blades, or temperature influence the modal parameters. The dependency of MP on operational factors is called “influence functions”. An example of such functions is shown in Fig. 3.1 as a function of modal frequency for selected modes over rotational speed in RPM for a helicopter blade.

A typical modal passport serves as a template for an *individual modal passport* of a certain structure.

Modal passport is realised either manually in *MS Excel* or semi-automatically in *Matlab* software, however, it can be realised in any data processing software.

Typical modal passport formation

The use of the modal passport is based on the assessment of changes in the modal parameters of the operating structure as a sign of a change in the state of this sample. In practice, change of mass can be attributed to an attached (or detached) element on the body of the structure, change of damping – due to changes in boundary conditions, and the stiffness changes mostly because of defects like cracks. These changes influence the FRF of a measured vibrational signal from the structure, which leads to modified modal parameters.

Modes should be stable and typical for the given structure to recognize changes in the state. Stable modes (in the context of a modal passport) are considered to be repeating the modes of similar shape between different measurements and/or samples. Stable modes are also more robust to slight variations in operational conditions. There are 3 criteria (verified in practical tests) for stable modes:

1. Repeating the similar mode shape and frequency at least 3 times out of 5 estimators of T tests. The number of tests should be at least 3, but 5 or more tests are recommended.
2. Limited frequency deviation. An acceptable frequency deviation is usually in the region of a few percent.
3. MAC value (Section 1.3, Eq. (1.8)) between stable mode shapes at least 0.9, but smaller than 1.

The sequence of steps to create a typical modal passport:

Step 1

OMA of a structure in the s state. The initial state of a typical passport requires the structure to be undamaged (healthy).

Step 2

Processing of the acquired data using five modal parameter estimation methods (EFDD, CVA, UPC, PC, UPCX, further in the text – estimators). Selection of relatively stable modes estimated with at least 3 estimators. Mode shapes given by different estimators have different scales. To bring them to a common (–1.0... 1.0) range, each n element of eigenvector ψ_m^n of the m mode is normalized to the square root of the sum of squares of all N elements. This step is called *normalization.*

Step 3

Selection of a stable mode from relatively stable modes using the above-mentioned criteria of limited frequency deviation and $0.9 \leq \text{MAC} < 1$. Each such mode is represented by $2N + 4$ data vector:

- shape and its standard deviation ($2N$ elements);
- frequency and its standard deviation (2 elements);
- damping coefficient and its standard deviation (2 elements).

N is essentially equal to the number of sensors on the structure, as the shape is represented by as many DOFs as there are sensors.

This way, a $M \times (2N + 4)$ matrix is formed from a set of tests, where M is the amount of stable modes. Steps 1–3 are repeated for each of T tests. Naturally, for each test, the number of resulting modes may differ. But using the three criteria mentioned above, a selection of modes is performed, and a full set of stable modes K is acquired for T performed tests. This way a $T \times M \times (2N + 4)$ matrix is obtained.

Step 4

Different estimators may reflect the same mode shape in opposite phases, so the *phase alignment* is performed. The selection of modes to be phase-aligned is done using the correlation function.

Step 5

Modal *enhancement* – calculation of the mean and variance of the modal parameters:

- frequency $\bar{f}_m$ and δf_m;
- damping $\bar{\zeta}_m$ and $\delta\bar{\zeta}_m$;
- mode shape $\bar{\psi}_m$ and $\delta\bar{\psi}_m$.

Mode shape averaging is done for each element of the mode shape vector, but the variance is proposed as an integral parameter – single for one eigenvector.

After Steps 3–5 have been performed for the reference state of the tested sample (structure, specimen), the trials are repeated for the structure's other states. A state is represented by external influence factors. For rotating blades, the applied forces are centrifugal forces during rotation, so the state is defined by the rotation velocity (Fig. 3.1). Influence function of the m^{th} mode frequency f_m against rotation velocity v is described using the 2nd order polynomial:

$$f_m(v) = \beta_0 + \beta_1 v + \beta_2 v^2. \tag{3.1}$$

The functions' coefficients β are then found using the regression method.

Individual modal passport

Typical modal parameters, which are carefully selected (as shown above), serve as guiding references for selecting modal parameters when processing data from individual structures. For the individual passport to function properly, it needs healthy state data, which are obtained by testing the particular structure (sample) in its healthy state under arbitrary conditions. Testing under arbitrary conditions allows to avoid inconvenient and expensive testing in laboratory conditions. Using the influence functions of a typical modal passport, these modal parameters are recalculated from arbitrary conditions to reference conditions. The health monitoring is then done in reference conditions. The variance of individual modal parameter values is compared to the reference confidence intervals of individual passport. An indication of damage is when the measured variance exceeds the reference confidence intervals. Further measurements of the particular structure are also being subjected to recalculation to the reference conditions, so that the monitoring of damagesensitive features is being done for these conditions.

As an example, temperature influence functions for frequency $f(t)$ and damping $\zeta(t)$ are shown in Fig. 3.2. Some dependencies are linear (mostly for frequency), some are not. These functions allow to approximate modal parameters for other temperatures.

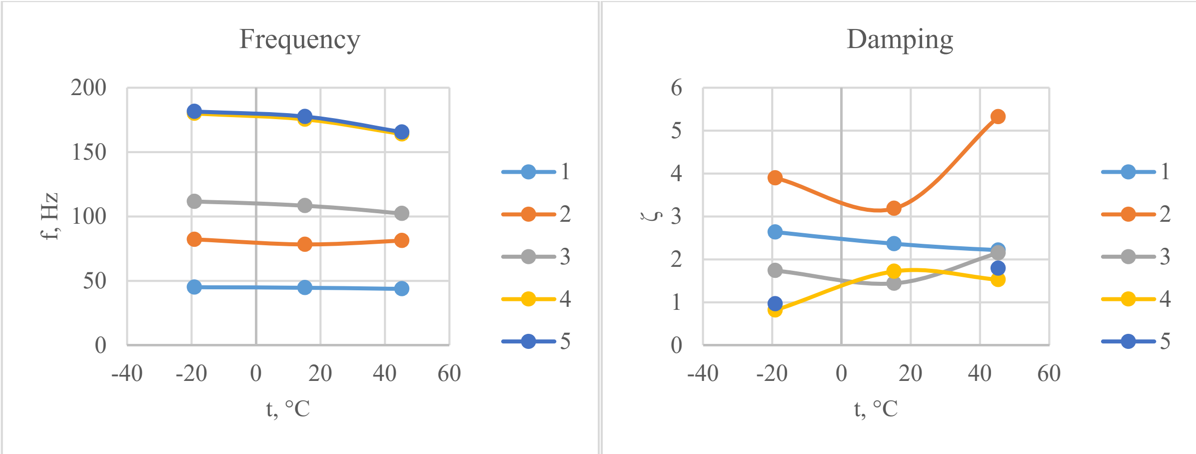


Fig. 3.2. Temperature influence functions for a glass fibre composite cylinder for the first 5 modes.

Individual MP considers the possibility of detecting damage. Detection of the damaged state (if one occurs) is performed using the damage detection algorithm. Estimation of damage severity can be done using the modal parameter variation (MPV).

3.2. Modal Parameter Variation

For damage detection and its severity, a comprehensive evaluation of the object's modal parameters modification is required. There are examples and some experience in the evaluation of modal parameter variation in [30]. The Thesis offers a mathematical formulation of modal parameters variation evaluation.

To estimate modification of m^{th} mode from a structure's test, which has not been used for the formation of the typical modal passport, the modal parameters variation (MPV) is used as an integrated parameter, which considers modal frequency, damping and shape modification from its reference state (baseline). MPV is an integral part of a modal passport.

A modal test i of a typical structure is considered. It is assumed that the structural condition of this structure is unknown. Modal parameters are estimated using the standard approach, as in the typical passport formation's Steps 1 and 2. Normalization and phase alignment are also performed to match new modal shapes $\bar{\psi}_m^i$ to the typical ones. Typical modal parameters serve as a reference to which the newly obtained parameters are compared to using simple modal difference. For frequency and damping, the normalized modal difference for mode m is:

$$\Delta\bar{f}_m = \bar{f}_m^i - \bar{f}_m, \tag{3.2}$$

$$\Delta\bar{\zeta}_m = \zeta_m^i - \bar{\zeta}_m, \tag{3.3}$$

The shape deviation $\Delta\bar{\psi}_m$ compared to the typical shape is calculated as a geometrical sum of all the shape element's deviations $\delta\bar{\psi}_{m,n}$:

$$\Delta\bar{\psi}_m = \sqrt{\sum_{n=1}^{N}\left(\bar{\psi}_{m,n}^{i} - \bar{\psi}_{m,n}\right)^2}. \tag{3.4}$$

It is advantageous to estimate an integral deviation of the tested structure where deviations from all modes are considered. For this purpose, parameters of integral deviation of frequency $\Delta\bar{f}$, damping $\Delta\bar{d}$, and shape $\Delta\bar{\psi}$ are calculated:

$$\Delta\bar{f} = \sqrt{\sum_{m=1}^{M}\left(\Delta\bar{f}_m\right)^2}; \qquad \Delta\bar{\zeta} = \sqrt{\sum_{m=1}^{M}(\Delta\zeta_m)^2}; \qquad \Delta\bar{\psi} = \sqrt{\sum_{m=1}^{M}(\Delta\bar{\psi}_m)^2}. \tag{3.5}$$

The integral modal deviation is referred to as modal parameters variation. When it is necessary to perform an overall modal assessment of the structure using a single value, then modal parameters variation intensity can be used:

$$MPVI = \sqrt{\Delta\bar{f}^2 + \Delta\bar{\zeta}^2 + \Delta\bar{\psi}^2}. \tag{3.6}$$

3.3.Modal field comparison method

The modal field comparison method is a vibration signal processing method, which allows to obtain the numerical assessment of the structure's condition. Modal field here is a term to describe the matrix of singular vectors $\Phi(\omega)$ and values $s(\omega)$. The assessment is relative, meaning that it requires a reference condition to be defined, which serves as a baseline. This baseline can be a modal field of a single measurement of a healthy state or a modal field averaged between several measurements. In order to objectively compare a modal field, the presented modal field comparison method (MFCM) was developed.

Fig. 3.3 shows the flowchart for the calculation algorithm for the modal field comparison method parameter. A detailed description of the method is given in the full text of the Thesis.

