Acoustic Sensing Based Operational Monitoring of Wind Turbine Blades

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Abstract. This paper presents a general overview of the different aspects of a novel structural health monitoring technique developed for wind turbine blades. The proposed technique is based upon detecting the changes in acoustic transmission loss due to structural deformation and damage incurred. This acoustics-based damage detection technique consists of two complementary approaches, namely, the active and passive acoustic damage detection approaches. The proposed approaches can be applied to both onshore and offshore turbines and requires minimum number of acoustic sensors positioned internal and external to the blade structure. Both approaches will be detailed from the structural health monitoring, acoustics, aeroacoustics as well as the practical implementation perspective. The potential benefits of using the proposed approaches and the corresponding technology on wind turbine blades is also discussed.

1. Introduction

Modern wind turbines possess condition monitoring systems for components in the nacelle, however current blade condition monitoring systems can only detect for ice build-up or indirectly identify changes to the structure based on accelerometer measurements. Existing damage detection approaches of wind turbine blades primarily focus on non-destructive inspection for quality assurance to identify manufacturing defects and do not lend themselves for in-situ/operational damage detection. Although structural health monitoring (SHM) technologies of blades do exist and can perform well in a laboratory setting, they are generally not well-suited for monitoring in the field, largely because of their limited damage detection range in composites requiring a significant number of sensors to cover a large area of interest (e.g. strain gages, piezoelectric and acoustic emission sensors), cost (fiber-optic sensors), or effectiveness (accelerometers). The traditional sensing approaches (e.g. strain-gage networks, acoustic emission sensors, fiber-optic cables, ultrasonic, and piezoelectric transducers) heavily depend on contact-type measurement sensor arrays that are either difficult to instrument, challenging to maintain, unreliable, costly, or ineffective in identifying and localizing distributed damage, or are impractical to be implemented in service [1-15]. The acoustic sensing based damage detection approach proposed is a non-destructive, contactless approach. Only a few acoustic sensors placed within the blade's internal cavity samples the acoustic signals generated due to natural wind flow and its interaction with the blade structure. Consequently, it provides a distributed sensing approach with the use of limited sensors [16].

This paper overviews the fundamental ideas energizing the new acoustics-based damage detection and identification approach developed for wind turbine blades. This new and complementary approach will enable operational monitoring of wind turbine blades. It consists of an active detection approach with actively controlled sound sources implemented inside the blades, and a complementary passive detection approach with blade-internal microphone acoustically interrogating the system with no actively controlled sound sources involved. The active detection approach involves acoustically exciting the internal air domain of the cavity structure and extracting information about the health of the system from external and or internal microphone pressure responses. Controlled acoustic excitation ensures a consistent energy source to excite the blade structure from inside, and thus provides a robust and repeatable non-contact excitation. The main disadvantage is that it requires more hardware, and energy supplied to the acoustic exciters (speakers) making it a more complicated system, potentially with more reliability problems. Consequently, a complementary passive detection approach with no active excitation is proposed to back-up the active detection approach. The passive detection approach rely on wind flow generated external acoustic excitation as received by the blade-internal microphones. The passive detection approach only requires blade-internal acoustic sensors (microphones), and thus consists of less hardware.

The considered acoustic approach is an innovative approach for structural damage detection from wind turbine blades. It provides a non-contact form of excitation with control over how the structure is excited. Moreover, this technique offers flexibility in the instrumentation of the structure. The instrumentation of the structure can be limited to an external microphone located on the tower (or inside the hub) and a few blade-internal microphones. These two approaches, how they function, and their implementation along with their potential other uses will be explained in the next section.

2. Methodology

The team has demonstrated the feasibility of the acoustics-based wind turbine blade structural health monitoring and operational damage detection technology that can be integrated on both new and existing wind turbines (retrofit) using in-lab testing as well as testing at the Massachusetts Clean Energy Center's WTTC (Wind Technology and Testing Centre located in Charlestown Massachusetts). The newly developed operational blade monitoring approach is based on an understanding of the influence of structural damage on the deviations in the acoustic transmission loss of blades exposed to internal and external acoustic excitations. Because of continually varying aerodynamic forces, gravitational loads, lightning strikes, and weather conditions, all blades will experience leading and trailing edge splits, cracks, or holes that are currently not detectable except by visual inspection or post blade failure. The proposed innovative technique will address this need and utilizes (1) low-cost, low-maintenance microphones for passive monitoring of natural aerodynamically-driven, flow-induced noise that couples with the structural damage and (2) acoustic sources to excite the dynamic cavity structure from within (Fig.1). The blade damage will manifest itself in changes to the acoustic cavity frequency response functions and to the blade acoustic transmission loss. A number of optimally-located wireless microphones can be used for the (1) internal passive detection and a single microphone located outside but nearby the blades will be used for the (2) external active detection of damage.

