Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 1918-1928

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

CHALLENGES TO OVERCOME OBSTACLES IN THE APPLICATION OF STRUCTURAL HEALTH MONITORING

CHRISTIAN BOLLER

LZfPQ
Universität des Saarlandes
Am Markt Zeile 4, 66125 Saarbrücken, Germany
email: c.boller@ mx.uni-saarland.de

Abstract. Smart technologies need a platform of demonstration to allow them to get applied and to serve a market. One of those smart technologies, where a remarkable market should be expected is Structural Health Monitoring (SHM). Despite decades of intense research and development much more application should have been expected and the question that arises is: Why is application in SHM still so limited? An assumption made as an answer to this question are the diverse elements leading to a process chain along the design and life cycle of an engineering product and where SHM has all an impact in. This impact needs to be shown on true demonstrators and this possibly with respect to the SHM technology's evolution. SHM related demonstrators so far have been mainly related to a specific R&D project, realized towards a project's end and easily forgotten after the project's completion. This paper describes an initiative launched recently, where a set of SHM related demonstrators, possibly even from past projects are made available to a broader community and over a longer term. The outcome of and hence progress through this initiative is a wider usage of demonstrators in view of overcoming various of the obstacles preventing SHM to be brought into a wider application, will be consecutively reported and demonstrated at scientific events and possibly even trade fairs, hopefully allowing its target to be met.

Key words: Structural health monitoring; technology demonstration; sensors; application

1 INTRODUCTION

Research and development of Structural Health Monitoring (SHM) has been around for decades now. SHM as an explicit field has been discussed since around thirty years. However, what SHM claims to perform may have emerged much earlier. Aviation has been a significant technology driver in the past, specifically when it comes to the design of engineering structures. The biggest milestone in the design of aerostructures ever made has possibly been in the development and realization of the De Havilland Comet airplane, where besides a pressurized fuselage and jet engines the damage tolerance principle has been introduced in a civil transport aircraft. Consequences of this development have been well described and discussed, and resulted in aircraft loads monitoring systems to be realized, flight load spectra to be generated and major airframe fatigue tests to be performed as a requirement, all in view

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9961.451325

to allow civil aviation to operate as safe as it does today, irrespective of the damage tolerance principle being applied as a means for light weight design and its resulting need for non-destructive testing (NDT). The tolerance of damage in a structure in operation is an issue difficult to be understood and the resulting inclusion of NDT along the structure's operation can become a laborious and costly process. Smart structures' technologies emerging in the late 1980ies as well as the inclusion of advanced materials such as composites into structural design have opened expectations on how to get the NDT-based inspection process within a damage tolerant designed structure automated by getting sensing devices and hence NDT to become an integral part of those structures. Incubating this thought into structural design and realization has been where the expression of SHM has come into play and where predictions were made, that SHM would become a multi-billion € business within a few years. However, after around 30 years those predictions are far from having been met and the question arises, why this expectation has not been met and what might be a solution to get SHM better applied in the longer term. Throughout the following an insight into different observations made with respect to SHM applications in the fields of aviation, wind energy generation and civil engineering are given. However, prior to this the breadth of an engineering structure's life cycle management process will be illustrated including the role of SHM before explaining that successful SHM applications are driven by business opportunities and a holistic view regarding the structure's life cycle management process. This may only be achieved successfully if this process is adequately 'orchestrated'.

2 PROCESS CHAIN FOR STRUCTURAL INTEGRITY ASSURANCE

Structural integrity is a must in structural engineering design. Assurance of this integrity is based on various input criteria and adequate safety factors, that have to cover any uncertainties the structural design might be associated with. To adequately design a structure the operational loads the structure might be exposed to need to be known. As a next step the distribution of stresses and strains within the structure need to be determined. This requires a link to materials data, would those be related to simple tensile strength, fatigue, fracture, corrosion, or even other phenomena. Damage is an expression used widely, that needs a quantifiable scale in case it should be considered in engineering terms. Usually, damage is considered in terms of materials separation and hence as a crack. However, the existence of a crack does not automatically mean that a structure's integrity is impaired. It is rather which crack size can be tolerated without impairing the structure's integrity.

To allow cracks (damage) to exist at a tolerable level is what has been applied in aeronautical structures as damage tolerance design in terms of lightweight design with success. However, this design is not limited to lightweight design only but can be also used for the assessment of a structure's operational life extension. The price of such a gain is the availability of prognostic tools as well as tools for inspection, which may require the inspection process to be automated through integrated sensing in the sense of SHM.

