

Modelling and empirical development of an anti/de-icing approach for wind turbine blades through superposition of different types of vibration

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Abstract

The generation of green, safe and inexpensive energy by wind turbines is often decreased or interrupted in severe climate areas during cold weather. When the blades are even partially covered by different types of ice their efficiency drops suddenly due to degradation of the blade profile from the ideal. The present study presents a new approach using ultrasonic guided waves as an anti/de-icing technique supplemented by low frequency vibrations to effect shedding of the ice from the turbine blades. The study consists of a series of steps including initial theoretical studies and finite element simulation of representative plates and turbine blades, followed by a number of experimental validations concluded by tests of the complete approach in an icing wind tunnel. The results show the efficacy of the developed approach in tackling the different types of ice which can form on the blades, using very low power compared to available thermal techniques.

Keywords: wind turbine blades, anti-icing, de-icing, vibration, ultrasonic guided waves

1. Introduction

Today, wind energy is an efficient source to supply green power. The relatively cheap and reliable harvest of this energy has extended its use into wide geographical regions, even those with an icing climate. However the power generation by wind turbines in such regions usually suffers from the harshness of the weather in mid-winter when the wind turbine blades are subject to ice formation. It has been well reported that ice accretion on wind turbine blades can drop the turbine efficiency and reduce output power [1, 2, and 3]. To solve the icing problem, a range of techniques has been developed and applied to date. Thermal technologies including electrical resistance heating and hot air circulation have shown some success but they are usually energy inefficient as they consume considerable amounts of energy themselves. For example, hot air circulation can use up to 15% of the turbine's nominal output power [2]. Some attempted/proposed methods such as microwave heating have poor performance [3]. Likewise, other available techniques including coating and

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37 painting blades, use of anti-freeze chemicals and active pitching are associated with major
38 drawbacks such as excessive heat absorption, damage risk to structural integrity of the blades,
39 and environmental pollution [4].

40 In this work, an approach has been proposed and tested to overcome the icing problem
41 effectively for the blades of a 75-kW wind turbine using relatively little energy. The
42 technique exploits the advantages of two previously attempted techniques in a synergistic
43 way to cover up one another deficiencies. These two techniques are Ultrasonic Guided Waves
44 (UGW) and Low Frequency Vibrations (LFV). The main action is carried out by application
45 of UGW which has been used for non-destructive testing for many decades but it is relatively
46 new as an ice protection technique. Guided waves are considered as the long-range waves
47 propagating through materials in which vibrations of high frequency compared to LFV are
48 created on the surfaces. The technique of UGW has recently been considered to be
49 developed, improved or adapted in different ways for protecting surfaces against icing [5, 6,
50 7]. The idea in this approach is to induce shear stress at the interface of ice with blade outer
51 surface sufficient to de-bond the accreted ice layer. The challenge is how to excite the
52 appropriate waves that generate such an effective stress on the material surfaces. This
53 depends on factors such as wave mode, excitation frequency, direction of excitation, and the
54 arrangement of a possible transducer array, and requires that the dispersion curves of the
55 propagating waves be extracted and analysed. The analysis can be very complicated due to
56 the complex geometry of the blade. Moreover, it is very important to select an optimum
57 frequency and wave mode at which minimum power is consumed consistent with the
58 required shear stress at the ice layer/blade substrate being produced. For this reason, a so-
59 called interfacial stress concentration coefficients (ISCC) factor has been developed
60 previously to characterise the wave mode, minimal power and frequency maximising the
61 shear stress induced at the interface (see [8] for details). The ISCC values should be then
62 superimposed with dispersion curves to complete the criteria for selection of excitation
63 frequency. According to the definition of ISCC, the higher ISCC, the more shear stress can be
64 induced at the ice interface. So a frequency band with high ISCC value is the first criterion.
65 Dispersion is normally defined as the dependency of the wave velocity on the frequency at
66 which wave propagates in a medium. One of the desirable characteristics for an ideal wave
67 mode in UGW applications is having lower dispersion i.e. the less variation of wave
68 properties with frequency. In addition, it is very important to avoid energy dispersion and
69 dissipation by selecting a non-dispersive frequency range for the wave mode. Moreover, it
70 should be noted that dispersive wave modes undergo more attenuation and therefore less
71 coverage than non-dispersive ones. So the second criterion to be taken into account is
72 selection of a wave mode without any or with minimum dispersion.

73 The complementary action in this approach is provided by LFV which was first utilised by
74 Bell Helicopter to tackle ice formation on helicopter blades [9]. It showed successful results
75 on the blades except in the vicinity of the leading edges. In the current work, LFV plays a
76 supplementary role to ensure that the ice will be shed simultaneously with or immediately
77 after the ice/substrate bond is weakened by UGW action. The idea is based on generation of
78 high accelerations, from 25g to 30g, enough to cause stress at the blade surface. These levels
79 of acceleration and stress can be reached at a frequency close to one of the first 4-6 natural

80 frequencies of the blade between 0 and 50 Hz. It should also be stated that the wave
81 frequency must not match the resonance frequency precisely due to possible risk of damage
82 to structural integrity of the blade. Accordingly this level of vibration should not be applied
83 for more than two seconds to prevent reduction in fatigue life according to the original
84 studies in this area [9].

85 In the following section, a summary of the computer simulation and numerical modelling
86 will be presented. Then some of the prominent results from laboratory trials that validate the
87 model findings are illustrated. Finally the experimental setup and outcome of this new
88 approach in an icing climatic chamber will be demonstrated.