The first approach leverages the energy caused by the wind/flow-induced noise, exterior to the cavity. It is inexpensive, in-situ, and effective to detect holes, cracks and leading/trailing edge splits in bonded surfaces. The blade can be continuously monitored and when damage is originated, the internal acoustic signature will change due to the changes in the transmission loss (caused by the hole or crack) and/or the distorted acoustic pressure field. The sound field inside the blade will be significantly different when the blade cavity is no longer sealed to the fluid passing over the exterior of the blade (Fig.2a). A single microphone inside the blade cavity can be used to track the differential noise component caused by the damage which essentially couples the blade cavity to the exterior airflow (like a Helmholtz resonator or the noise generated by the airflow over a glass bottle). The second approach involves mounting an audio speaker (with controlled output frequency and level) inside of the blade to excite the internal cavity acoustics. It will then be possible to detect cracks or damage within the structure by observing the deterministically controlled sound radiation from inside the cavity (Fig.2b).

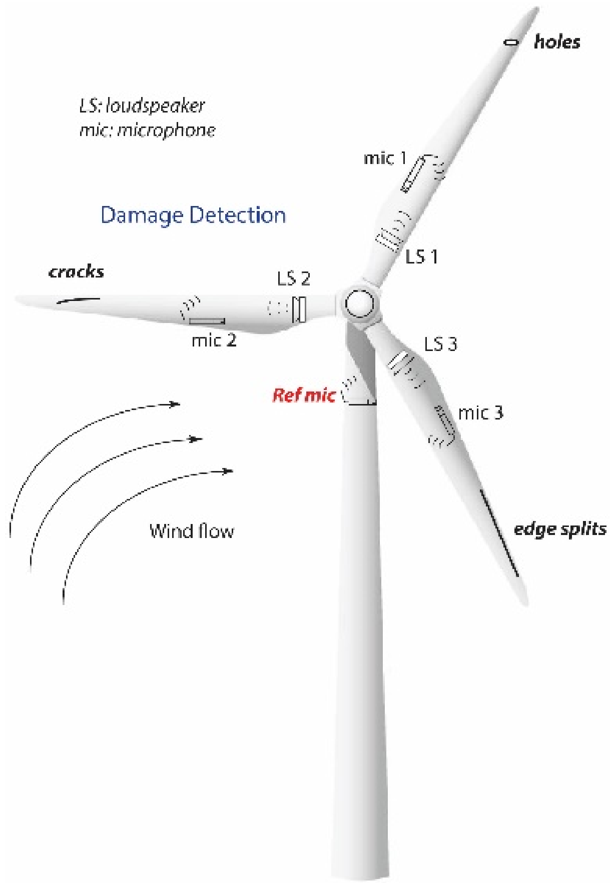


Fig.1. Interrogation concept for damage detection applied to a utility-scale operating wind.

A perfectly healthy hollow enclosure is assumed to have no direct interface between the internal and external air domain. Thus, sound generated internal to a structure must transmit through the material of the structure experiencing all associated losses. Upon the introduction of damage to the enclosure, the internal and external acoustic domain are now coupled by some fluid interface (an air hole, crack, or gap). The acoustical energy now has a direct path to the external domain without the interference of a solid barrier. As a result, it is assumed that an increase in acoustical energy or change in the external sound field will be exhibited. The external sound field is most commonly and easily monitored by assessing the sound pressure level (SPL) measured by a microphone. An increase in the sound pressure level (lower acoustic attenuation) measured is a potential indicator that structural damage is present. This can be simply quantified using the following equation:

$$\Delta SPL = SPL_{Damage} - SPL_{Healthy} \tag{1}$$

In Equation (1), SPL_{Damage} is the SPL measured at a discrete point external to the structure when it is damaged, $SPL_{Healthy}$ is the SPL measured at the same discrete point external to the structure when the structure is healthy, and ΔSPL is the difference between the two. The difference in SPL (acoustic attenuation) will be used to assess the ability to detect damage throughout this work. When the ΔSPL is positive, damage will be considered as identifiable. If the ΔSPL is negligible or negative, the damage will be considered as unidentifiable. In addition, the ΔSPL will be used as an indication to how well damage is identifiable by comparing the relative magnitudes to different test cases.

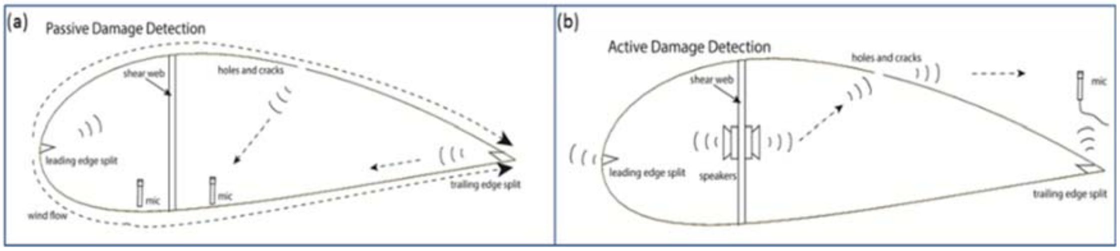


Fig.2. (a) Representation of the passive detection approach, (b) active detection approach.

The hypothesis generated has been tested and evolved through several experimental, computational, and analytical investigations. These investigations are briefly explained in the subsequent subsections.