The MFCM is an optional technique and can be used as a separate tool for structural health monitoring. The main advantage of MFCM is that it does not require modal parameter estimation. This saves a lot of processing time. On the other hand, this method is not as robust as the modal passport approach.

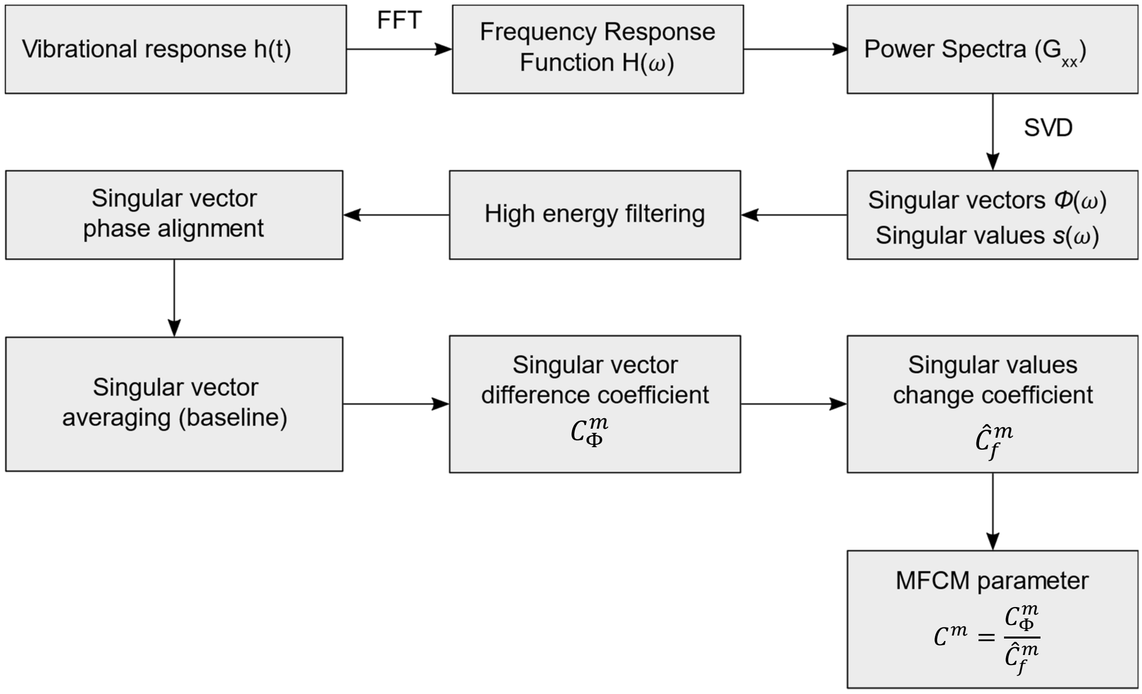


Fig. 3.3. MFCM parameter calculation algorithm.

4. CASE STUDIES

This chapter covers the proposed SHM system's application cases. The experimental verification of the described approaches is based on both existing methods, mainly OMA and the established modal parameter estimation techniques, and several novel solutions:

- use of PVDF piezo film sensors for OMA;
- application of wireless data transmission solutions for OMA of rotating blades;
- evaluation methods of estimated modal parameters for damage detection and identification.

The concepts and theories presented in the Thesis were tested using the following objects: an 85 cm long aluminium beam, a 1.5 m high model of a wind turbine, a 20 m high airport radar tower, and a 2 m small helicopter composite blade.

4.1. Application of deformation sensors

The findings obtained in Section 2.4 need experimental validation – a comparative analysis of vibration and deformation shapes of a testing object, which is one of the goals of the Thesis. Additionally, this study aims for validation of piezo film sensors' application without preamplifiers.

The trial sample of the composite blade was chosen as an object for an experimental research study. Two modal techniques provide the experimental estimation of the blade's modal parameters: experimental modal analysis (EMA) and OMA. Within the EMA, the blade was excited by a dynamic hammer with a force transducer, while the response measurements were carried out by two accelerometers. OMA technique uses 10 piezo film sensors that measure blade deformations. In OMA, the blade is excited with ordinary hammer hits to the metallic details, fixing the blade's root to a test stand. The frequency and strength of the impacts varied, providing arbitrary excitation that was consistent with the limitations of OMA. The measurement setup for both methods is shown in Fig. 4.1. The blade is connected to the rotor through the adapter and the torsion.

There are 10 piezo film sensors on the surface of the blade in five sections along its axis and in two lines: one near the front and the second near the rear blade edge. At the blade tip and at its root, two 3-component accelerometers are fixed for reference vibrations measurement.

Piezo film deformation sensors embedded in the structure

For advanced composite structures, piezo film sensors provide an important advantage due to their ability to be embedded in the structure. As an example, in Fig. 4.2, an experimental sample of a composite blade with film sensors embedded in its surface layers is presented. The sensors are glued onto the surface of the blade (as described in Section 2.5) and covered with a glass mat, which is then soaked with epoxy resin. This creates an extra protective layer on the blade, which copies the aerodynamic shape of the blade and keeps the sensors intact and in place.

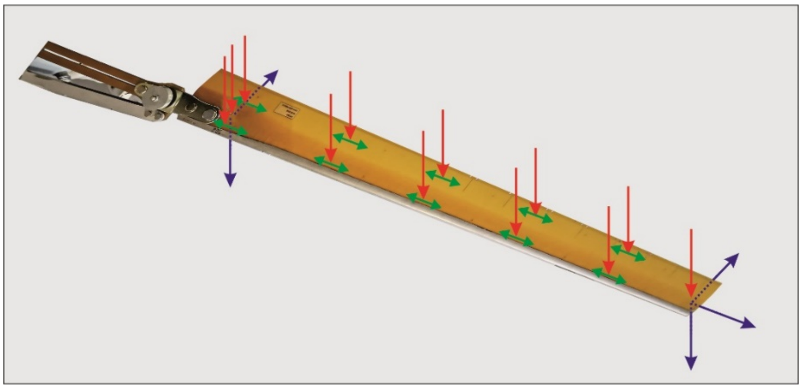


Fig. 4.1. Measurement setup for the blade vibrations and deformations: acceleration (blue), deformation (green) and the direction of impact (red).

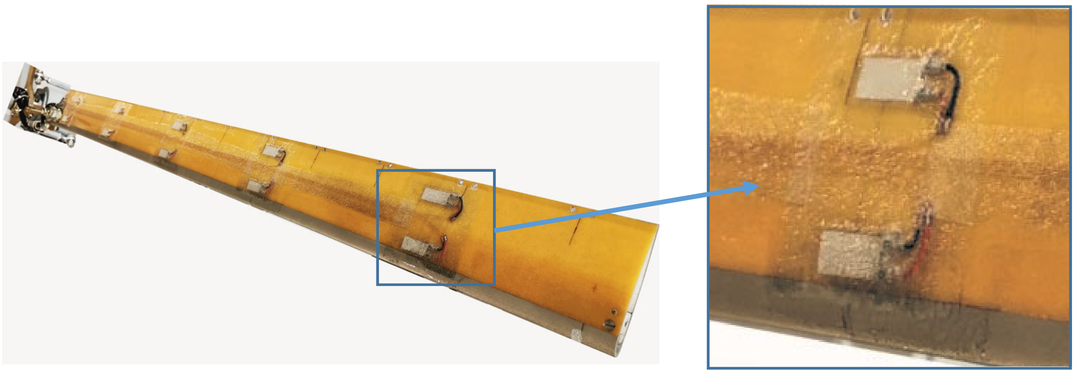


Fig. 4.2. Piezo film sensors embedded in the composite blade surface.

Processing of mode shapes

Accelerometer responses from EMA tests are measured and processed using *Pulse Labshop* software to obtain the modal parameters with classical mode shapes (deflections/displacement).

Responses from the piezo film sensors during the OMA tests were recorded and processed in *Artemis* software. The obtained modal parameters contain the deformation mode shapes. Two types of mode shapes are compared.

The modal shapes obtained using OMA provide the eigenvector of each mode $\bar{\varepsilon}(x)$ in the relative scale normalized to the maximum value of the blade deformation in this mode ε_m:

$$\bar{\varepsilon}(x) = \varepsilon(x)/\varepsilon_m. \quad (4.1)$$

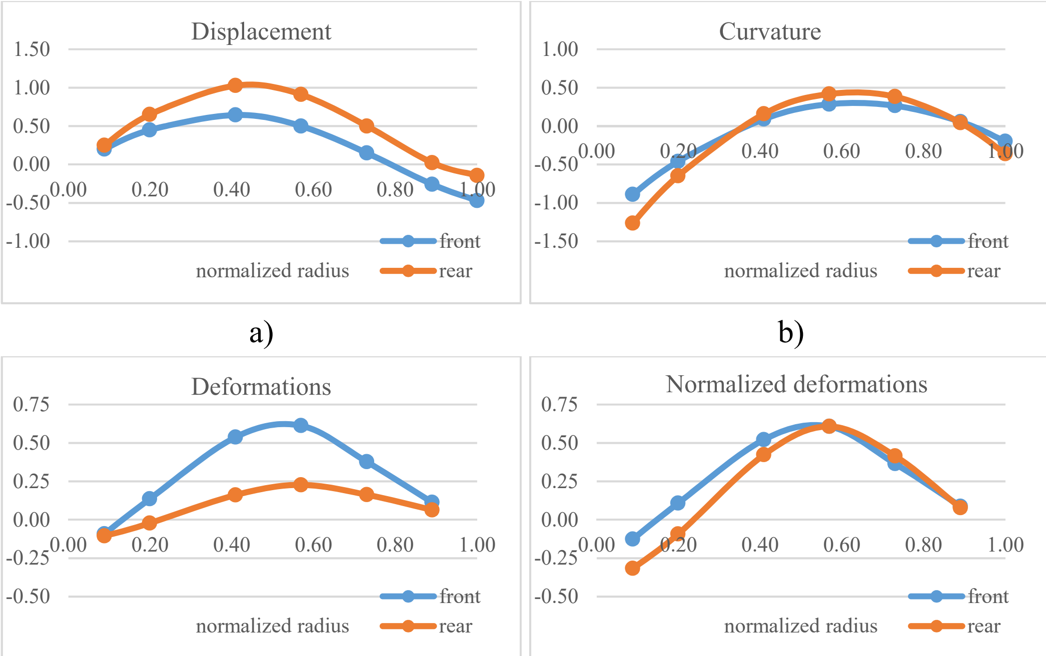
As deformations are the function of surface height (from the neutral layer), the coefficient C (height consideration) is applied:

$$\bar{k}(x) = \bar{\varepsilon}(x)/C. \quad (4.2)$$

As the curvature of the surface layer at an arbitrary point is proportional to the tensile-compression deformation in this layer $k_i = C\varepsilon_i$, so the normalized curvature $\bar{k}(x)$ corresponds to the normalized deformation of the blade with a coefficient of proportionality C, reflecting the height of the blade profile at measured DOF.