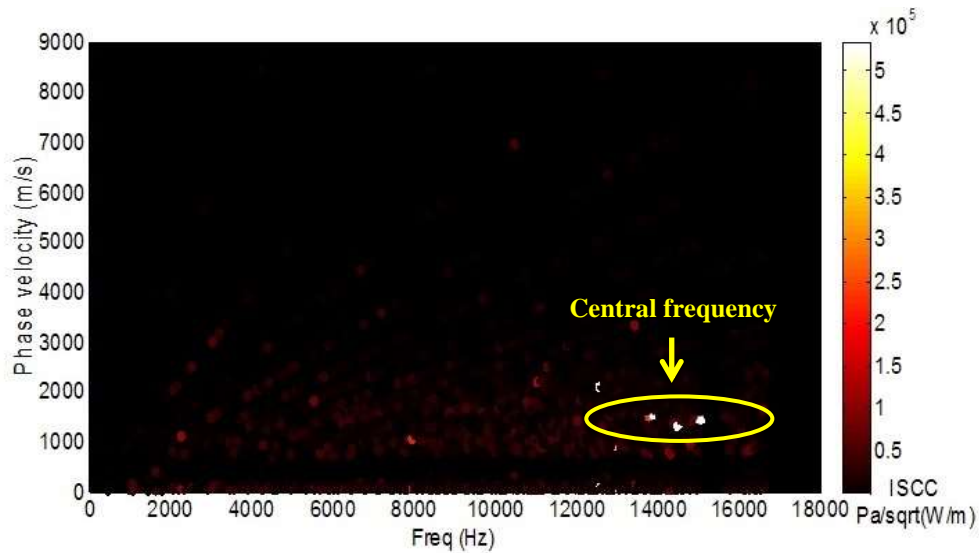
89 2. Numerical modelling

90 As mentioned above, the proposed strategy combines two types of vibration burdening
91 technique at both low frequency (below 50 Hz) and high frequency (10 - 20 KHz). Each
92 technique however needs to be first individually configured and optimised according to its
93 own criteria and requirements in order to be suitable for superposition in the final synergistic
94 approach.

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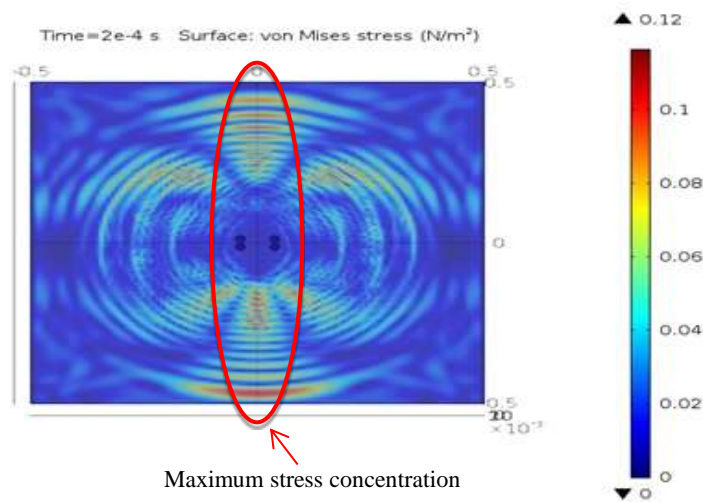
96 2.1. Ultrasonic guided waves

97 Regarding the UGW, the first step is to work out the dispersion curves superimposed with
98 ISCC values for determining the most appropriate wave mode and frequency. This procedure
99 was initiated with modelling of the leading edge of the blades using different thicknesses as
100 well as with different thickness for ice. The ice properties were selected according to a
101 specific type called glaze ice which is one of the most common types forming on wind
102 turbine blades. For example, Fig. 1 represents the combination of dispersions with ISCC
103 values for a 7-mm thick composite blade covered with a 2-mm glaze ice layer. The brightest
104 dots encircled by yellow ellipses indicate the area of highest ISCC. Although it is not quite
105 clear exactly which wave mode should be picked due to the complication of the composite
106 blade geometry, the clustering of several points with high ISCC values implies the central
107 frequency for excitation signal. According to this diagram, the central frequency of the
108 excitation signal should be $f=14.86$ kHz which corresponds to a phase velocity of $v=2093.5$
109 m/s. Since $v = f \lambda$, the wavelength would be $\lambda = 0.1409$ m which is the value considered in
110 calculating the best distance between the transducers. A trial process was then applied on a
111 representative plate with different thickness for a modelled ice layer to figure out the best
112 possible scenario for a transducer array. A sample of these simulations can be seen in Fig. 2
113 which shows the distribution of *von Mises* stress over the plate caused by the propagating
114 waves using a 4-by-4 array and trying different sets of transducer distance in vertical and
115 horizontal directions. In conclusion, a pair of transducers placed $\lambda/4$ away in a vertical
116 direction leads to the best stress distribution and energy concentration on a target line, e.g. the
117 leading edge.