2.1. Experimental Investigations

Several experimental investigations with a gradually increasing complexity level have been conducted to test the fundamental scientific question in this study. The tests are related to different aspects of acoustic transmission loss and its potential use to detect damage from operational turbine blades. The test structures included i) a composite box, ii) blade sections, iii) turbine blade in the field, iv) turbine blade under fatigue test at the WTTC (Wind Technology Testing Center).

Initially, a relatively simple rectangular prism composite box is used for the active detection experiments. The structure under consideration is kept simple such that the theoretical mode shapes and natural frequencies can be easily computed [17]. This is geared towards understanding the influence of excitation frequency, resultant pressure distribution inside the structure and their interactions. The experiments are performed in an anechoic environment at UMASS Lowell. The same geometric positioning is used with the origin specified at the rear corner of the box closest to the floor. The speaker is positioned in the corner of the rectangular enclosure to excite the most modes. An internal microphone is installed into the direct center of the rear XY face to provide an internal reference measurement and frequency response for all tests (see Fig. 3). Two microphones are positioned at the centerline of the box various distances from the damaged face of interest, one in the near field and the other in the far field. The two microphones are used to compare results with the computationally simulated results. All microphones used are random incidence microphones to account for sound coming in all directions.

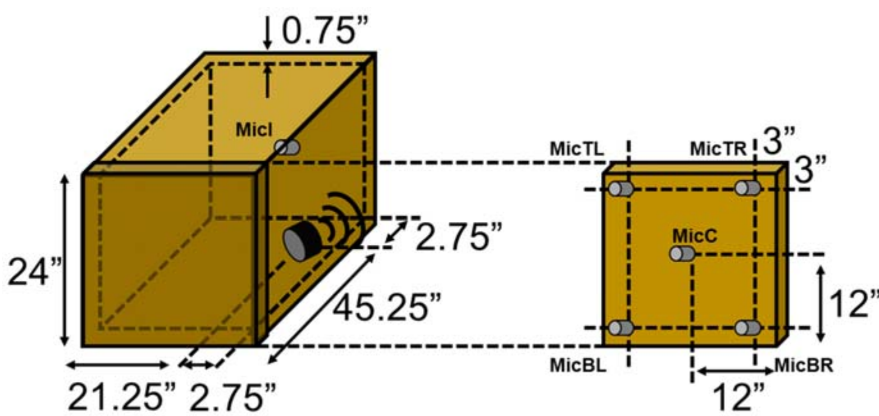


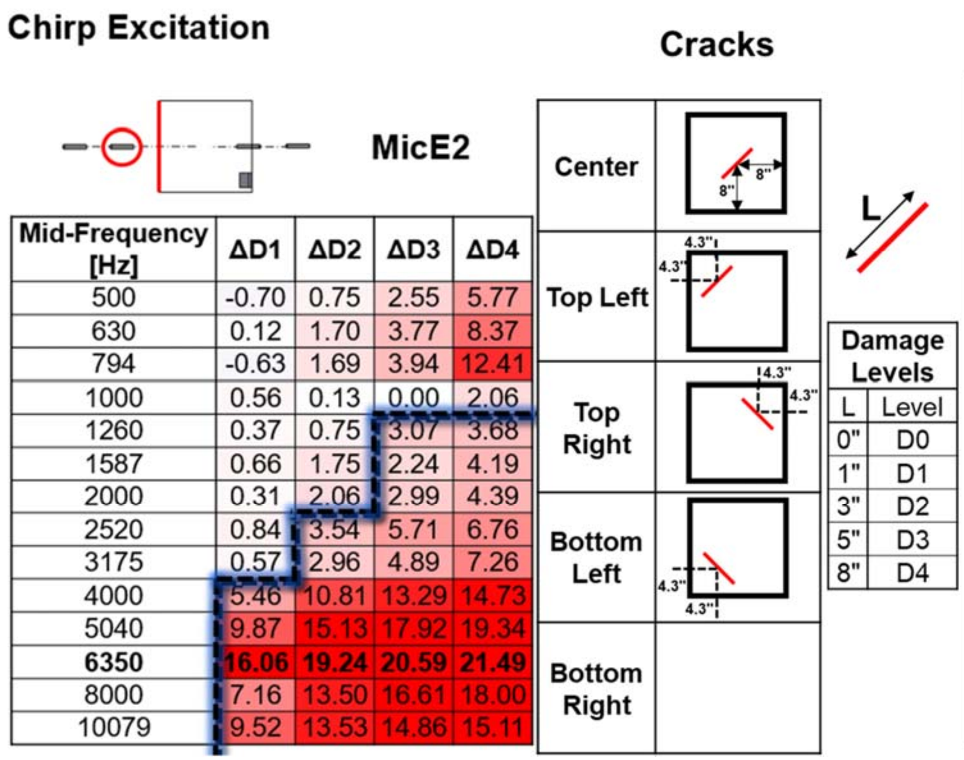
Figure 3. Schematic illustration of the set up used during the acoustic tests.

The speaker was excited by the appropriate voltage signal that generated a chirp tone with a frequency range of 500-15000 Hz and the associated testing parameters are listed in Table 1.

Table 1. Acoustic Modal Analysis Testing Parameters.