Comparative analysis of curvature and deformations

To compare the blade mode shapes of displacement and deformation, diagrams are used illustrating the distribution of curvature or deformations along the longitudinal axis of the blade, i.e. the eigenvector. Blue dots in the diagrams show the eigenvector calculated using the measurements in DOFs along the leading edge of the blade, and red – along the rear edge. The diagrams in Fig. 4.3 allow to compare the shapes of the 2nd bending mode reflected by: the mode shape computed using EMA (displacement) (Fig. 4.3 a)); the curvature derivative from the said mode shape (Fig. 4.3 b)); deformations measured by piezo film sensors (Fig. 4.3 c)); and normalized deformations (Fig. 4.3 d)).

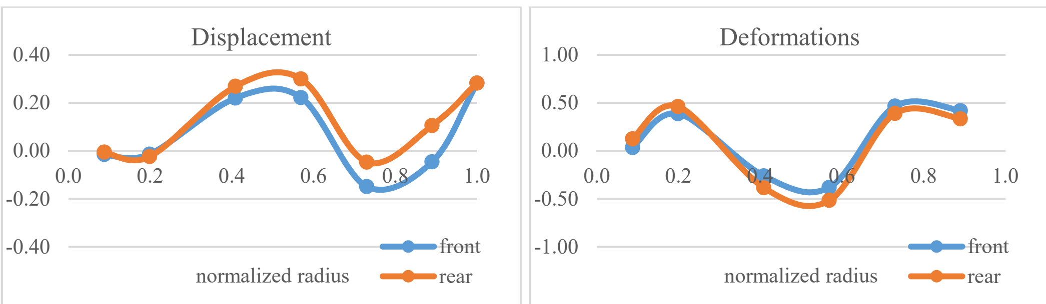


a) b) c) d)

Fig. 4.3. Diagrams of eigenvectors: a) – displacement; b) – curvature; c) – deformations measured; d) – normalized deformations.

Resuming the consideration above and applying the half-wave approach to the bending mode identification, we can consider the curve in Fig. 4.3 a) as the 2nd bending mode, which lacks the left side, located on invisible torsion. The curvature diagram (Fig. 4.3 b)) has a 180° shifted phase compared to the displacement curve. Since the deformations must be similar to the 2nd derivative, the phase shift must also be 180° relative to the shape of displacement. This shift is observed between the curves of the diagrams in Fig. 4.3 a) and d). Thus, the similarity of experimentally obtained estimates of the displacement and deformation shapes of the 2nd bending mode confirms the validity of the above assumptions.

Fig. 4.4 illustrates the diagrams of displacement and deformation shapes characterizing the 4th bending mode of the same blade. There is a noticeable similarity between the displacement shape (Fig. 4.4 a)) and the deformation shape (Fig. 4.4 b)), with a shift between them of approximately 180°.



a) b)

Fig. 4.4. Normalized eigenvectors: a) – acceleration, b) – deformation.

The experimental verification confirms the validity of the assumptions made in Section 2.4 on the relation between the 2nd derivative of displacement and the deformation shape of the surface layer. This linear dependency allows the use of the measurement of deformations of beam-like structural elements to determine the modal parameters.

4.2. Periodic component suppression

The task of this study is to validate the periodic component suppression method formulated in Section 2.6. The testing object is a helicopter blade on a rotating rotor shaft. The blade is of the same type as in the previous case study. There are 5 sections with 2 sensors in each, parallel to the axis of the blade, and 10 sensors in total. Additionally, a tacho probe is installed on the shaft, which records the speed of rotation giving impulses as output. The sensors are fixed to the blade's surface via a double-sided adhesive tape and are covered with a layer of low-density glass fibre mat and epoxy resin. The signals from sensors are fed into the DAQ system, which transmits the data wirelessly to the PC using WiFi.

Time synchronous averaging was applied to measured vibrational signals for harmonic component enhancement. Fig. 4.5 shows 3 graphs for the measured signal, where the upper one has both periodic and random components ("mixed signal"), the middle one has a periodic signal, accumulated using tacho impulses, and the lower one – the resulting signal ("corrected signal"), which is received by the subtracting periodic component from mixed signal. The time domain is shown on the left, and the frequency domain is shown on the right using the fast Fourier transform. The phase alignment of mixed and periodic is very important and is achieved by careful usage of the tacho signal.

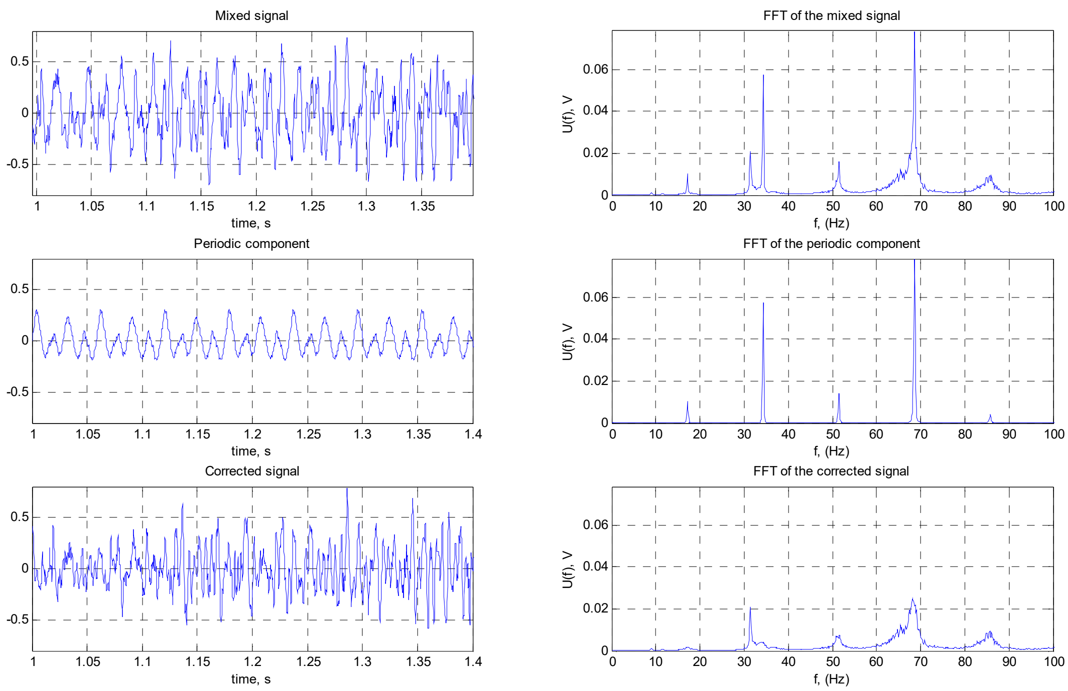


Fig. 4.5. Example of TSA extraction for vibrational signal.

The fundamental frequency of the periodic component is 17.1 Hz. The magnitude of the 2nd harmonic at 34.2 Hz for mixed signal is 57.5 mV. The signal correction reduces this harmonic sixteen times – down to 3.5 mV.

Modal parameter estimation

The procedure of modal parameter estimation was performed using the enhanced frequency domain decomposition (EFDD) analysis. The resulting modal frequency, mode shapes, and damping coefficients for 10 estimated modes are shown in Table 4.1 It has been observed that the highest change of frequency and damping after harmonics extraction appears at harmonic frequencies, which is expected, because these frequencies were affected by the extraction algorithm.

As the result of extraction, it was possible to estimate two additional modes, one of which lies on the 2nd harmonic frequency (34.29 Hz) and another mode (137.27 Hz) is a high order mode.

In order to quantifiably evaluate the difference between the same mode shapes before (original) and after (extracted) processing, again MAC is used (Fig. 4.6). Modes can be regarded as similar when MAC is >0.8. It is a good indication that same mode pairs (before and after processing) show MAC values close to 1. That means that processing did not alter modal information in the signals in significant way.

When comparing same pairs of modes between original and extracted sets, MAC value is 0.618 and 0.583, respectively, showing no significant anticipated reduction of MAC values.

Another approach to evaluate the difference between before and after processing is to use modal complexity and its measure – mode complexity factor (MCF).

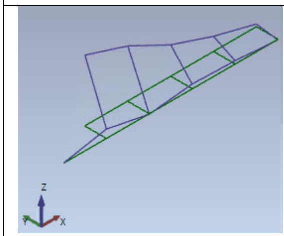
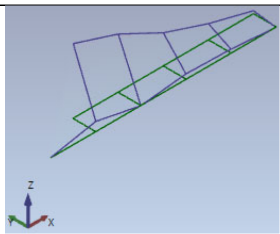
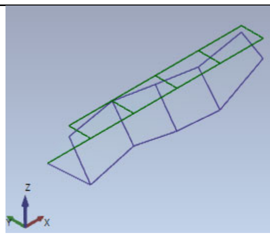
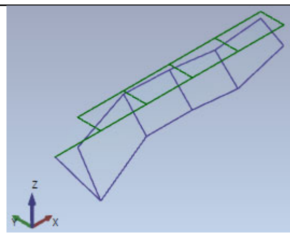
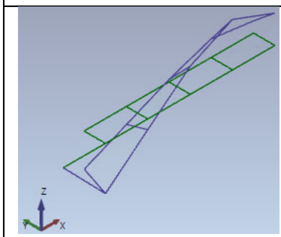
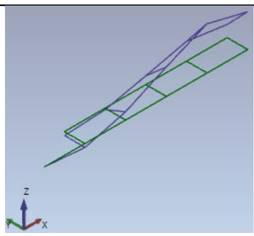
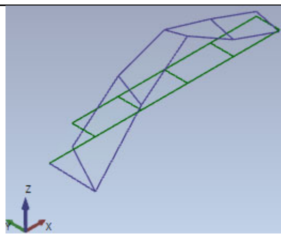
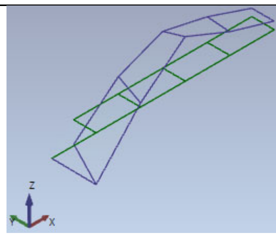
Table 4.1