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Fig. 1: Dispersion of a 7-mm thick blade's leading edge with a 2-mm thick layer of glaze ice superimposed with ISCC values



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Fig. 2: Aluminium plate with 2mm-thick glaze ice at 150 μ s

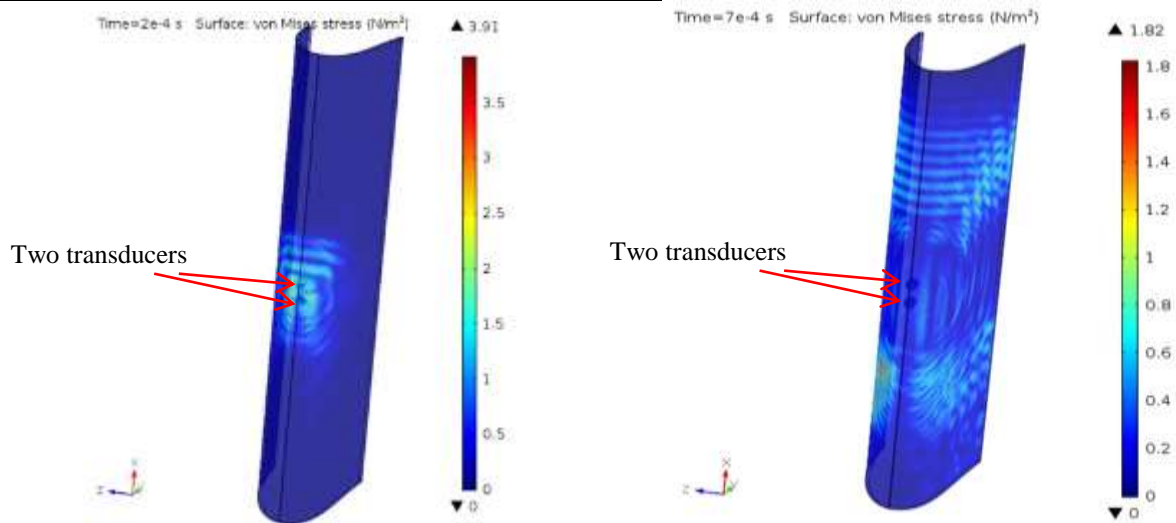
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In addition to the modelling trials for configuring the transducer array, the best excitation direction of the transducers was also investigated. Based on all the scenarios modelled and analysed, it was inferred that a pair of transducers placed at the centre of a 1m-long section of a representative blade leading edge excited in the direction Z (see Fig. 3) leads to the most efficient result which is the propagation of wave as uniformly as possible on the blade surface to create required level of stress in the most of the area. Figure 3 shows the wave propagation and the resulting distribution of *von Mises* stress at two different times. The input was applied as a force per unit area (selected to be 1 MN/m² in this case as an optimum value) on the transducers. As seen in these two diagrams, although the wave does propagate into the composite blade materials, the level of stress caused in the blade surface is not high enough for de-bonding the ice layer due to attenuation. According to previous experimental studies, a range of stress from 0.5 to 3 MPa is required for de-icing [10, 11]. In fact the composite blade

137 section was subject to a rapid attenuation as the waves travel along the blade away from the
 138 transducers. One solution to this problem is using more transducers to cover broader surfaces.
 139 However, it would lead to more energy consumed which degrades the efficiency advantage of
 140 the technique. For this reason, a different approach as attachment of an aluminium shield on
 141 the leading edge was proposed and studied as will be explained in the next section. This
 142 shield not only improves the effectiveness of the wave propagation which leads to higher
 143 shear stress while consuming lower power, but it can also serve for other purposes, e.g.
 144 protection against lightning strike. The properties corresponding to the composite blade
 145 model and the aluminium shield used for the leading edge are given in Table 1.

146 Table 1: Mechanical properties of composite blade and aluminium shield

Mechanical properties	Density (kg/m^3)	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{23}	ν_{12}	ν_{13}
Fibreglass composite used for the blade model	1860	5.62	4.59	4.59	0.41	0.41	0.28	0.24	0.22	0.22
Aluminium used for the shield	2700	70.3			--			0.345		



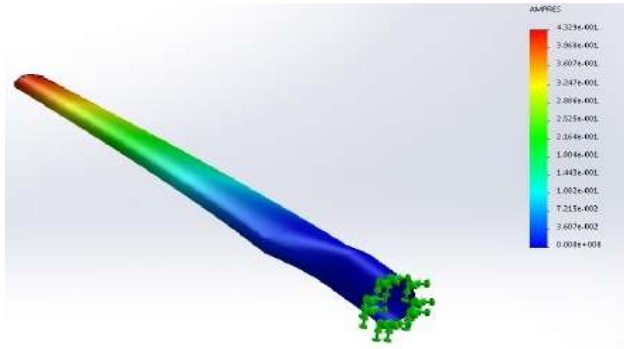
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 148 Fig. 3: Wave propagation in a representative section for blade leading edge at a) $t=2e-4$ sec; b) $t=7e-4$
 149 sec.