Parameter	Value
Sample Rate [Hz]	32768
Block Size	65536
Sample Time [s]	2.00
Blocks	15
Spectral Resolution [Hz]	0.500
Time Resolution [s]	3.052×10^{-5}

The experiments were performed to measure the sound field when the box was healthy and later when it was damaged. The acoustic response was measured using two external microphones MicE1, Mic E2, and an internal microphone MicI. The center hole (prescribed) was the damage case considered. This is because the pressure incident on the XY face at the center hole was an antinode region for mode 1 and a node region for mode 2. The test involved first obtaining a healthy baseline measurement while the structure was completely undamaged for both modal frequencies. A 1.5" hole was then introduced into the structure at the center hole position. The acoustic sound pressure level (SPL) measured from external microphones MicE1 (36 inches away from the damaged face of the box) and MicE2 (221 inches away from the damaged face of the box) are used to identify trends experimentally and compare them to the simulated results. The ΔSPL values obtained for an example test with prescribed cracks on the front face of the box structure is summarized in Fig. 4. The results indicate the higher the frequency the higher the likelihood of detecting damage. Increasing damage severity also helps the detection rates, in general.



Mid-Frequency [Hz]	ΔD1	ΔD2	ΔD3	ΔD4
500	-0.70	0.75	2.55	5.77
630	0.12	1.70	3.77	8.37
794	-0.63	1.69	3.94	12.41
1000	0.56	0.13	0.00	2.06
1260	0.37	0.75	3.07	3.68
1587	0.66	1.75	2.24	4.19
2000	0.31	2.06	2.99	4.39
2520	0.84	3.54	5.71	6.76
3175	0.57	2.96	4.89	7.26
4000	5.46	10.81	13.29	14.73
5040	9.87	15.13	17.92	19.34
6350	**16.06**	**19.24**	**20.59**	**21.49**
8000	7.16	13.50	16.61	18.00
10079	9.52	13.53	14.86	15.11

Damage Levels	
L	Level
0"	D0
1"	D1
3"	D2
5"	D3
8"	D4

Figure 4. Deviation in Acoustic SPL due to damage (prescribed cracks) with the severity levels indicated on the right hand side.

To demonstrate the underlying physics, representative acoustic beamforming tests were performed on a ~41 cm cubic enclosure, 4 m lab-scale wind turbine blade and ~46 m utility-scale wind turbine blade. The cubic enclosure and 4 m blade were internally excited by white noise whereas the 46m blade was excited by chirp signals to identify frequency-related trends across the audible spectrum. Acoustic source strength maps were computed from the test data and a few examples are shown in Fig.5. Overall, damage could be detected on all structures shown by the concentration of the color corresponding to the max limit of the color map local to the damage. It was observed that analyzing the data at higher frequencies and over larger frequency bands augmented the ability to detect damage both visually and numerically. Ultimately, the beamforming case study verified that damage alters the acoustic transmission properties of cavity structures and can be used to detect damage on structures even as large as a utility-scale wind turbine blade [18, 19].

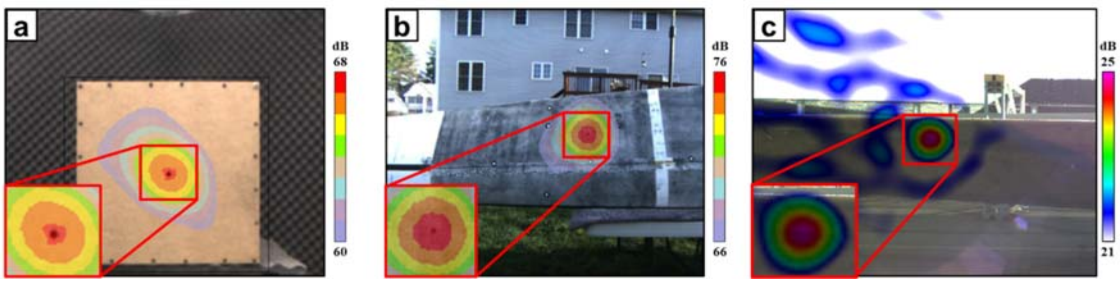
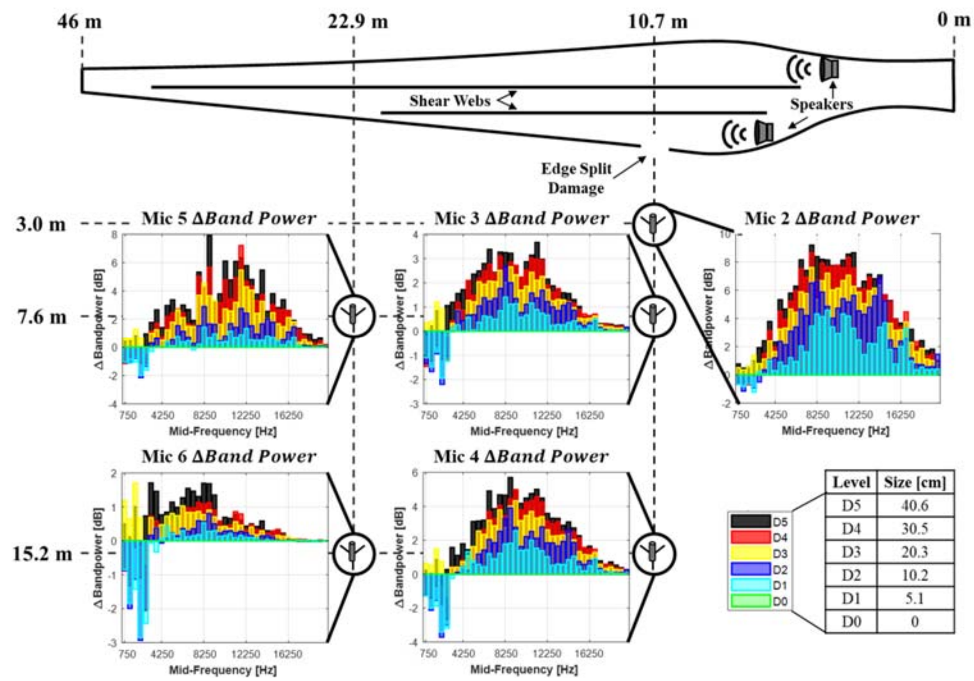