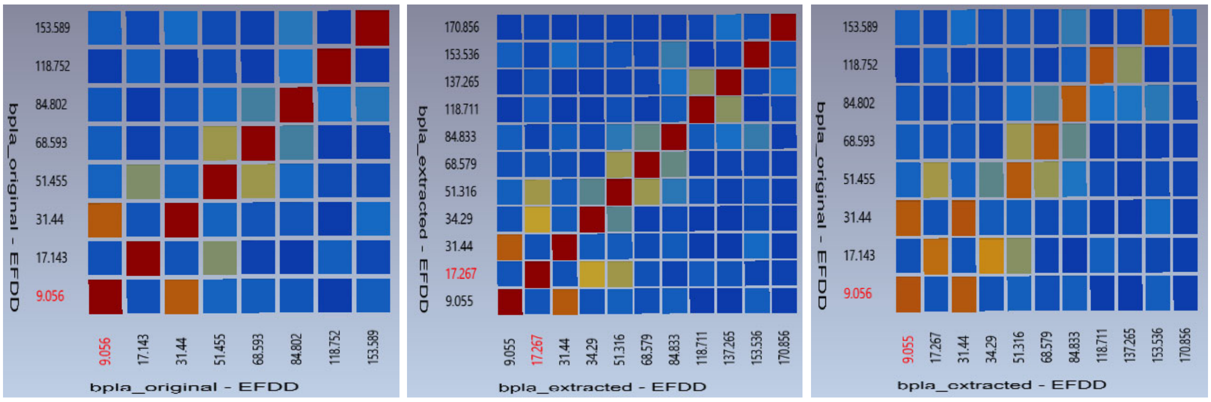
Modal Frequency and Damping of a Composite Blade. Estimation Without and with Periodic Extraction

No.	*f*, Hz		Damping		Complexity		Mode shape description
	Original	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	
1	9.06	9.06	1.756	1.755	15.4	14.9	1st bending Y axis
2	17.14	17.27	0.337	0.864	14.3	37.4	forced bending (1st rotor harmonic)
3	31.44	31.44	0.234	0.235	21.2	21.3	1st bending Z axis
4	-	34.29	-	1.058		4.0	forced bending Z axis (2nd rotor harmonic)
5	51.46	51.32	0.368	1.394	99.2	94.2	(3rd rotor harmonic)
6	68.59	68.58	0.921	1.321	10.3	13.7	3rd bending Z axis (4th rotor harmonic)
7	84.80	84.83	0.118	0.166	70.7	66.9	2nd bending Y axis
8	118.75	118.71	1.284	1.293	0.8	0.7	4th bending Z axis
9	-	137.27	-	0.072		48.2	
10	153.59	153.54	0.546	0.557	42.6	35.0	3rd bending Y axis

Table 4.2

Mode Shapes of a Composite Blade. Estimation Without and with Periodic Extraction.

original	extracted	original	extracted
9 Hz		17 Hz	
			
51 Hz		84 Hz	
			



a) b) c)

Fig. 4.6. MAC values for mode shapes between original and extracted mode sets: a) autoMAC for original; b) autoMAC for extracted; c) MAC between original vs. extracted.

As can be observed in Table 4.1, the harmonic extraction decreases the influence of periodic parts. This results in a decreased complexity for Modes 5, 7, and 10 – 5.5 % improvement in average. On the other hand, Modes 2 and 6 obtained higher complexity after processing. This might be explained by the fact that the mentioned modes are basically a superposition of several modes (most probably of two modes), one of which is a forced harmonic mode, and another is a natural one. The modes that are not in the vicinity of harmonics (Modes 1, 3, 8) did not show serious modification of MCF parameter.

Case study conclusions

The influence of harmonic components extraction algorithm on modal parameters is rather low, which means also low influence on the response and therefore – low error. The processing gives the possibility to estimate some extra modes, which might be hidden by harmonics. The extracted harmonics dataset shows improvement in the quality of modal parameter estimation. The ability to compare original and extracted versions provides more insight on the structural response and the impact of harmonics in the response, which leads to better understanding of oscillations of the specific object and allows better judgement on the latter.

4.3.Modal passport application

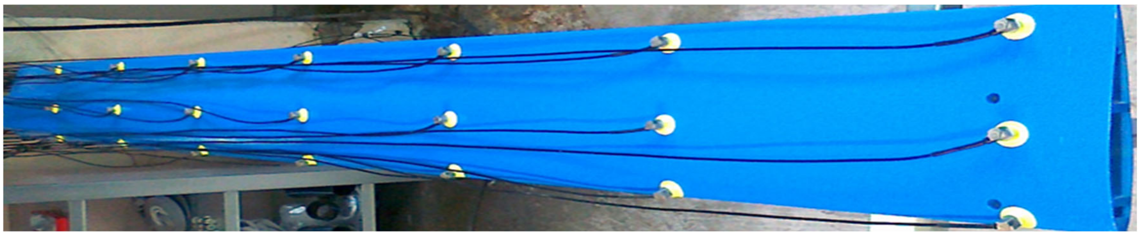
The presented study aims to validate OMA techniques and modal passport application to a rotating blade. The Thesis considers comparative analysis between the vibration and deformation sensors and of the data transmission system, as well as validation of the formation of modal passport for composite helicopter blades.

There are two stages of a composite blade’s modal testing. At the first stage, the blade is tested in a static position using EMA and OMA, and at the second stage –only OMA techniques are applied to rotating blades.

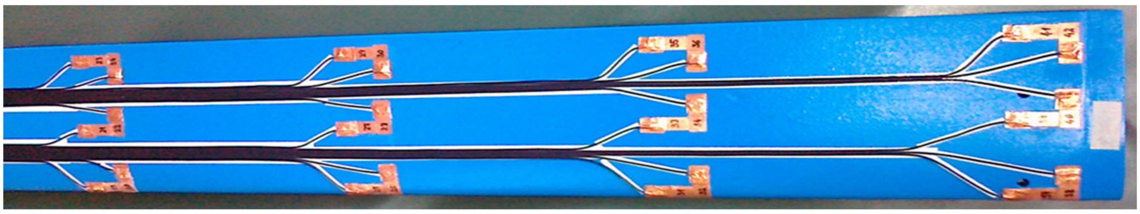
Static testing

Two experimental blade models were fabricated. The first model is equipped with 21 accelerometers (Fig. 4.7 a)). This blade is used for experimental modal analysis in static using a roving hammer technique.

The second blade is equipped with piezo film deformation sensors (Fig. 4.7 b)). OMA technique is being used for this blade using random manual excitation with a hammer on the blade’s fixing parts.



a)

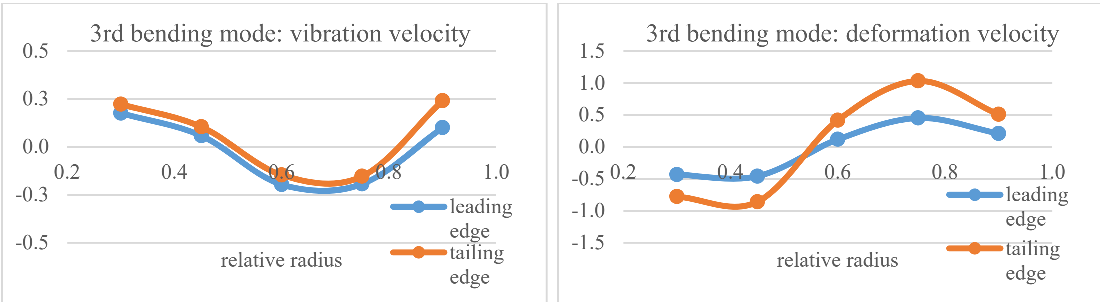


b)

Fig. 4.7. Vibration accelerometers (a) and vibration deformation sensors (b) on similar blades.

Fig. 4.8 a) shows a diagram of mode shape for the third bending (flapping) mode, where the blue line illustrates the mode shape vector distribution along the front edge of the blade and the green line – along the tailing edge.

Identification and classification of vibration modes is carried out based on the modal parameters obtained from both static tests. When identifying vibration and deformation modes, standard methods (such as MAC, COMAC, etc.) are not appropriate, since, even if they reflect the same mode, their curves are different. Therefore, an analytical approach shall be used for the modes' matching and identification, concerning the nature of vibrations and deformations distribution along the length and chord of the blade for each vibration mode, considering findings of the study in Section 4.1. When classifying the modes of composite blades, typically bending (flapping and chord wise) as well as torsional modes are defined.



a) b)

Fig. 4.8. Diagrams of vibration velocity (a) and deformation velocity (b) shapes of third flapping mode.

Testing of rotating blades

The testing is performed on a different type of blade. The technology for rotating blade testing includes a methodical and a measurement part. The advanced multichannel system measures and transmits the signals of vibration deformation sensors. Fig. 4.9 shows the measurement setup of rotating blades with deformation sensors as in Fig. 4.7 b), and Fig. 4.10 shows a multichannel data acquisition unit (DAU) with a wireless data transmission device on top of the propeller.

Fig. 4.9. Integrated array of deformation sensors and wiring.

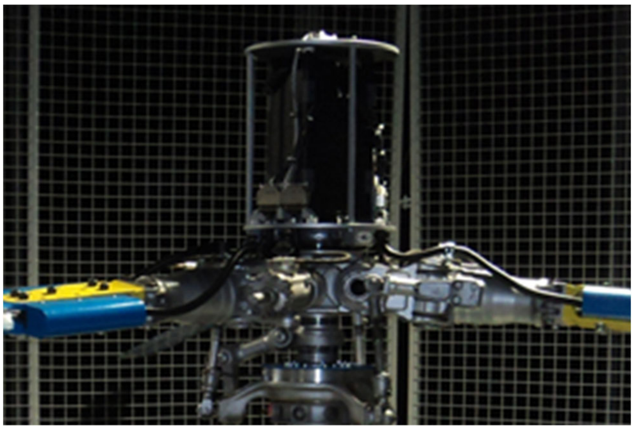


Fig. 4.10. Multichannel wireless DAU with connecting cables from blades rotates together with the propeller.

The system providing measurement data and transmission complies with the harsh environment at rotation speeds of up to 1200 rpm. The wireless router rotating with DAU transmits the data to the workstation that ensures receiving, storing and further processing of data. Constant centrifugal loads acting on the blade influence modal parameters.