150 2.2. Low frequency vibrations

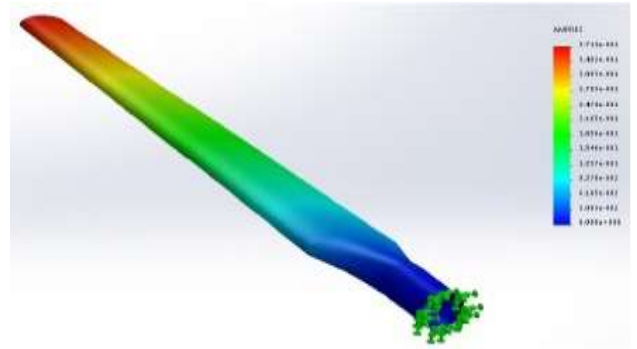
151 In terms of LFV, the modelling process consists of two main parts, i.e. modal analysis and
 152 harmonic analysis through which the best points to induce vibrations are characterised.
 153 Figure 4 shows the first four mode shapes of the blade derived via the finite element software
 154 COMSOL Multiphysics. The blade modelled in COMSOL is 4.5 m long in which a standard
 155 internal structure including skin, spar (shear webs) and caps are considered. This three-

156 dimensional FEM model was constructed using element SHELL181 which is usually an
157 appropriate choice for modelling composite shells and lay-up plates. The blade was generated
158 by 17354 shell elements in total with an increased mesh density towards the edges. Fixed
159 boundary conditions in all directions and rotations were then applied to the root of the blade.

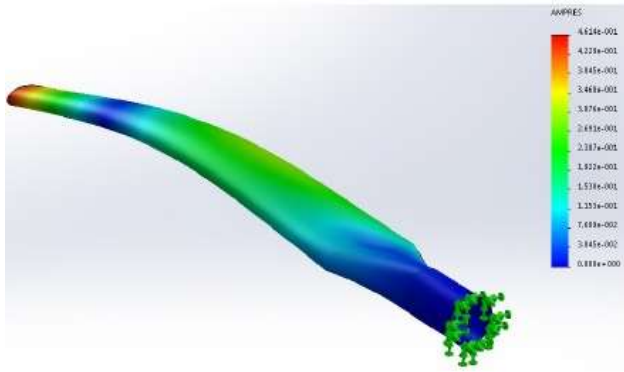
160 The first three modes are flexural bending modes in either flapwise or edgewise directions
161 and the fourth mode is torsional. This analysis was carried out to determine the places that
162 can generate the required acceleration (i.e. 25g -30g, [9]) which leads to sufficient shear
163 stress at the blade surface for de-icing action. For this reason, it is important to excite the
164 proper modes through shakers mounted at the correct points, i.e. the antinodes corresponding
165 to those modes. Having studied all the low frequency modes, the three points indicated in Fig.
166 5 were chosen as the best potential places to be used for a shaker set-up. This arrangement
167 was capable of generating enough acceleration in such a way that the created stress does not
168 exceed the threshold for reduction in fatigue life of the blade (below 10^6 - 10^7 cycles, [12]).
169 This setup is aimed to excite the third mode shape at a frequency close to its natural
170 frequency, i.e. 25.91 Hz. (Note that the operational frequency should not precisely match the
171 natural frequency but only be picked in its vicinity.) For this reason, harmonic analysis of the
172 blade was carried out to monitor the frequency-domain response of the model from 0 to 50
173 Hz. Figure 6 depicts this response as displacement versus frequency in which the resonance
174 frequency corresponding to the third mode shape ($f=25.91$ Hz) is of high interest as it can
175 cause required stress on the blade while not exceeding stress which poses damage to the
176 blade in terms of reduction in fatigue life. In Fig. 7, the stress distribution in the ice layer
177 modelled on the blade, due to application of the optimal shaker set-up at $f= 26.2$ Hz is
178 displayed. As can be seen, the created stress in this mode is high enough to remove the ice
179 while the maximum stress generated due to the first and second mode shapes was sufficient
180 to cause considerable fatigue life reduction to the blade.



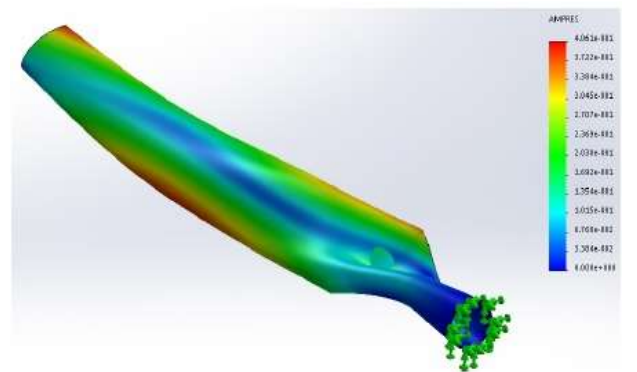
1st mode shape: first flexural bending in flapwise; $f=5.58\text{Hz}$



2nd mode shape: flexural bending in edgewise; $f= 10.72\text{ Hz}$



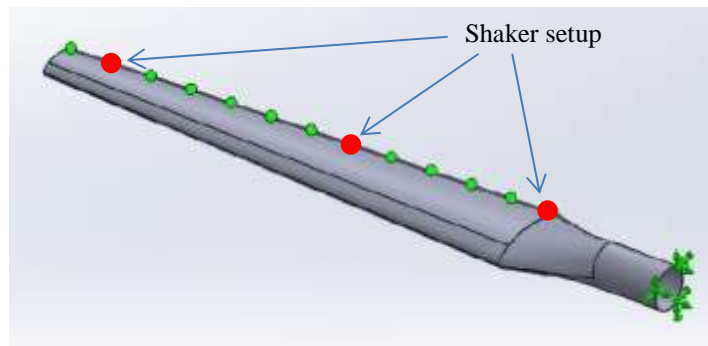
3rd mode shape: second flexural bending in flapwise; $f= 25.91\text{ Hz}$