Figure 5. Acoustic source strength maps visualizing high source strength local to the defects with respect to the (a) 41 cm cubic enclosure exposed to a 1.27 cm diameter hole processed between 5.7 - 5.75 kHz, (b) 4 m blade exposed to a 1.27 cm diameter hole processed between 4.35 - 4.4 kHz and (c) 46 m blade exposed to a 5.1 cm long crack processed between 5.0 - 20 kHz [18, 19].

An experimental case study was performed on a ~46 m utility-scale wind turbine blade considering limited external microphones to test the active detection approach at the more realistic full-scale [20]. This would constitute an example investigation on the active detection approach as opposed to the costly number of microphones considered in the beamforming case study. The ~46 m blade, located in the storage yard of WTTC in Charlestown, MA, was damaged over six levels of severity (D0 corresponding to undamaged through D5 corresponding to the max level of damage). Damage was implemented on the trailing edge, 10.7 m away from the root of the blade. Five microphones were positioned external to the blade, three in line with the damage and two in line with the mid-length of the blade at various distances from the structural surface. The blade was internally excited by two loudspeakers using a chirp signal sweeping from 0.2 kHz to 20 kHz over 75% of the measurement block. In total, 150 measurement blocks were acquired at each level of damage and the acoustic band power computed from the measured pressure responses was used to quantify variations in the transmission properties of the cavity. The overall position of each sensor and the resultant differences in average band power (computed with respect to the undamaged baseline) are compared in Fig.6 for every microphone and level damage.

The passive detection part of the novel acoustics-based damage detection approach is realized through a test plan that considers a wind turbine blade section subject to various damage types, severity levels, and locations as well as wind speeds tested in a subsonic wind tunnel [21]. Statistics-based metrics, including power spectral density estimates, band power differences from a known baseline, and the sum of absolute difference (SAD) are used to detect damage. The results indicated that the passive acoustic damage detection approach is able to detect all considered hole-type damages as small as 0.32 cm in diameter and crack-type damages 1.27 cm in length. It is observed that the ability to distinguish damage from the baseline state improved as the damage severity increased. Observations regarding the influence of damage type and location, and flow speed on the damage detection rates indicated that these parameters are not significant enough to prevent detection. The laboratory-scale results reveal that the passive detection approach has great potential to be used as a new structural health monitoring technique for utility-scale wind turbine blades.

The passive structural health monitoring approach for damage detection in wind turbine blades using airborne sound is also tested at the utility-scale during fatigue tests at the WTTC [22]. The approach utilizes blade-internal microphones to detect trends, shifts, or spikes in the sound pressure level of the blade cavity using few internally distributed airborne acoustic sensors and naturally occurring passive excitation. A comprehensive test campaign is performed on a utility-scale wind turbine blade undergoing fatigue testing to demonstrate the ability of the method for structural health monitoring applications. The signal processing steps used include Principal Component Analysis and K-means clustering. These techniques are applied to the feature space representation of the dataset to identify any outliers in the measurements. The performance of the system is evaluated based on its ability to detect those structural events in the blade that are identified by making manual observations of the measurements. The approaches proposed are found to be successful in detecting structural and acoustic aberrations experienced by a full-scale wind turbine blade undergoing fatigue testing. The team is working on developing signal processing approaches that will be used in conjunction with machine learning to detect damage under different operational and environmental conditions and different scales [23-25].



Level	Size [cm]
D5	40.6
D4	30.5
D3	20.3
D2	10.2
D1	5.1
D0	0

Figure 6. Experimental setup of the ~46 m blade test case and differences in the average band power computed with respect to the undamaged baseline for each microphone and level of damage.

The next step in this work includes field tests with the system developed being tested on full-scale operational wind turbines in a wind farm. This is expected to shed some more light on the detection rates when there are extraneous noise sources (both wind turbine and environmentally originated), sensors operating in dynamic (moving and vibrating) blades and changing operational (rotational speed, wind speed and direction, etc.) and environmental conditions (temperature, humidity, etc.).