Tests on the rotating blade are conducted in operational range from static to the maximal rotation speed that exceeds the nominal speed by 20–30 %. The modal parameters are computed separately for each rotor speed.

Modal passport formation

The resulting modal parameters are stored in tables for each operational condition tested. For example, modal frequency dependency from the rotation velocity is shown in Fig. 4.11, together with the respective 2nd order polynomial approximation – influence function.

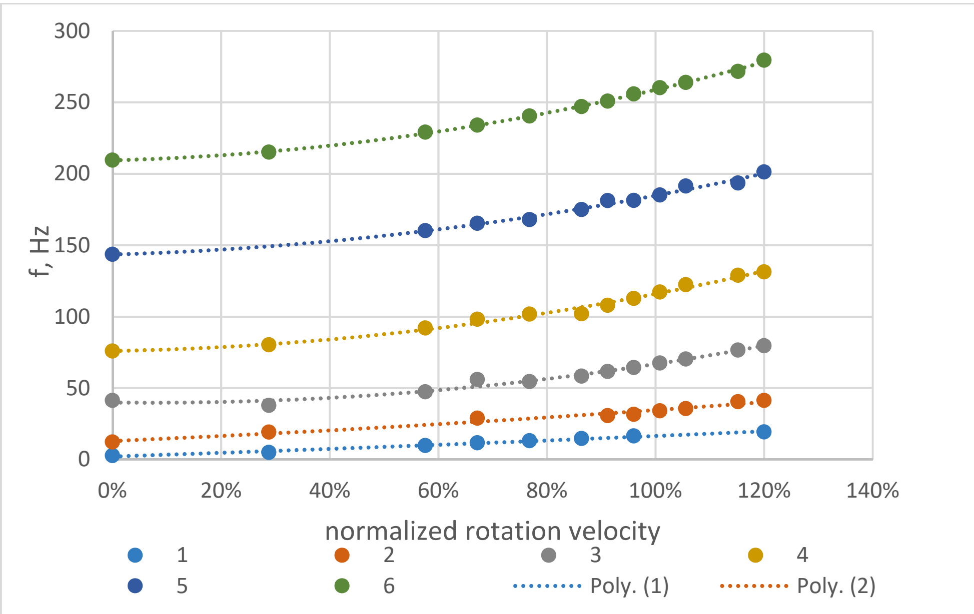
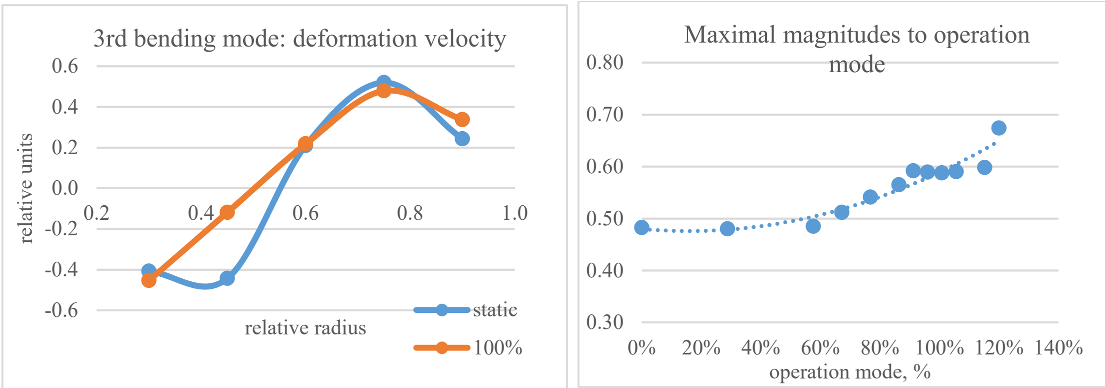


Fig. 4.11. Rotation velocity influence function on modal frequency.



a) b)

Fig. 4.12. (a) Modal shape deformation with rotation speed increase; (b) magnitude of the 3rd flapping mode as a function of operation mode.

The influence function for 6 bending modes of the blade (Fig. 4.11) can be used further for monitoring purposes. It is possible to perform OMA on the blade during rotation at any rotation velocity, then to recalculate estimated modal parameters to the reference state, which is 0 % or no rotation, static position. The recalculated modal parameters are then compared to previously obtained individual healthy modal parameters.

As one can see from Fig. 4.11, parameter values of the same mode vary for different rotation velocities. For instance, the 3rd bending mode significantly changes its properties under the impact of centrifugal load. The modal frequency increases from 41 Hz in a static position to 64 Hz at the nominal rotation speed, and the damping coefficient drops from 4.1 % to 0.6 %. At the same time, the modal deformation shape is modified, as it is illustrated in Fig. 4.12. Due to applied centrifugal forces the blade becomes stiffer, which increases the modal frequencies.

4.4. Laboratory model of a wind turbine

The current study sets forth the following tasks:

1. Validation of OMA methods applicability for the detection of modal parameter modifications.
2. Testing of multi-patch OMA approach for the reduction of necessary measurement channels.

During this study, the approach to taking into account natural conditions that could influence the precision of damage detection is tested. For this purpose, a wind turbine's laboratory model was designed and manufactured as a model of a typical structure with operating mechanisms.

The model is equipped with 28 deformation transducers allocated in 7 vertical levels, 4 sensors on each level. The piezo film sensors are paired with pre-amplifiers, which were proven unnecessary during later phases of the Thesis development. Each sensor is attached to the surface of the frame beams using adhesive tape. Transducer leads are soldered to the flat ribbon cable, stretching along the tower, curving around obstacles. Cables are terminated in the commutation box allowing signal grouping by patches.

The data processing system includes DAQ that is Brüel & Kjær PULSE 48 channel frame and a processing unit that is PC with *ARTeMIS* software platform.

While testing possible vibration excitation approaches, it was established that excitation of tower's modes is not suitable for OMA using purely the rotation of the rotor due to towers rigidity, limited frequency band of excitation, and periodic excitation.

For the current study, random impacts on the base of the model were used to provide excitation.

Modal parameter variation for a single condition

Variation of modal parameters in all tests was estimated using MPVI. Fig. 4.13 illustrates separate (frequency and shape) MPV values as well as combined ones (MPVI). *Base 1* and *Base 2* are two sessions of 5 repeated tests using simultaneous OMA. *MP* is a similar test but performed using multi-patch OMA. Multi-patch cases have scatter 1.5–2 times less than for simultaneous cases. Established MPVI values are used as a reference.

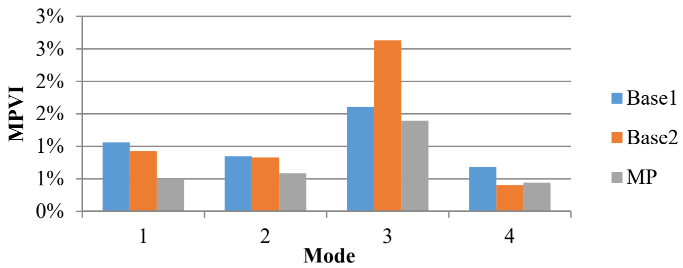
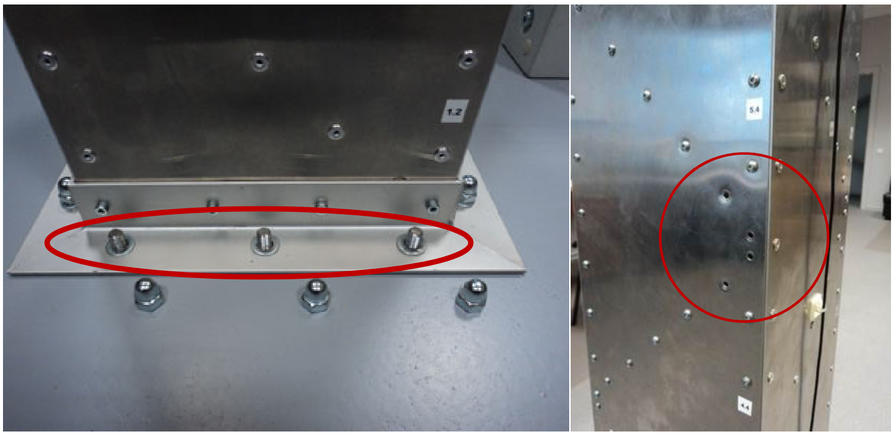


Fig. 4.13. Modal parameter variation integrated (MPVI) in three test series.

Damage detection

Experimental validation of the abovementioned techniques includes consequent implementation of two defects into the structure (defects are not mixed). The first defect – unscrewed nuts on the base are fixed on one side of the tower (Fig. 4.14 a)), marked here as Defect 1. This can be classified as a global defect because it alternates the boundary conditions of the system. The second defect is of a local nature – four unscrewed screws in one joint in the middle of the tower (Fig. 4.14 b)). These screws serve as connection between the frame and the panel, which means that local stiffness becomes alternated. This defect is marked as Defect 2. The tests aimed at damage identification were done using simultaneous OMA measurements only.



a) b)

Fig. 4.14. Artificial defects: (a) – Defect 1; (b) – Defect 2.

Table 4.3 shows comparison of MPVI parameters between baseline measurements (also shown in Table 1 as *Base 1*) and faulted states of the structure. Defects caused different changes in modal parameters. Fig. 4.15 displays combined MPVI values for all three states.