Trying to describe the above process as a process chain may lead to a sequence as shown in Fig. 1 below. This process chain defining the frame of SHM includes a variety of hardware but also software tools. It starts with sensors allowing real operational load sequences on the engineering structure considered to be monitored. It further requires the stresses, strains and possibly other parameters within the structure to be determined and this favorably through numeric analysis such as FE. The information generated will allow prognostics to be performed on the basis of fatigue life evaluation as to when a crack is to be expected and at which size. All of this will also allow to predict the damage (crack) mechanism to evolve, which builds the basis on what damage needs to be detected reliably. Based on such evaluations finally an SHM system can be configured, that then will have to be realized in hardware in the end.

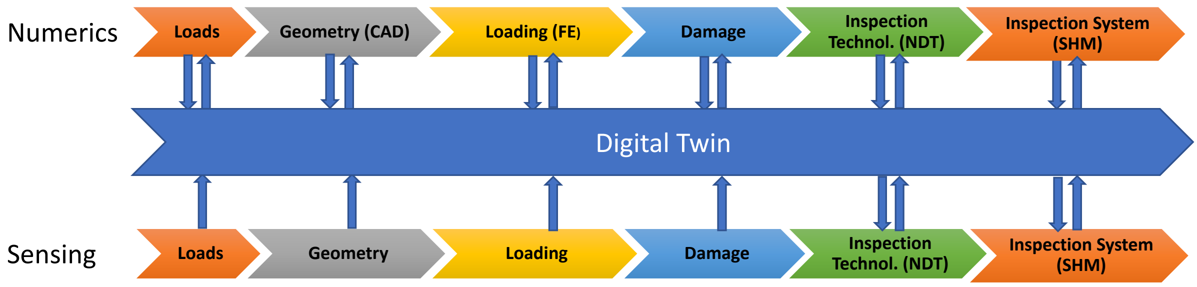


Figure 1: Process chain of holistic life cycle management in view of SHM

What is to be seen from this extensive process chain depicted in Fig. 1 is, that this can be virtually performed on a fully numeric basis. In that case it first allows to demonstrate what might be possible with respect to an engineering structure's enhanced life cycle management using smart technologies within the frame of SHM. To get this applied requires sensors and sensing systems to be integrated into those structures. In each of the process steps a large number of data may be generated that may allow this data to be merged to a digital twin. This exciting opportunity being widely discussed today but possibly not fully realized so far may be given here in case manageable demonstrators could be made available.

Such demonstrators do indeed exist and specifically with respect to SHM. Numerous research projects have been performed over the past decades [1] with different foci of application, which might be an interesting source to make those demonstrators available for a longer-term technology demonstration in the sense of the process chain shown in Fig. 1. As a consequence, an initiative has been started in Germany, which will look into potential opportunities and which is described in the following.

3 THE ‘SHM INTO APPLICATION!’ DEMONSTRATOR PLATFORM NETWORK

The initiative ‘SHM into Application!’ to get an SHM demonstrator platform established has been driven by the observation that SHM related technologies have still not achieved the breadth of application one would have expected in the past. Many of the applications shown and often even being very successful do focus on specific applications such as monitoring of loads, vibrational modes or cracks. However hardly a holistic approach regarding an engineering structure’s integrity assessment has been achieved so far, compiling the wide range along a structure’s life cycle starting from loads monitoring and ending with SHM system solutions including a digital twin. This lack of demonstration is due to the fact, that this could hardly be achieved within the frame of one of the conventional past R&D projects. However, with the availability of different SHM demonstrators realized and made available, the scope of those demonstrators could be possibly enhanced such that the broader potential of SHM could be demonstrated. Furthermore various technology updates and enhancements that may have occurred since the demonstrators’ realization or may emerge in the future could be demonstrated as well in continuation of past achievements.

This search for demonstrators has been started in Germany and in excess of the authors’ activities the following institutions have been able to provide inputs:

- Bundesanstalt für Materialforschung und -prüfung (BAM) in Berlin (Dr. Ernst Niederleithinger and Dr. Jens Prager)
- Technical University Clausthal jointly with Deutsches Zentrum für Luft- & Raumfahrt (DLR) in Braunschweig (Prof. Peter Wierach)
- Goethe University in Frankfurt/M. (Dr. Jochen Moll)
- Technical University Munich (TUM) (Prof. Christian Grosse).