2.2. Computational Investigations

The computational investigations to test the hypothesis include modelling and simulating healthy and damaged structures such as i) composite box, ii) subscale blade, iii) 9m blade section, iv) Utility-scale (~50m) blade. The last two structures are currently being studied by the team, whereas the composite box and subscale blade were investigated for their transmission loss behaviour with and without damage. The first structure considered is a rectangular enclosure constructed of medium density fiberboard (MDF). This structure was chosen due to its simplicity and ease of construction for experimentation. The complete list of geometric and material properties of the structure is presented in Table 2.

Table 2. Geometric and Material Properties of the Example Cavity Structure.

Parameter	Value
X-Dimension [in]	24.488
Y-Dimension [in]	24.016
Z-Dimension [in]	50.158
Thickness [in]	0.750
Density [lb/ft3]	46.821
Elastic Modulus [psi]	5.439×10^5
Poisson Ratio	0.25

Frequencies that are too low are avoided so that a more complex pressure gradient is exhibited internal to the structure enabling antinodes and nodes to be well distributed and easily distinguished on a single face. In addition, the frequency is kept below ~1500 Hz to avoid any effects from the coincidence frequency of the MDF panels and reduce the size requirements of the computational model. Finally, the modes are selected such that they can be exhibited during experimentation. Therefore, only modes that are present during an acoustic modal test of the structure are used. The two theoretical natural frequencies selected after all considerations are 1014.69 Hz and 1070.9 Hz. The two modes are computed included the ones with modal indices Mode-1 (2, 2, 4) and Mode-2 (2, 1, 6) (see Fig. 7).

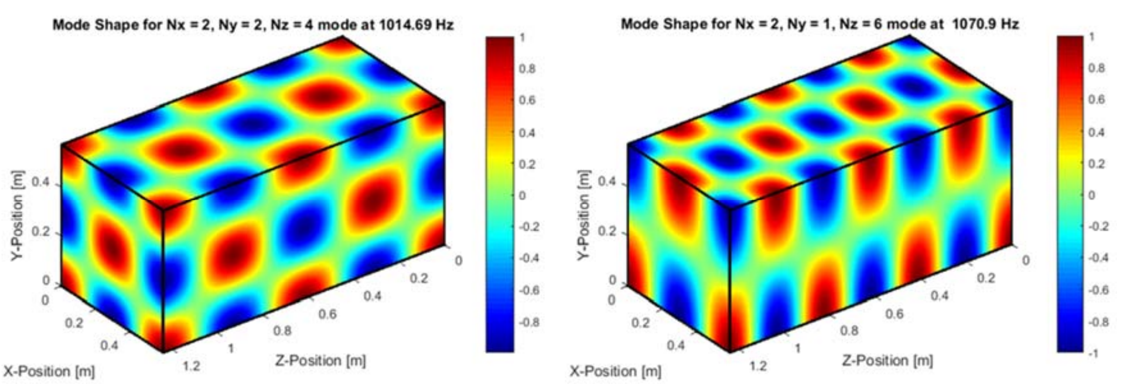


Figure 7. The cavity internal normalized pressure distributions for the two modes considered.

The finite elements used to computationally model the structure under investigation must be small enough to accurately model the acoustic waves and the external air domains must be large enough to ensure acoustic energy is not reflected back into the model. All associated model properties in regards to the external acoustic domains and element sizes are presented in Table 3 along with the minimum/maximum limits recommended for accuracy. A schematic of the computational model of the damaged structure as well as the modelling layers used are shown in Fig.8. Results obtained from the computational models have been compared and contrasted against the experimental results described earlier. An example results, normalized delta SPL (change in SPL) due to the existence of damage is shown in Fig.9.

Table 3. Computational Model Properties and Limits.

Parameter	Value	Limit
Acoustic External Domain [ft]	0.984	0.557 (Min)
Acoustic Buffer Domain [ft]	0.328	0.279 (Min)
Acoustic PML Domain [ft]	0.656	0.279 (Min)
Element Size [ft]	0.131	0.176 (Max)
Absorptive Surface	0.600	-
Speed of Sound [ft/s]	1134.580	-
Mode 1 Damping [%]	0.003	-
Mode 2 Damping [%]	0.0022	-