4th mode shape: first torsional mode; $f= 49.17\text{ Hz}$

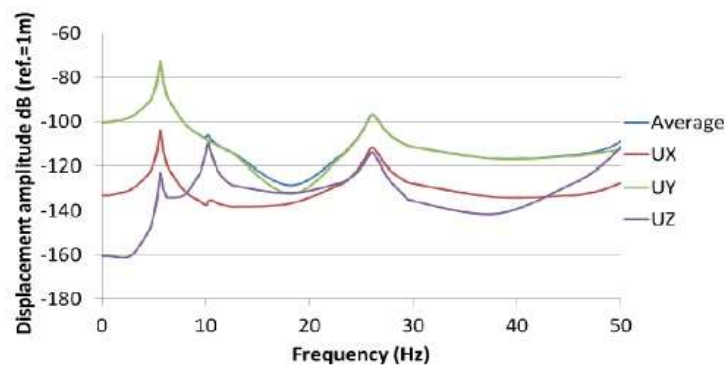
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Fig. 4: The first four mode shapes of the developed blade model



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Fig. 5: An optimal shaker setup to induce LFV on the blade model



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Fig. 6: Displacement frequency-response of the blade model between 0 to 50 Hz in three spatial directions (Ux, Uy and Uz)

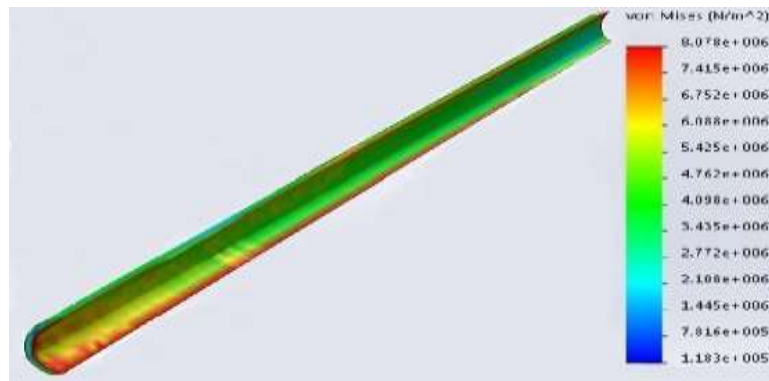


Fig. 7: Stress distribution in the modelled ice layer

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191 **3. Experimental validation**

192 **3.1. Laboratory trials**

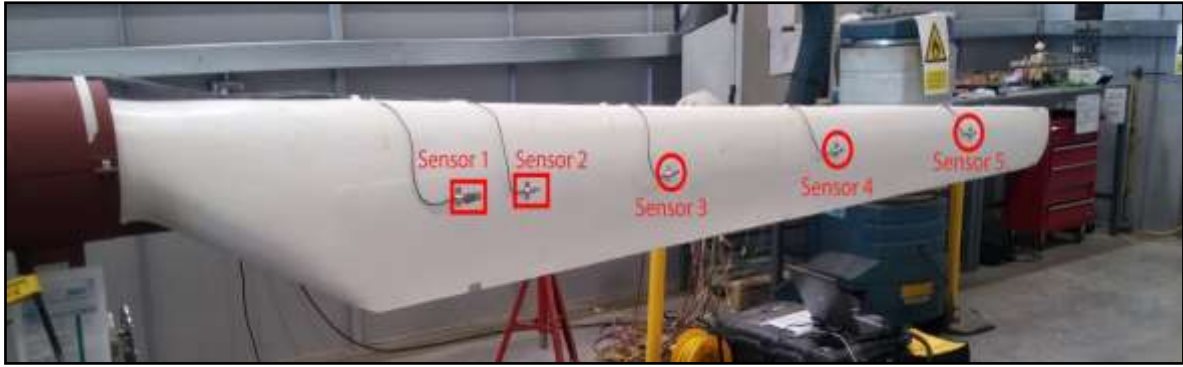
193 In order to predict the capability of the developed approach for tackling ice formation on
 194 the wind turbine blade, a number of laboratory tests were carried out prior to the wind tunnel
 195 trials through using a low-cost thermal chamber and basic standard equipment. The tests were
 196 implemented for both techniques, UGW and LFV, separately using different samples as each
 197 technique demands its own criteria and conditions for optimum performance.

198 **3.1.1. LFV tests**

199 There are a few parameters through which the empirical data can yield to demonstrate and
 200 validate the modelling results to ensure that the selected operational values meet the de/anti-
 201 icing criteria while no ice is used for the LFV experiments described as follows.