To additionally explore if potentials also do exist on an international basis, the following institutions have been invited an agreed to participate:

- AGH University of Science and Technology in Cracow/Poland (Prof. Wieslaw Staszewski and Prof. Tadeusz Uhl)
- Korean Advanced Institute of Science and Technology (KAIST) in Daejeon/South Korea (Prof. Hoon Sohn)
- Missouri University of Science and Technology, Rolla/MO, USA (Prof. Genda Chen)
- Stanford University, in Stanford/CA, USA (Prof. Fu-Kuo Chang)
- University of Patras, Patras/Greece (Prof. Dimitris Saravanos).

This selection of institutions and people is not limited but has rather shown, that already with a limited number of participants a remarkable number of demonstrators have been identified that have allowed this initiative to give it a start. What is currently thought of regarding this initiative can be structured as follows:

- Summarize a description of the different demonstrators in terms of their objective, available sensors and data, and conditions of availability of the demonstrators for external parties.
- Get the information of demonstrator availability accessible to a general public in science and technology including industry to encourage potential SHM technology providers to get their technologies demonstrated in a broader scope and context.
- Allow SHM technology providers to take data on demonstrators mutually agreed, provided that at least the results are published if not even the data being made available for further research.
- Present progress achieved within the network at various of the international scientific conferences and possibly even trade fairs organized as special sessions or maybe even mini-symposia.

A first status of the activities in that regard is given with this paper. What can be described at present are the demonstrators proposed, which is done as to the below.

4 DEMONSTRATORS CURRENTLY CONSIDERED

So far 13 demonstrators have been proposed which cover the fields of aerospace, civil engineering, wind energy, additive manufacturing, and a guided waves database. These are briefly described in the following.

4.1 Aerospace

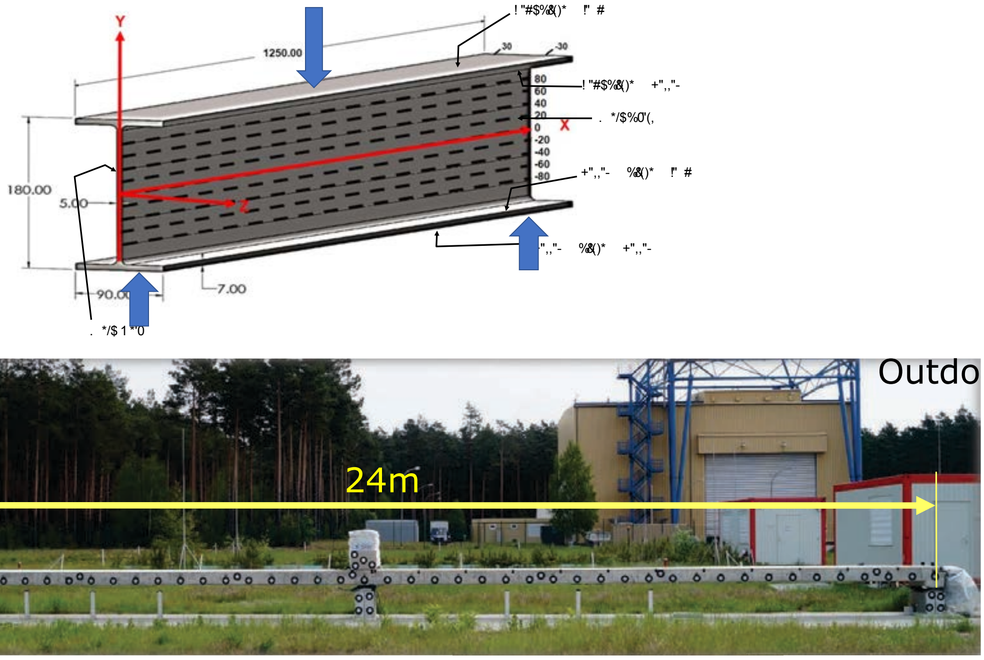
DLR is making two demonstrators available, which are shown in Fig. 2.

Figure 2: Aerospace related demonstrators: fuselage section of an Airbus A350 type (left) and composite air brake (right)

The Airbus A350 type fuselage section is a full-scale hardware demonstrator of a complex structure mainly made from CFRP and added by a variety of aluminum fittings. It is equipped with a huge network of piezoelectric transducers, which are integrated/adapted into/onto the structure at damage critical locations, allowing acoustic waves, and here specifically guided ultrasonic waves, to be used for the monitoring purpose. Data have been recorded but much more opportunities are to be sought which might allow SHM databases for the analysis of large data sets and the development of robust algorithms for damage detection based on machine learning to be established. The composite air brake with artificial flaws has been used to record data with different NDT techniques such as with thermography and to get those visualized on a virtual reality basis and this possibly also near to real time.