Table 4.3

Modal Parameter Scatter Obtained with MPVI for Baseline and Defected Conditions

Mode	f, Hz	Base 1			Defect 1			Defect 2		
		freq.	*shape*	*comb.*	*freq.*	*shape*	*comb.*	*freq.*	*shape*	*comb.*
1	67.0	0.8 %	1.37 %	1.06 %	4.4 %	2.49 %	3.44 %	0.6 %	1.66 %	1.11 %
2	205.7	0.4 %	1.26 %	0.85 %	2.3 %	2.03 %	2.18 %	0.1 %	1.73 %	0.93 %
3	324.1	0.3 %	2.95 %	1.61 %	0.4 %	5.16 %	2.76 %	0.2 %	6.50 %	3.32 %
4	532.1	0.7 %	0.72 %	0.68 %	1.3 %	2.78 %	2.04 %	0.5 %	1.51 %	1.01 %
Average		0.52 %	1.58 %	1.05 %	2.10 %	3.11 %	2.61 %	0.33 %	2.85 %	1.59 %

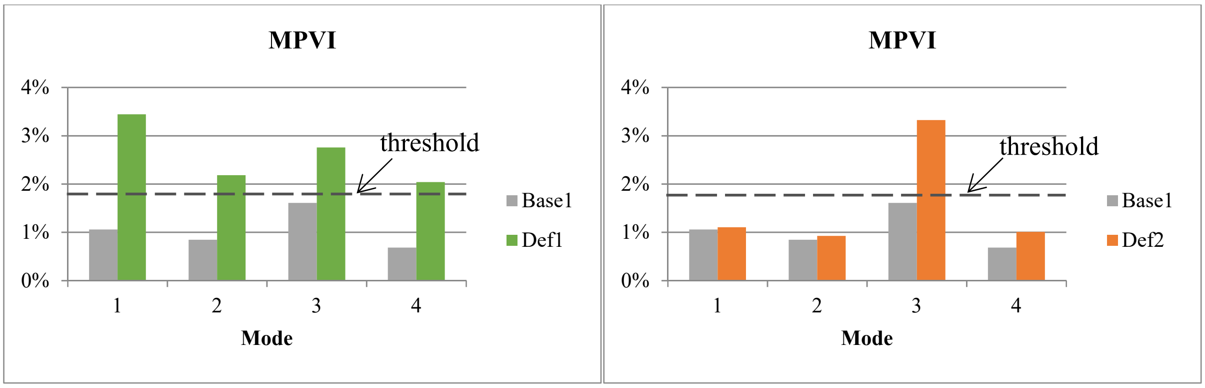


Fig. 4.15. MPVI parameters estimated for baseline and defected measurements.

Defect 1 resulted in modification of all 4 stable modes. This is a good indication that global changes in structural condition have occurred. Global modification of modal parameters is usually connected with the change of boundary condition. In practice it means that the structure's modification could be identified close to the base, and an inspection is needed for that part of the structure.

For the case of Defect 2, the shape's MPV value of the 3rd mode (6.5 %) clearly indicates that there is a problem with the structure. As MPVI value exceeds threshold only for the 3rd mode, it means that most probable damage location is the tower's central section where maximal deformations were found.

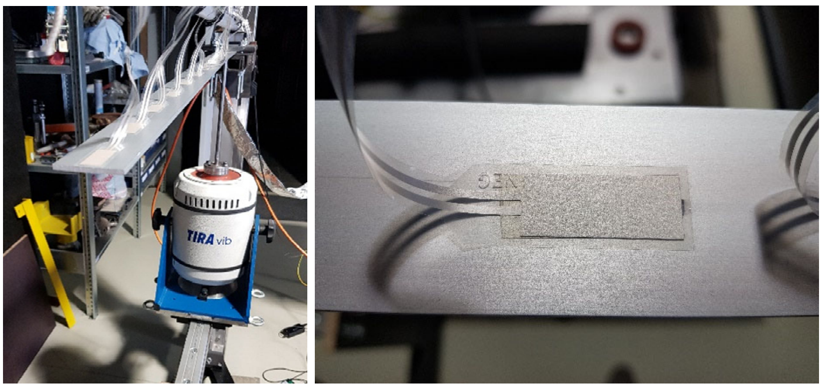
Case study conclusions

Modal parameter variation integrated together with mode shape visualisation are very handy for diagnostic purposes. An engineer with adequate understanding and experience can identify and localize defects by analysing MPVI and the mode shapes.

MPVI can be a convenient tool for SHM. When structures are measured with OMA technique, modal parameter estimation performed and MPVI parameter obtained, then this allows to analyse frequencies and mode shapes to potentially localize the damage. However, the severity of the damage can be evaluated only by careful inspection of a skilled and experienced engineer.

4.5. Aluminium beam

The goal of the experiment is to validate the modal field comparison method. This is done on a simple aluminium beam with one end fixed and another end free. The beam has a 3 x 40 mm rectangular cross-section. The length of the mounted beam is 850 mm, the weight is 275 g. 12 piezo film deformation sensors are used as vibration transducers (Fig. 4.16), which limits the identification of modes to first 6 bending modes. The beam is excited using a shaker and white noise signal.



(a) (b)

Fig. 4.16. a) Experimental setup; b) Piezo film deformation sensor.

To simulate the modification of the beam's structural condition, metal washers were used with different weights. The washers were glued to the middle of the beam. First, a heavy washer was fixed to the beam to test the detection of the condition change. Then, the washer was removed to validate if the MFCM parameter reflected the return to healthy reference values. Next, a sensitivity check was done using smaller washers with ascending weights.

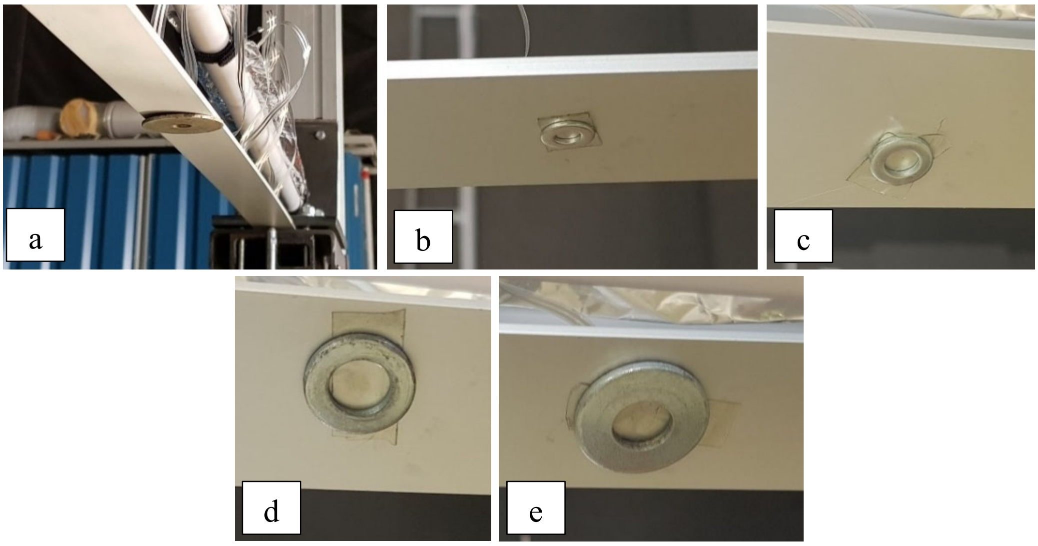


Fig. 4.17. Added masses, in order of application: a) 24 g; b) 0.3 g; c) 0.8 g; d) 2.9 g; e) 9.8 g.

The healthy reference baseline was formed as an average between first twenty measurements without added mass. Measurement results are related to the baseline and plotted in a bar plot, shown in Fig. 4.18. The mean value is 1, as the plotted parameter is normalized as in Eq. (23). The red line is three standard deviations value above the mean, which serves as damage detection threshold.

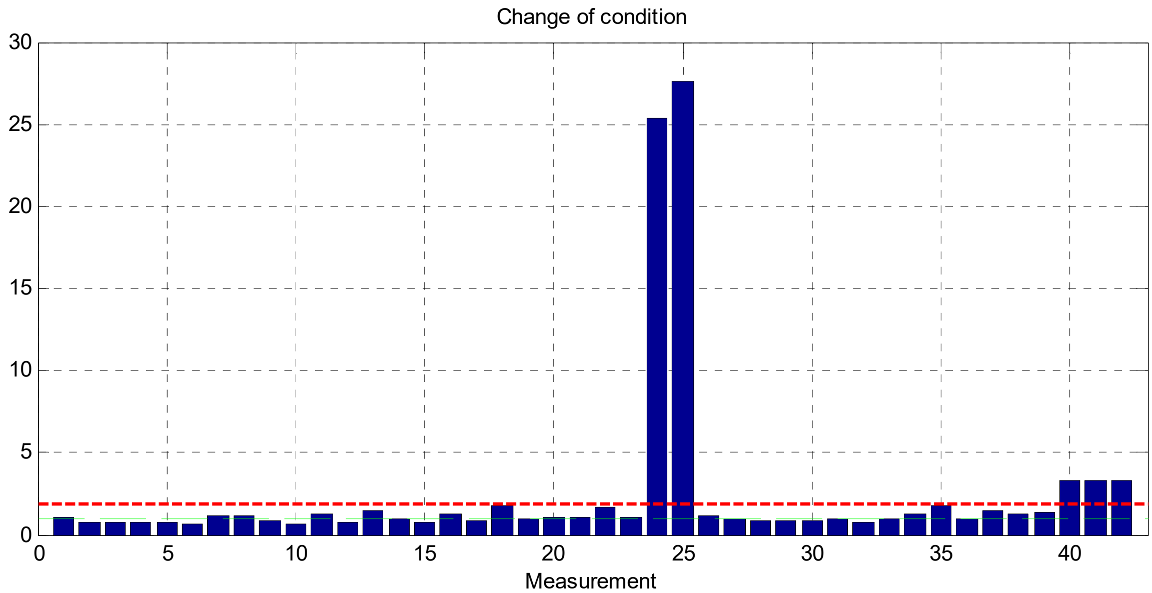


Fig. 4.18. MFCM parameter values for 42 experimental measurements.

It is obvious at a glance, that heavy washer (Fig. 4.17 a)) makes a considerable impact on the structure. This is shown as two bars with value above 25 for measurements 24 and 25. The fixed washer not only increases the mass by approximately 9 %, but also local stiffness. Sensitivity tests resulted in increased parameter only for the 9.8 g washer (Fig. 4.17 e)). All healthy condition MFCM values lie below the threshold, including the values estimated for measurements 21–23 and 26–31, which were not used for baseline calculation.

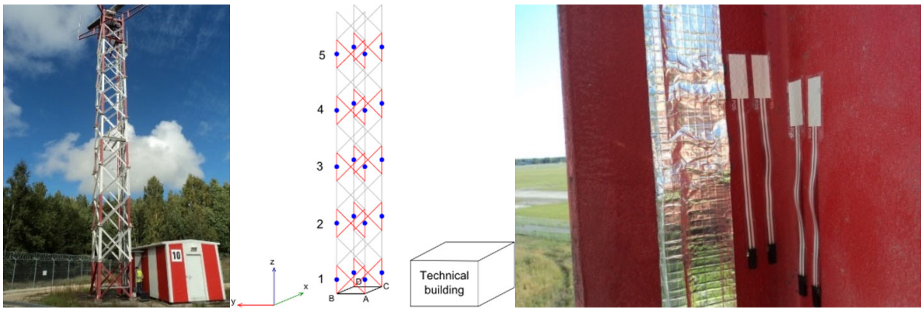
A notable parameter change has been achieved for mass change of approximately 3.6 % of the total beam mass and some undefined stiffness change.