202 *3.1.1.1 Strain gauge setup*

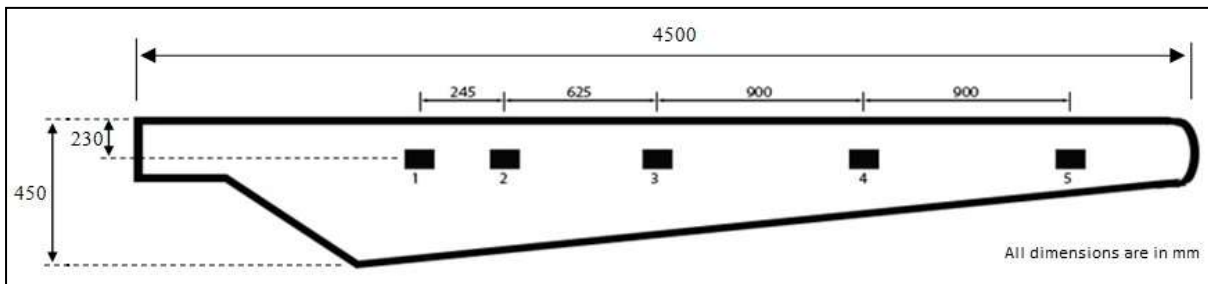
203 One of these parameters is the operational frequency of the shaker whose effectiveness can
 204 be verified through checking appropriate strain/displacement induced on the blade. As one
 205 method, five strain gauges were installed along the blade longitudinal axis, as shown in Fig.
 206 8, to measure the displacement of five different points of the blade while the harmonic force
 207 frequency was swept up to 30 Hz. Shown is also Fig. 9 in which the dimensions of the blade
 208 and the coordinates of the five strain gauges are specified. This setup should reveal the
 209 suitability of the operational frequencies determined by the modelling results. For this reason,
 210 the readings by the sensors undergoing strain needed to be processed. According to the
 211 measurements, the third mode shape which has the natural frequency at 26.2 Hz vibrating the
 212 blade in the flapwise direction is highly effective due to the maximum amount of required
 213 strain generated on the blade surface at this mode/frequency.



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Fig. 8: Experimental strain gauge setup indicating position and number of the sensors (strain gauges) on the blade

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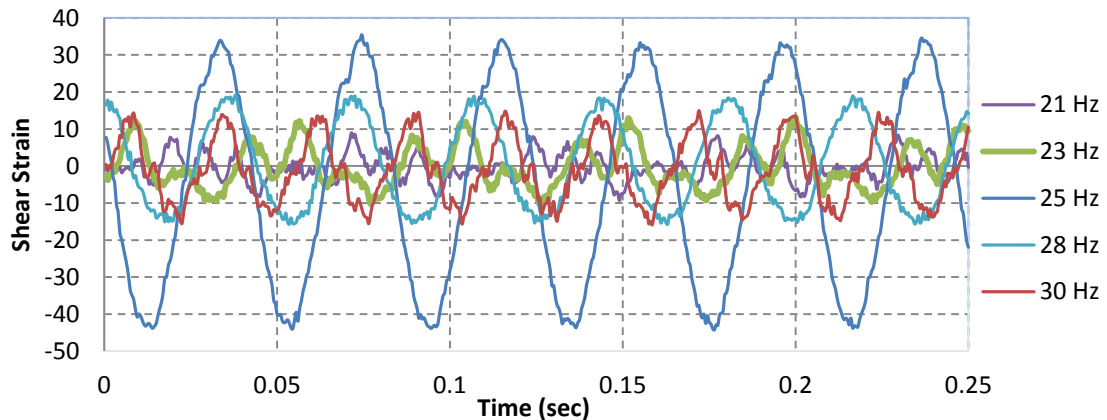


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Fig. 9: Dimensions of the blade and positions of the five installed strain gauges

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221 As a first example, Fig. 10 shows the shear strain recorded by sensor 2 over the first 0.25
222 seconds at four frequencies. More frequencies could have been displayed here but to avoid
223 confusion in the diagram, only a few frequencies around $f=25$ Hz have been presented.



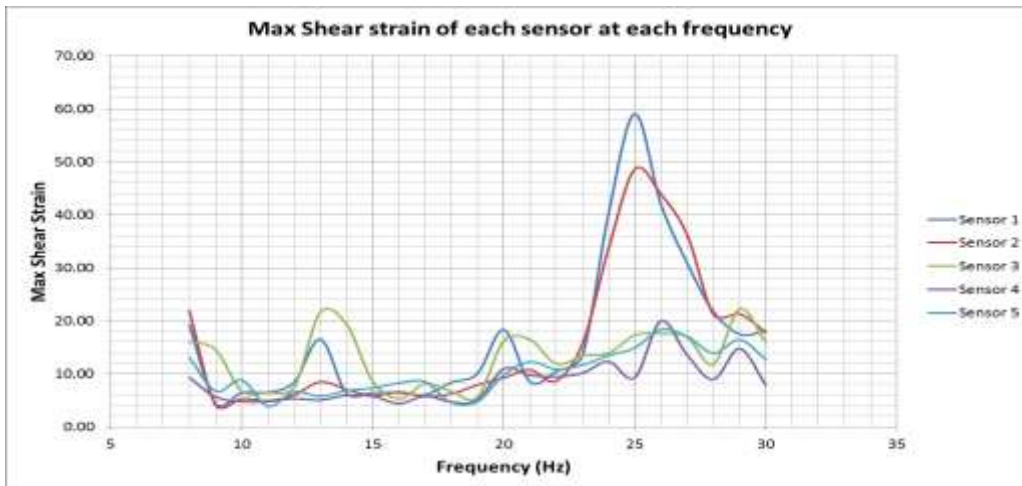
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Fig.10: Variations of shear strain recorded by sensor 2 over time at a few frequencies around $f=25$ Hz

226 As can be seen in Fig. 10, sensor 2 records the highest values of shear strain at 25 Hz
227 which is consistent with the modelling results. Likewise, the data taken from other sensors
228 confirm the same trend as sensor 2.