HI=}KLKM)-NOKN551KNO)

Monitoring has become of increasing interest in civil engineering. A large motivation is driven by the ageing infrastructure. However, also the exploration of more severe conditions would they be in terms of loads applied or the infrastructure's site have become of increasing relevance. Three demonstrators have been proposed, two of them on the basis of infrastructure components, as shown in Fig. 3 and provided by BAM and Saarland University and the third as robotic systems for monitoring civil engineering structures shown in Fig. 4 provided by Missouri S&T University [2].



! '#$%&:' Civil engineering demonstrators: steel beam under 3-point bending (top) and reinforced concrete beam with variable loading (bottom)

For the 3-point bent beam a variety of data has been generated including a visual 3D scan of the geometry, ultrasonic stress measurements and a variety of magnetic measurements allowing the material's condition to be assessed. The data is stored in a database such that the data formats are compatible to be used in the sense of a digital twin in the end.

The concrete beam shown in Fig. 3 is going to be made available shortly and can be equipped with a variety of sensors would those monitor loads, deformation or any type of degradation (cracking, corrosion, etc.). To get this established the structure can be exposed to variable loads representing traffic loads occurring in practice.

The robotic systems shown in Fig. 4 do include crawlers as well as micro aerial vehicles being equipped with a variety of different sensing techniques including visual, thermal, radar and possibly others.

Figure 4: Different types of robotic systems for automated remote inspection [2]

4.3 Wind Energy

Wind energy and specifically its power plants have become an attractive field for SHM application. Already 4 cases of demonstration have been put forward for the current initiative. They do include different types of sensors integrated in wind energy powerplants such as for monitoring ultrasonic guided waves and performing modal analysis (TU Clausthal jointly with DLR) [3], radar-based systems (Goethe Univ.) for monitoring the vibrational behavior of rotor blades [4] and the integrity of grouted joints [5], or loading on wind energy towers including monitoring of acceleration, temperature, strain, tilt, velocity or real time kinematics and feeding the data into digital models in the sense of a digital twin [6]. All of those demonstrators do provide data recorded from a variety of different sensors, that can be made available for further analysis as well as possibly merged in case circumstances allow. A longer-term option might also be to allow for further sensors to be installed in view of validation and benchmarking. Fig. 5 provides a view on some of the examples.

4.4 Additive Manufacturing

A very special demonstrator and possibly also quite unique is one provided by KAIST in South Korea [7]. It is related to monitoring the manufacturing process and hence the quality of additively manufacturing components using a thermographic and a laser ultrasonic system, which are used for retrieving the required information through splitters along the laser beam used for manufacturing. Besides the component's dimensions, the parameters being determined locally include Young's modulus, Poisson's ratio, porosity and possibly more. Parties being interested are invited to get in contact with KAIST and get their conditions for additive manufacturing exchanged and possibly validated in the respective equipment at KAIST.