4.6.Radar tower

The goal of this study is to validate the possibility to apply SHM for a full-scale industrial structure using the operational modal analysis based SHM system.

The structure under test is a radar tower in Riga airport (Fig. 4.19). It is 24 m high, with a rotating antenna on the top.

There are 20 measurement points on the tower placed in the corners of 5 horizontal sections (Fig. 4.19 b) and c) show the middle of the section corner, where sensors are installed. The placement is chosen on each side of the corner to register deformation in both directions. There are two sensors on each side, one is the main sensor, another is a reserve, in case the first one fails.



a) b) c)

Fig. 4.19. a) Radar tower; b) point locations (blue dots); c) single measurement point.

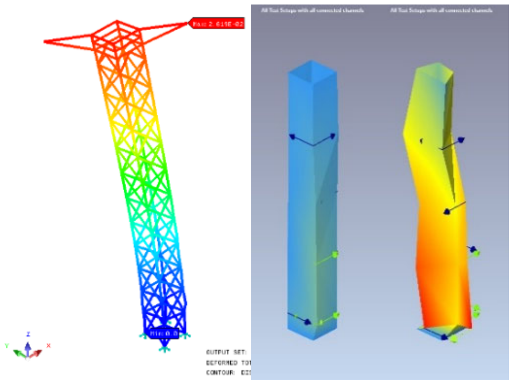
The sensors are paired with pre-amplifiers, which are inserted into the shielded ribbon cable (Fig. 4.19 c)). The cables are connected to the pathing panel (Fig. 4.20 a)). The patching panel allows connecting of the selected sensors to the input of DAQ unit (Fig. 4.20 b)).

a) b)

Fig. 4.20. a) Patching panel; b) data acquisition unit.

Experimental results

Fig. 4.21 shows modal shapes for the 1st bending mode. In Fig. 4.21 a), one can see the analytical 1st bending displacement shape in Y direction, Fig. 4.21 b) shows the tower geometry in steady state for comparison, and Fig. 4.21 c) shows the experimental 1st bending strain mode shape. The latter is a combined shape for bending shapes in X and Y direction. The shape is estimated as combined because the frequency resolution in OMA estimation is not fine enough to be able to separate two closely spaced modes. Also, due to periodic antenna excitation, the tower oscillation shape has torsional movement around its axis. This is observed for most shapes, not only the 1st bending one. Note, that experimental shapes show local deformation (strain) caused by stress, which is inversely proportional to displacement in the analytical results (see Section 4.1). This once again proves the possibility to use deformation signals for OMA as an alternative to acceleration.



a) b) c)

Fig. 4.21. a) Analytical 1st bending; b) experimental steady state; c) experimental 1st bending.

Table 4.4 shows the comparison of modal frequencies between the experimental and analytical results. Differences can also be explained by the fact that the frame sections in the technical project were 4 m high. The measurement of the real section showed 3.6 m. Full measurement of the real tower dimensions was not feasible, so the difference between the model and the object remained.

Table 4.4

Comparison of Modal Frequencies

Analytical			Experimental	
Mode	f, Hz	Shape	Mode	f, Hz
1	1.92	1st bending	1	2.21
2	2.14	*pair*		
5	12.11	2nd bending	4	12.84
6	12.76	*pair*		
8	16.47	1st torsional	6	16.93

Discussion on experimental SHM system in industrial environment

The developed experimental measurement system has turned out to be cost-efficient, as the used materials are widely accessible and inexpensive. Multi-patch OMA approach has proven to be applicable using the measurement system.

One month after the experiment the system was checked, and OMA measurements were repeated. Unfortunately, some of the system channel signals were corrupted. There was either low and noisy signal transmission, or no vibrational signal at all. Measurement network troubleshooting was done, which did not reveal connectivity problems. It is believed that environmental conditions had a strong impact on transducer's preamplifiers. Two particular causes are:

- humidity can create short circuit in the preamplifier;
- strong electromagnetic field could damage field-effect transistors (FET) in the preamplifier.

Condensed water was observed around the preamplifier after opening that area, which means that the cable was not sealed well enough. In laboratory conditions it was also observed that preamplifiers sometimes failed after touching them with bare hands, which could lead to static voltage discharge and FET damage.

It is obvious, that the weakest part of the prototype is the preamplifier. Other studies done within the scope of the Thesis showed that preamplifiers are not needed for applications in 3–4 m, or even more. It remains uncertain, however, whether piezo film sensors can provide a strong signal in tens of meters without preamplification.

5. CONCLUSIONS

The aim of the presented Thesis was to develop a SHM system technology for structures during their operation. The technology is based on the system identification using operational modal analysis taking into account the conditions of the structure's operation. Within the scope of the Thesis these conditions were different forces in the form of loads acting on the structure, e.g. different rotation speed for a helicopter blade model. As the result, a novel SHM system was developed and tested on 4 structures of different complexity and size.

The process of SHM system development and usage for a selected structure is shown in Chapter 2 in a form of a road map. These steps include:

- Mechanical procedures: sensors' installation, wiring, setting up data acquisition system and computer with OMA software.
- Measurement procedures: performing measurement of vibrational responses and registering operational conditions – loads, rotation velocity.
- Methodological procedures: harmonics extraction, modal parameter estimation, application of modal passport, and damage detection.

The main technological solution presented in the Thesis is the application of piezo film deformation sensors, which successfully substitute accelerometers as sensors for measurement of vibration signals.

Piezo film deformation sensors measure directly the stretching/compression longitudinal deformations of the surface layer. These sensors are very thin (only 28 μm), they have negligible mass and low costs that allows using large number of sensors to obtain modal data while making much smaller distortions in mechanical and aerodynamic properties of the object. Sensors and wiring allow to be wrapped by a thin protective layer, making a homogenous entity with the structure. Piezo films do not require balancing as conventional resistive strain gauges.

The comparison of mode shapes obtained using accelerometers and piezo film sensors proved the validity of theoretical foundation that surface deformations, which arise during vibration of the structure are related to the vibration displacement, and thus also to acceleration, which is conventionally used in OMA. Tests on a beam like structure (helicopter blade) showed that for bending modes, the deformation shape of the blade is shifted by 180° in relation to the shape of displacement, which shows that the 2nd spatial derivative of displacement shape correlates with deformation shape.

A harmonics extraction algorithm from vibrational responses of a structure with periodical excitation component was proposed and experimentally validated on composite helicopter blades. Extraction of these components cleared out the structural responses and decreased the influence of periodic parts of the signal, allowing to expose hidden modes, which increased overall quality of the modal analysis. There was an improvement in terms of decreased modal complexity by 5.5% for 3 modes out of 10, which were especially affected by periodic components.

Additionally, comparison of structural responses and estimated modal parameters before and after harmonics extraction is useful for in-depth analysis of the structure's condition.

In Section 3.3, modal field comparison method was introduced. This method is very useful for pre-analysis of measured structural responses without the need to estimate modal parameters. As the result, the method can identify a measurement which shows modification of structural properties, whether it is a mass increase or stiffness change induced by damage.

Tests on the aluminium beam with washers as additional masses showed the following. The reference state value of the MFCM parameter is 1, whereas the healthy state threshold is at 1.9 units. A notable parameter change (MFCM value around 3.36 units) has been achieved for a mass change of approximately 3.6 % of the total beam mass and some undefined stiffness change. It was observed that the washer's weight on the beam increases by2.5 times (from 9.8 g to 24 g) resulting in the parameter value increase approximately by 8 times (from 3.36 to 25–27 units).

The disadvantage of MFCM is that it does not take into account variability in external conditions, so extra load or temperature change will potentially sound a false alarm. However, this disadvantage is dealt with by introduction of modal passport.

Modal passport is a framework for modal parameter assessment between multiple measurements of a structure with different operating conditions. It is both a database for storing existing measurement data (modal parameters and external influence factors) and a set of tools realized in *Excel* or *Matlab*. The main damage assessment tool is the modal parameter variation and its integrated version MPVI. It uses straightforward arithmetical calculations to assess modal frequencies and mode shapes between different measurements.

MPV was successfully implemented for damage detection of a global defect on the mentioned WT model foundation and a local defect on the structure's side. The global defect resulted in MPV values of 3.4, 2.2, 2.8 and 2 % for Modes 1–4, accordingly, which was above the 1.8 % healthy state reference level. At the same time, local defect resulted in MPV values of 1.1, 0.9, 3.3 and 1 % for Modes 1–4, accordingly, which shows that only the Mode 3 MPV signalizes changes in modal parameters. By observing this mode's shape, it was possible to draw conclusions on the location of the defect.

It was shown, that SHM can be done also using a multi-patch OMA, which is an effective way to save costs. Another advantage of the multi-patch OMA is the fact that the system receives more excitation energy due to longer measurement time, which stabilizes the MPV parameter for the reference state. This allows for higher damage detection precision in later stages. Tests on a wind turbine laboratory model showed that multi-patch OMA results in 1.5–2 times lower initial MPV parameter values compared to simultaneous OMA measurements.

The framework of modal passport simplifies different research and industrial procedures related to modal analysis, as illustrated in the results of composite blade testing in Section 4.3. It allows identification of vibration/deformation modes of an individual structure using the data independent from test or operation conditions. For instance, data measured in winter or summer, of fixed or rotating structure, maximally loaded or in idle mode could be used.

In order to predict the change of an individual structure's properties as a function of some operational factor, one does not need to study the behaviour of a particular blade. It is enough to have only its modal parameters in some state and then use the influence functions of typical modal passport on the above operational factor.

The presented set of technological and methodological solutions is combined into a structural health monitoring system prototype for usage during varying operational conditions. The underlying technology would benefit from further research, particularly in application of modal passport for different structures and testing of temperature influence on modal parameters, which was not within the scope of this Thesis. There is a research project going on, which tests the proposed SHM system on a set of glass fibre composite cylinders, together with temperature tests, apart from everything else.

REFERENCES

[1] Y. Lin, L. Tu, H. Liu, and W. Li, “Fault analysis of wind turbines in China,” *Renewable and Sustainable Energy Reviews,* vol. 55, pp. 482–490, 2016.