229 Finally, to have an overall view of the performance of all low frequencies tested on the
230 blade over the full-time operational period from 0 to 10 seconds, Fig. 11 displays the

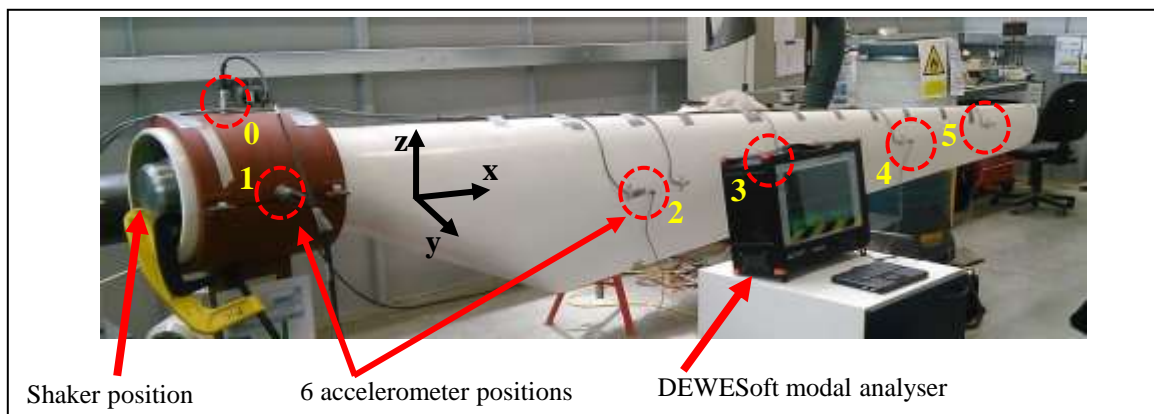
231 maximum shear strain recorded by all 5 sensors. As can be seen, for the first two sensors
 232 taking the data from the critical points of the blade, i.e. close to the hub, the maximum shear
 233 strain by far occurs for the third mode shape. For the other three sensors, although the shear
 234 strain does not maximise at $f=25$ Hz, there is still a high amount of strain at this frequency-
 235 noting that the last three points are not as crucial as the first two ones in terms of being prone
 236 to ice accretion. For this reason, the frequency at which the first sensors show higher values
 237 should be considered top priority. Thus, $f=25$ Hz should be selected as the optimum
 238 operational frequency for the induced low-frequency vibration of the blade.



239
 240 Fig. 11: Representation of maximum shear strain recorded by the 5 strain gauges mounted on the
 241 blade over a 10-sec operational period versus a frequency spectra from 8 Hz to 30 Hz.

242 *3.1.1.2 Operational modal analysis*

243 Another verification of the modelling results is via operational modal analysis to work out
 244 the mode shapes of the blade and hence the optimal excitation frequency. The experimental
 245 setup adopted for this experiment is shown in Fig.12 where the shaker (eccentric rotating
 246 mass) has been fitted inside the root of the blade generating the harmonic force.



247
 248 Fig. 12: Experimental setup for modal analysis using 6 piezoelectric accelerometers.

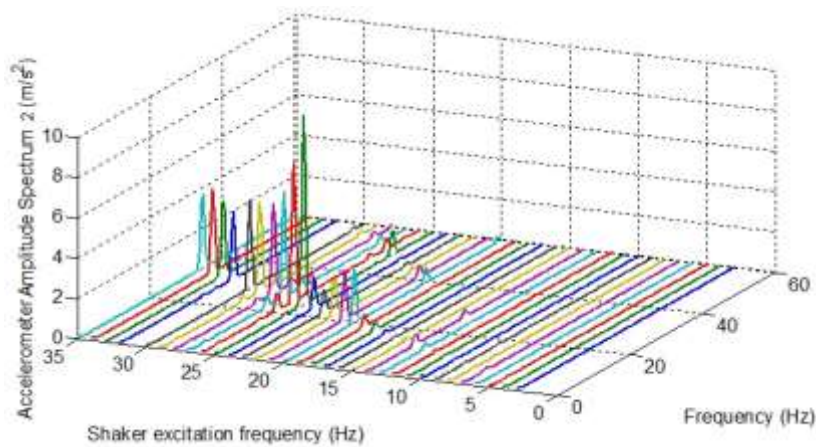
249 The acceleration responses are measured in six different positions; five along the
 250 longitudinal axis of the blade (root to tip) to measure acceleration in the horizontal direction
 251 (y) and one, numbered 0, in the root of the blade to measure vertical acceleration (z). The

252 coordinates of these six accelerometers are displayed in Table 2. Fourier analysis was
 253 performed by a commercial system, DEWESoft's SIRIUS R8. Measurements were
 254 performed over 10 seconds with 20 kHz sampling rate at each excitation frequency between 0
 255 and 35 Hz. Each excitation frequency is adjusted manually and the software rerun in each
 256 case. Then the Fourier spectrum of acceleration is calculated by the software, making it
 257 possible to visualise data during the experiment and record it in a *txt* file for post-processing.