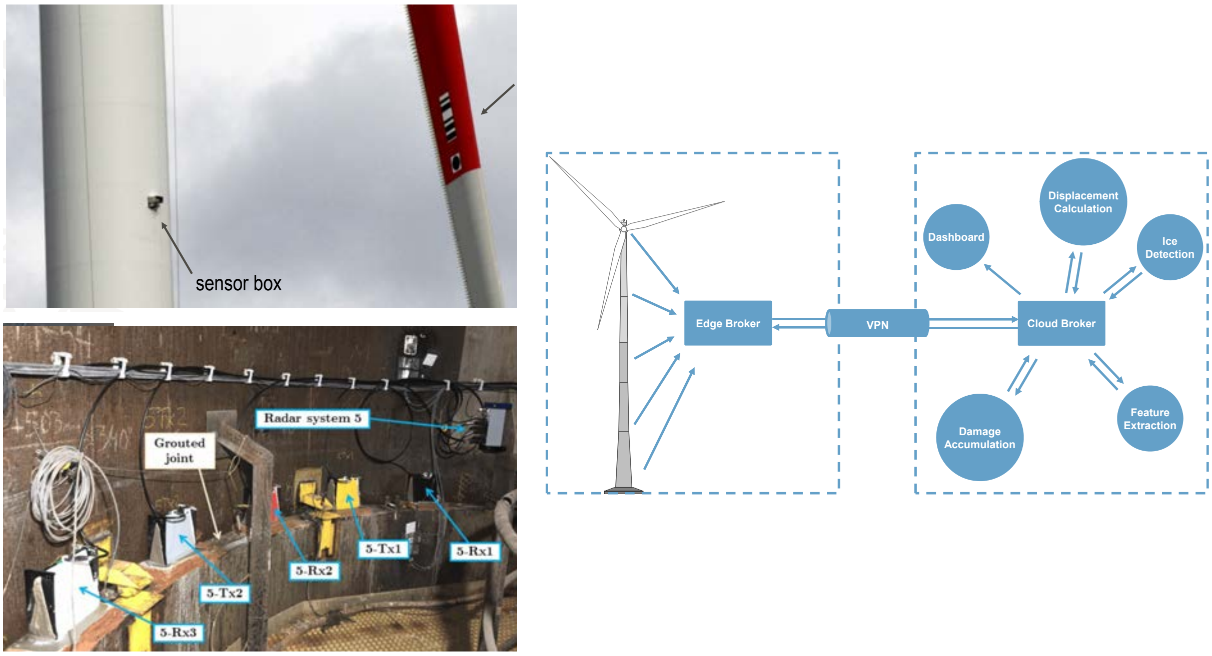


Figure 5: Demonstration of wind energy applications radar-based sensor implementation by Goethe Univ. Frankfurt (left) and concept of a digital infrastructure by TU Munich (right)

4.5 Guided Waves Database

A demonstrator of a different character is the Open Guided Waves platform [8,9]. The central idea and motivation are to make experimental data available to a general public to get algorithms developed validated. The platform currently contains four datasets of components made of CFRP as well as a wave dispersion calculator. The datasets are differentiated in accordance to the complexity of the different structures considered. The most basic configuration is a plate only, followed by a plate exposed to varying temperature, a plate reinforced by a stringer and a plate with a bonded stringer, where the stringer shows a certain disbond in the sense of poor bond quality. The data recorded is generally presented in a Matlab format, where the respective files can be downloaded from the website.

5 HOW TO USE DEMONSTRATORS TO GET SHM ALIVE

The limited selection of demonstrators presented here already shows that the demonstrators have a potential being much beyond what they have been initially conceived to be. Looking at the different intentions of the demonstrators and the SHM technologies being involved a first clustering can be made, which might include the following:

- **Applications:** It looks like the field of wind energy generation has found a very strong interest with respect to SHM applications. This includes the rotor blades regarding their dynamic behavior would that be as a result from external impacts, the implications those impacts would have on the integrity of the rotor blades, or the quality of the rotor blades' manufacturing. Another significant case of a similar nature is the dynamical behavior of the tower and with this the quality of grouting. These cases do lead to the more generalized application field of civil engineering. This field is dominated by silica-based, metallic and wooden materials. From these materials very little has been demonstrated with respect to wooden structures, possibly driven by the limited volume of use and the limited critical/accidental cases observed so far. However, this is not valid for the silica-based materials such as concrete, where a lot of infrastructure built in the last 50 to 100 years is approaching the end of its design life. To get the degree of degradation of this infrastructure assessed and possible residual operational life determined a significant effort is still required to be performed, where state-of-the-art technology has to be demonstrated, also from its economic value point of view, such that a necessity can be argued as to where to place future research activities in terms of structural integrity assessment, would this be in terms degradation mechanism understanding and modelling, sensing technology or sensor signal processing. Where those aspects have possibly been best explored so far has been with metallic materials. However, also there a lot needs to be demonstrated including the economic aspects, and this also to a community being outside of the engineering field, such as the infrastructure operators. Aerospace, which has possibly been a major driver of SHM, at least from a technological point of view, is the application field, where much less of an explicit need for SHM is to be seen. This may be due to the fact, that damage, and hence degradation has been generally always a part of the structural design. However, the SHM solutions being provided with respect to aerospace applications can be possibly considered as one of the most advanced and could as such possibly stimulate other application fields on how to optimize their SHM application cases.
- **Sensing:** A lot of sensing options have been proposed in the past, that allow a variety of structural phenomena to be monitored. However, those have hardly been demonstrated in a comparative way such that a potential user could get an impression on what might work best. A good example is again wind energy turbine blades, where different options have been shown for monitoring the modal vibrational behavior of rotor blades including piezoelectric acceleration