[2] “Sāremā salā nolūzusi un apgāzusies 60 metru augsta vēja turbīna,” Apollo.lv, 16 Febraury 2022. [Online]. Available: https://www.apollo.lv/7455790/sarema-sala-noluzusi-un-apgazusies-60-metru-augsta-veja-turbina. [Accessed 15 March 2022].

[3] “This Day in the Aviation History – On April 1, 2011, Southwest Airlines Flight 812 suffered rapid depressurization due structural failure,” FL360aero, 1 April 2021. [Online]. Available: https://fl360aero.com/detail/this-day-in-the-aviation-history-on-april-1-2011-southwest-airlines-flight-812-suffered-rapid-depressurization-due-structural-failure/155. [Accessed 15 March 2022].

[4] H. F. Zhou, H. Y. Dou, L. Z. Qin, Y. Chen, Y. Q. Ni, and J. M. Ko, “A review of full-scale structural testing of wind turbine blades,” *Renewable and Sustainable Energy Reviews,* vol. 33, p. 177–187, 2014.

[5] B. Chen, S. You, Y. Yu and Y. Zhou, “Acoustical damage detection of wind turbine blade using the improved incremental support vector data description,” *Renewable Energy,* vol. 156, pp. 548–557, 2020.

[6] R. Yang, Y. He, and H. Zhang, “Progress and trends in nondestructive testing and evaluation for wind turbine composite blade,” *Renewable and Sustainable Energy Reviews,* vol. 60, p. 1225–1250, 2016.

[7] HBM, “Structural Health Monitoing | HBM,” [Online]. Available: https://www.hbm.com/en/5530/structural-health-monitoring/?product_type_no=Structural%20Health%20Monitoring. [Accessed 24 May 2022].

[8] SGS, “Structural Health Monitoring | SGS,” [Online]. Available: https://www.sgs.com/en/industries-and-environment/power/asset-integrity-management-services/non-destructive-testing-ndt/structural-health-monitoring. [Accessed 24 May 2022].

[9] C. P. Fritzen, “Vibration-Based Structural Health Monitoring – Concepts and Applications,” *Key Engineering Materials,* Vols. 293–294, pp. 3–20, 2005.

[10] N. M. M. Maia and J. M. M. Silva, Theoretical and Experimental Modal Analysis, Wiley, 1997.

[11] C. Ventura and R. Brincker, Introduction to Operational Modal Analysis, Wiley, 2015.

[12] M. Döhler, P. Andersen, and M. Mevel, “Data Merging for Multi-Setup Operational Modal Analysis with Data-Driven SSI,” in *Proceedings of the IMAC-XXVIII*, Jacksonville, Florida USA, 2010.

[13] L. Zhang, T. Wang, and Y. Tamura, “A frequency–spatial domain decomposition (FSDD) method for operational modal analysis,” *Mechanical Systems and Signal Processing,* vol. 24, no. 5, pp. 1227–1239, 2009.

[14] M. Döhler, E. Reynders, F. Magalhaes, M. Mevel, G. De Roeck, and A. Cunha, “Pre- and Post-identification Merging for Multi-Setup OMA with Covariance-Driven SSI,” in *Proceedings of the IMAC-XXVIII*, Jacksonville, Florida USA, 2010.

[15] L. Zhang, M. Boeswald, D. Goge, and H. Mai, “Application of Operational Modal Analysis for Wind-Tunnel Testing of an Aircraft Wing Model with Control-Surface,” in *IMAC XXVI conference*, Orlando, Florida, 2008.

[16] E. Neu, F. Janser, A. A. Khatibi, C. Braun, and A. C. Orifici, “Operational Modal Analysis of a wing excited by transonic flow,” *Aerospace Science and Technology,* vol. 49, pp. 73–79, 2016.

[17] M. L. Wymore, J. E. Van Dam, H. Ceylan, and D. Qiao, “A survey of health monitoring systems for wind turbines,” *Renewable and Sustainable Energy Reviews,* vol. 52, pp. 976–990, 2015.

[18] S. Chauhan, “Parameter estimation algorithms in operational modal analysis: a review,” in *6th International Operational Modal Analysis Conference*, Gijon, Spain, 2015.

[19] E. Bechhoefer and M. Kingsley, “A Review of Time Synchronous Average Algorithms,” in *Proceedings of the Annual Conference of the PHM Society 2009, Vol. 1, No. 1*, 2009.

[20] F. B. Zahid, Z. C. Ong, and S. Y. Khoo, “A review of operational modal analysis techniques for in-service modal identification,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* vol. 42, no. 398, 2020.

[21] D. Mironovs and S. Chauhan, “Modal Parameter Estimation in multi-patch Operational Modal Analysis: Perspectives and Approaches,” in *35th International Modal Analysis Conference*, Garden Grove, California, USA, 2017.

[22] Measurement Specialties, Inc., “Piezo Film Sensors Technical Manual,” Norristown, PA, 1999.

[23] M. Electronics, “Vibration Sensors DT2-028K W/RIVETS,” Measurement Specialties, [Online]. Available: https://eu.mouser.com/ProductDetail/Measurement-Specialties/1-1003744-0?qs=sGAEpiMZZMs29kr3d%252BndI2Ss0dvAm%252B%252B8smsI%2Fyg21D0%3D. [Accessed 28 February 2022].

[24] A. K. Pandey, M. Biswas, and M. M. Samman, “Damage detection from changes in curvature mode shapes,” *J. Sound Vib.,* vol. 145, pp. 321–332, 1991.

[25] A. Deraemaeker, “On the use of dynamic strains and curvatures for vibration based damage localization,” in *Proceedings of the 5th European Workshop on Structural Health Monitoring*, Sorrento, Italy, 2010.

[26] Y. Gu, L. Long and P. Tan, “Surface strain distribution method for delamination detection using piezoelectric actuators and sensors,” in *Proceedings of 9th International Conference on Damage Assessment of Structures*, Oxford, UK, 2011.

[27] E. Neu, F. Janser, A. A. Khatibi, and A. C. Orifici, “Fully Automated Operational Modal Analysis using multi-stage clustering,” *Mech. Syst. Signal Pr.,* vol. 84, pp. 308–323, 2017.

[28] S. Ručevskis, T. Rogala, and A. Katunin, “Optimal Sensor Placement for Modal-Based Health Monitoring of a Composite Structure,” *Sensors,* vol. 22, no. 10, 2022.

[29] D. Solovyev, S. Dadunashvili, A. Mironov, P. Doronkin, and D. Mironovs, “Mathematical Modeling and Experimental Investigations of a Main Rotor Made from Layered Composite Materials,” *Mechanics of Composite Materials,* vol. 56, no. 1, pp. 103–110, 2020.

[30] A. Mironov, P. Doronkin, A. Priklonskiy, and I. Kabashkin, “Structural Health Monitoring of rotating blades on helicopters,” *Aviation,* vol. 20, pp. 110–122, 2016.

[31] M. Derriso, C. McCurry, and C. Chubert Kabban, “2 – A novel approach for implementing structural health monitoring systems for aerospace structures,” in *Structural Health Monitoring (SHM) in Aerospace Structures*, Woodhead, 2016, pp. 33–56.

[32] D. Balageas, C.-P. Fritzen, and A. Güemes, Structural Health Monitoring, Hoboken, New Jersey: Wiley & Sons, 2006.

[33] "Annual Analyses of the EU Air Transport Market 2016," European Comission, 2016.

[34] M. Luo, H. Huo, D. Axinte, and D. S. Liu, "A wireless instrumented milling cutter system with embedded PVDF sensors," *Mechanical Systems and Signal Processing,* vol. 110, p. 556–568, 2018.

[35] T. Bregar, B. Starc, G. Čepon and M. Boltežar, "On the Use of PVDF Sensors for Experimental Modal Analysis," in *Topics in Modal Analysis & Testing, Volume 8, Proceedings of the 38th IMAC, A Conference and Exposition on Structural Dynamics 2020*, Cham, Springer, 2020.

[36] Y. Xin, H. Sun, H. Tian, C. Guo et al., "The use of polyvinylidene fluoride (PVDF) films as sensors for vibration measurement: A brief review," *Ferroelectrics,* vol. 502, no. 1, pp. 28–42, 2016.

[37] TE connectivity, "Piezoelectric Sensors," TE connectivity, [Online]. Available: https://www.te.com/usa-en/products/sensors/piezo-film-sensors.html?tab=pgp-story. [Accessed 1 June 2022].

[38] D. Liu, M. Luo, Z. Zhang, and Y. Hu, "Operational modal analysis based dynamic parameters identification in milling of thin-walled workpiece," *Mechanical Systems and Signal Processing,* Vols. 167, Part A, no. 108469, 2022.

[39] E. L. Oliveira, N. M. M. Maia, A. G. Marto, R. G. A. da Silva et al., "Modal characterization of composite flat plate models using piezoelectric transducers," *Mech. Syst. Signal Pr.,* vol. 79, pp. 16–29, 2016.

[40] Measurement Specialties, Inc., "SDT Shielded Piezo Sensors, Technical Data," 2009.

[41] J. M. Ha et al., "Autocorrelation-based time synchronous averaging for condition monitoring of planetary gearboxes in wind turbines," *Mechanical Systems and Signal Processing,* Vols. 70–71, pp. 161–175, 2016.

[42] M. D. Coats, N. Sawalhi, and R. B. Randall, "Extraction of tacho information from a vibration signal for improved synchronous averaging," in *Proceedings of ACOUSTICS 2009*, Adelaide, Australia, 2009.

[43] R. Janeliukstis, R. Riva, E. Di Lorenzo, M. Luczak et al., "Comparison of wind turbine blade models through correlation with experimental modal data," in *Proceedings of ISMA and USD, International Conference on Noise and Vibration Engineering and International Conference on uncertainty in Structural Dynamics*, Belgium, Leuven, 2020.

[44] D. J. Ewins, "Model validation: Correlation for updating," *Sadhana,* vol. 25, pp. 221–234, 2000.

[45] C. Devriendt, F. Presezniak, G. De Sitter, K. Vanbrabant et al., "Structural health monitoring in changing operational conditions using transmissibility measurements," *Shock Vib.,* vol. 17, pp. 651–675, 2010.

[46] A. Güemes, A. Fernandez-Lopez, A. R. Pozo,structure and J. Sierra-Pérez, "Structural Health Monitoring for Advanced Composite Structures: A Review," *Journal of Composites Science,* vol. 4, no. 1, 2020.

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