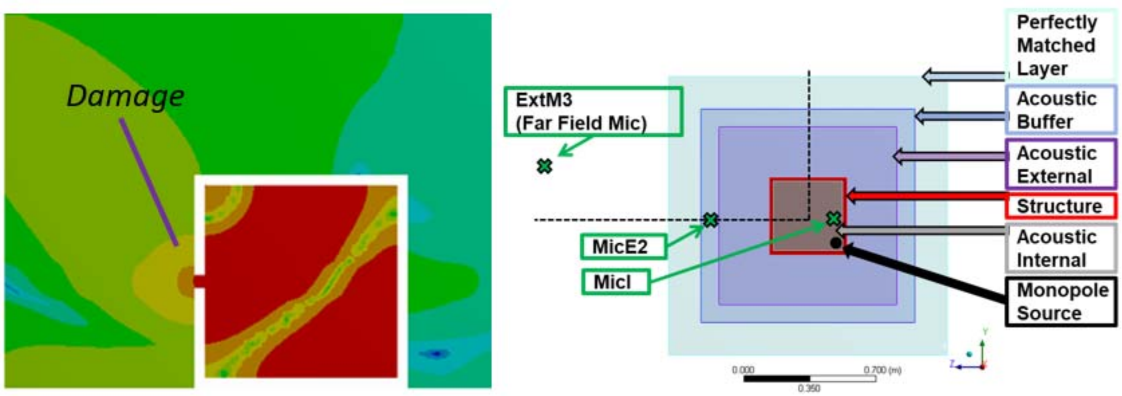


Figure 8. Schematic of the computational model of the example damaged composite box and the modelling layers.

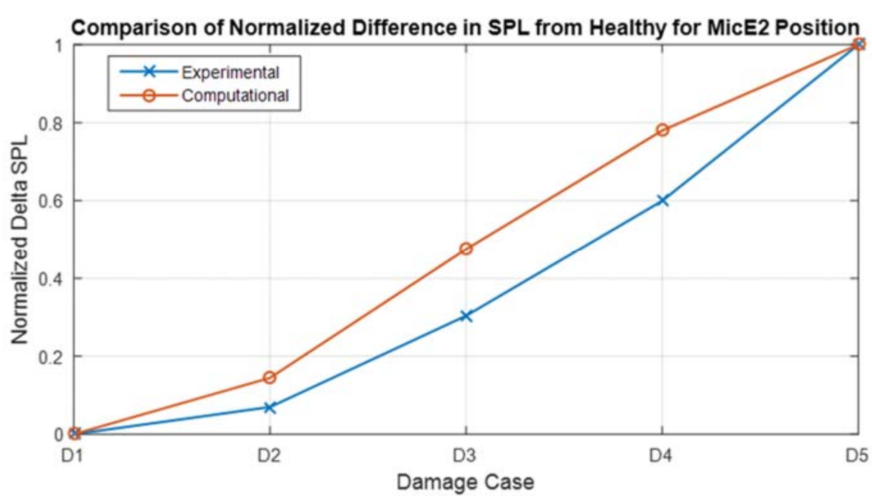


Figure 9. Example results comparing the experimentally and computationally obtained SPL external to the box structure with prescribed damage.

In order to ensure that the computational modelling environment to reasonably reflect the experimental testing environment, the semi-anechoic environment that experimental testing was performed is modelled as the boundary conditions in the model. Acoustic modal damping is included in the model using the values obtained experimentally. The box is positioned on the floor of the anechoic chamber which is layered with 60% acoustic sound absorbing foam. This is accounted for by defining an acoustic absorptive surface with an absorption coefficient of 0.6 on the bottom faces of the structure, external acoustic domain, and both acoustic buffer layers [19]. Fluid structural interaction is included in the model and defined on all interfaces between an acoustic domain and the structure. The acoustic excitation source is specified as a monopole source in the rear corner of the internal acoustic domain.

Lastly, a zero pressure boundary condition is applied on all outer faces of the PML (Perfectly Matched Layer) to ensure all acoustic energy is attenuated as if it were in a free field environment. Damage is only considered on a single face of the structure and implemented as holes with a single damage size of 1.5 inches in diameter. Three cases are tested for each mode: damage incident on an antinode, node, and a mixture region that contains a pressure gradient between a node and an antinode. The single face selected for the analysis is the fontal XY face of the structure at the 50.158" z-position in the model. Considering the mode shapes incident on the rigid-walled cavity of the frontal XY face, the positions of the damages can be specified for each test case. The mode shapes used to select the damage locations are results from the coupled structural-acoustic finite element analysis to ensure the pressure distribution is most representative to the true physical system. Similar computational approach was also followed for the blade section. Results revealed were different numerically, but similar in regards to the trends in terms of the damage type and severity and how they relate to the damage detection frequencies. It is challenging to use the finite element approach for damage detection (acoustic) simulation at the high frequencies and especially for larger structures due to the large number elements and solution times incurred. The team is looking into other approaches for simulating large scale structures.

Finally, the team has also been developing aeroacoustics simulation approaches for computational investigation of the sound transmission through and from the blades in order to verify the acoustic pressure magnitudes and optimal sensor placement. This generalized computational methodology takes the acoustic-structure interaction into account and does reduced order aeroacoustics modelling of a wind turbine blade [26]. This methodology is used to investigate the acoustic pressure distribution in and around airfoils to guide the development of a passive damage detection approach for structural health monitoring of wind turbine blades. Simple acoustic sources are determined from a turbulent k-ε flow simulation, where the model is tuned based on existing experimental data. The methodology is applied to a computational case study of a 0.3048 m chord NACA 0012 airfoil with two internal cavities, each with a microphone placed along the shear web. Several damage locations and damage sizes were studied and compared to the healthy baseline case for three strategically selected acoustic frequencies, 1 kHz, 5 kHz, and 10 kHz. In 22 of the 36 cases in which the front cavity was damaged, the front cavity microphone measured an increase in SPL above 3 dB, while rear cavity damage only resulted in 6 out of 24 cases of a 3 dB increase in the rear cavity. Depending on the frequency and microphone location, the internal SPL measurements for the healthy baseline case ranged from ~70 to ~100 dB. The success of identifying damage with an increase in SPL was dependent on damage location, damage size, and frequency. The investigation into the impact of damage to the blade indicated that damage to a cavity caused significant increase in SPL for many front cavity cases. The case study has confirmed that the passive acoustic detection approach can be used to detect blade damage, while also providing a template for application of the methodology to investigate the feasibility of passive detection for any specific turbine blade.