transducers, optical fiber strain sensing, radar-based sensing, thermal sensing and possibly more. This proceeds when looking at the monitoring of degradation mechanisms or poor quality in those rotor blades such as delaminations, porosity or weak bonds, just to name a few. Here again different sensing options may exist would it be related to manufacturers, types, or the NDT methods being applied. A combination of acoustic emission, ultrasonic guided waves, thermographic methods and robotic systems all demonstrated on the same rotor blade could be an interesting benchmark never performed before and could even serve as a calibration sample for any future benchmarks. Furthermore, this could encourage to explore the option of a combination of methods, in case this would be a viable economic option.

- **Internet based platforms for numerical evaluations:** The Open Guided Waves platform [8,9] has been a first attempt to make NDT and SHM related data available online to a general public. However, this is currently a very limited source of information since it only allows people to download the few experimentally and numerically provided data and to use this data for further processing in combination with own algorithms. Any feedback from users of this data provided is currently still missing including the algorithms they may have used. A significant expansion of such online activities is therefore required in a way, that further algorithms may be provided for comparative evaluations as well as more measurement data from experiments, preferably based on a standardized evaluation procedure set. The same might be valued for numerical evaluations, would those be the algorithms, or the data generated with those. A further service to be provided on such a platform could be the access to different numerical tools with which the respective numerical simulations could be made. It is clear, that all of this has to be considered as a dear wish, but it is important to express this vision in view of making the steps ahead from what has been generated so far.

6 CONCLUSIONS

It looks like SHM has not been sufficiently demonstrated such that it is adequately recognized so far. Reasons for this have to be seen in the complexity of the subject or in other words the various fields and topics SHM is involved with. SHM demonstrators with a true application value and are quite limited. This limitation stems from the fact that they may just have covered a limited if not even single number of aspects. However, there may be alternative SHM-related aspects that could be covered with the same demonstrators and this specifically with respect to alternative SHM related technological solutions, would those be related to sensors, signal processing algorithms, methods, applications or maybe all of those, that could not have been explored in the respective program in which the demonstrator was originally conceived for. However, such an extended use of the demonstrator could become highly valuable for demonstrating the wide gammut of technologies which SHM provides. Keeping such existing demonstrators therefore alive and a technology demonstration platform open for a longer period of time could also lead to an interesting benchmarking opportunity of competing technologies as well as for a discussion forum to be established, that may not simply stimulate discussions within an academic community but rather also into an industry and a community of infrastructure operators, specifically if the demonstration initiative would be extended into the field of trade fairs. The initiative having been described here is a first trial to do so. Although a limited number of partners have taken a piloting role so far, there is no limitation of further partners to join. However, there is still an open question on how to get such an initiative funded or in other words, where the added value lies and who would be willing to get this paid for. Hopefully this first presentation regarding the demonstrator initiative may be a step towards solving those open questions in the near future.

REFERENCES

[1] W.J. Staszewski, C. Boller and G.R. Tomlinson, Eds., *Health Monitoring of Aerospace Structures*. Chichester: Wiley, 2004.

[2] G. Chen, L. Li, H. Zhang, Z. Shi and B. Shang: *Aerial Nondestructive Testing and Evaluation (aNDT&E);* Materials Evaluation **81**(1), p. 67-73, 2023

[3] https://forschungspark-windenergie.de

[4] Maelzer, J. Moll et al. IWSHM 2023

[5] Maetz, J. Moll, EuCAP, 2023

[6] J. Rupfle and C.U. Grosse; *Soft real-time framework for Structural Health Monitoring of wind turbine supporting structures;* Internat. Conf. on NDE 4.0; DGZfP; Berlin; 2022

[7] H. Sohn, P. Liu, I. Jeon, K. Lee, S.-H. Park, L. Yang and S. Shin: *Online Monitoring and Process Control during Metal Additive Manufacturing;* Proc. of 10th European Workshop on SHM; Palermo/Italy, 2022

[8] http://openguidedwaves.de

[9] Moll, J.; Kathol, J.; Fritzen, C.-P.; Moix-Bonet, M.; Rennoch, M.; Koerdt, M.; Herrmann, A.; Sause, M.; Bach, M.: Open Guided Waves – Online Platform for Ultrasonic Guided Wave Measurements, Structural Health Monitoring, 2019, vol. 18(5–6), 1903–1914