2.3. Analytical Investigations

Analytical approaches that have been applied to the problem under investigation included modeling of the transmission loss of walls with damage (openings) to observe general trends and relationship between damage size and damage detection frequencies, simplified acoustic radiation model from the turbine blades and signal processing/machine learning approaches that are needed to post-process data obtained. This paper is not targeted to go into the details of the analytical approaches developed and used. However, the authors would like to highlight the fact that the analytical approaches developed have generated noteworthy information in regards to the general trends related to acoustic transmission loss from damaged structures and thus help explain certain trends.

3. Discussion

The damage detection approaches developed are used in developing a cost-effective and robust wind turbine blade monitoring solution. There is currently limited to no competition for this unique system in the market. This novel technology is expected to reduce project risks and associated costs by reducing LCOE through an increase in turbine reliability and operability. This will enable creation and presentation of a better case for the establishment of clean energy through the use of efficient wind turbines. This system utilizes low-cost, low-maintenance microphones for passive monitoring of wind flow-induced aerodynamic noise that couples with the structural damage, and actively-controlled acoustic speakers to excite the blade's cavity from within for active monitoring with an acoustic sensor located outside the blades near the turbine base. The blade damage will manifest itself in changes to blade's cavity acoustic frequency response functions and blade acoustic transmission loss. The proposed system is inexpensive, in-situ, and effective to detect holes, cracks, edge splits in bonded surfaces and potentially (with the use of minimum number of accelerometers located inside the blades) for icing with a ~$100k savings over the life time of an average size turbine.

Initial market and cost analysis indicates that blade-related cumulative O&M costs, using conservative model assumptions, range between $75K-$120K on average per 2.5MW turbine over 20 years. The range of potential cumulative avoided cost created by the monitoring solution assumes that the solution eliminates between 50-80% of blade O&M costs. The key assumptions used in this analysis were: 2.5MW turbine, power purchase price range $0.03 - $0.05/kWh, O&M costs range $4.00 - $6.00/MWh energy generated, 10% discount rate for present value, 20 year turbine life.

The following table illustrates the impact that the blade monitoring solution could have on a on a 100 Megawatt (MW) wind farm. Note that the cost of the blade monitoring solution is not included, as it has not been determined. At 80% avoided cost, about $1.6 million minus the cost of the blade monitoring system for 40 turbines would be added to the bottom line. Assumptions used were: 2.5MW turbine, power purchase price range $0.05/kWh, O&M costs 6.00/MWh energy generated, 10% discount rate for present value, 20 year life. The size of the blade O&M cost problem was also estimated. Based on US data only, average US turbine size of 1.4MW was used to roughly estimate # of turbines to be 400,000 in 2019. The collective costs of blade O&M are over $1 billion. Note that the economics are driven by present value of lifetime cost savings over 20 years as opposed to average annual savings per turbine. Total Market size in 2019 for blade monitoring systems would be about $2 billion, assuming system sale price of $5000 and 400K turbines and $4 billion at $10K sale price.

Table 4. The estimated impact of the blade monitoring solution on a 100 MW Wind Farm.

100MW Wind Farm

	No Blade Monitoring	With Blade Monitoring	Improvement
Revenue	$103,373,700	$103,771,794	0.4%
Expense	$93,976,091	$92,785,226	1.3%
Gross Profit	$9,397,609	$10,986,568	16.9%
ROI	10%	11.8%	18.4%

The implementation of the damage detection technique developed on operational wind turbines have some challenges. For example, the sensors to be located internal to blades has some challenges in regards to their positioning, powering scheme and potentially reliability. The team has been developing general approaches and mitigation strategies for these potential issues with the implementation. Some of the other primary risks for implementing this damage monitoring approach include: the technique being insensitive to some types of damage due to their size, data transmission limitations, and classification algorithms being incapable of detection and identification. These risk factors will be mitigated by utilizing microphones with different sensitivity, adaptive sampling rates that increase the sampling frequency upon detection and a hybrid Markov Chain based machine learning approach that learns and adapts itself to new baseline conditions thereby enabling detection.

4. Conclusion

An acoustics-based structural health monitoring technique consisting of an active and a passive detection approach was outlined with an application to wind turbine blades and their monitoring. Overall, the outcome of this investigation successfully demonstrated the feasibility of using both the active and the passive damage detection approach on full-scale wind turbine blades. The approaches developed will enable new monitoring solutions which will help improve turbine reliability and thus will reduce the levelized cost of wind energy.

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