258 Table 2: Accelerometer positions on the blade

Accelerometer No.	Distance from blade root (mm)	Measurement direction
0	200	z
1	200	y
2	1400	y
3	2240	y
4	3140	y
5	4040	y

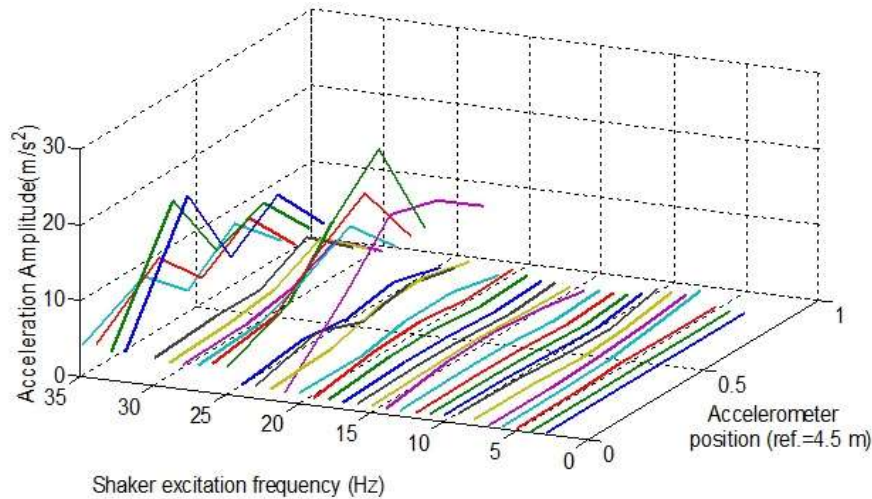
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 260 Using the commercial software MatLab, a routine was created to extract and plot the data
 261 (amplitude spectrum values of accelerations) from all the *txt* files. These results were
 262 recorded as 3D plots and represent the acceleration response spectrum for each individual
 263 accelerometer reading as a function of the frequency response of the structure and the
 264 excitation frequency. As an instance, the plot in Fig. 13 shows the spectrum for accelerations
 265 taken at accelerometer 2, close to the hub.



266
 267 Fig. 13: Fourier amplitude spectrum for the acceleration of the blade read by accelerometer 2

268 Figure 13 shows that the mode shape corresponding to a frequency around $f=25\text{Hz}$, shown
 269 by the green curve, can create considerable acceleration helpful for shaking off the ice. Other
 270 accelerometers also show high values of acceleration at this frequency, which is consistent
 271 with the modelling results. Figure 14 presents the maximum amplitudes of accelerations
 272 measured at each accelerometer position as a function of frequency excitation. As seen in the
 273 plot, the two mode shapes with the resonance frequencies of 21 Hz and 25 Hz generate the
 274 highest acceleration making them suitable for ice removal.

275 The main objective of this work (operational modal analysis), i.e. identification of the
 276 mode shapes, especially the third flexural bending modes, was achieved as the result
 277 compares satisfactorily with the modelling results.



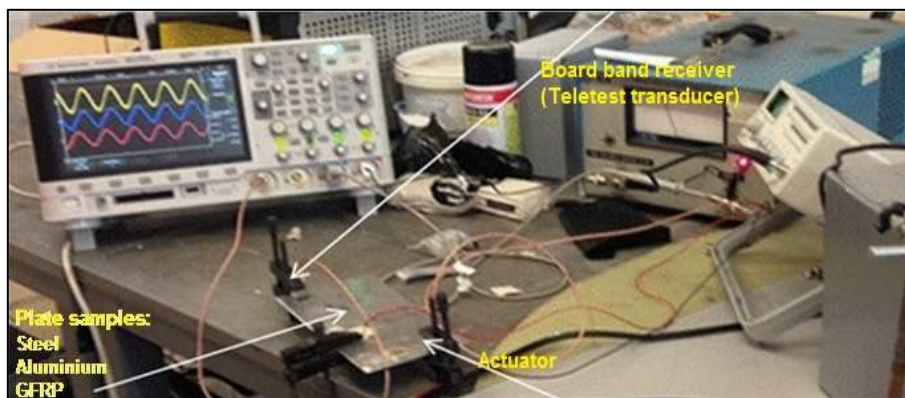
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279 Fig. 14: Maximum acceleration obtained at each acceleration position over the excitation frequency
 280 spectra.

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282 **3.1.2. UGW tests**

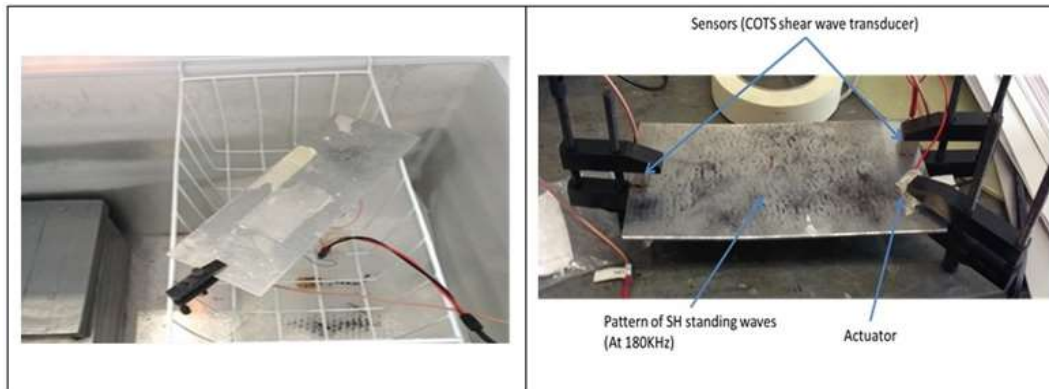
283 For the laboratory trials, UGWs were propagated in a range of steel, aluminum and glass
 284 reinforced plastic plates, 0.5mm – 2mm and small enough to place inside a freezer, with
 285 UGW actuators clamped to the plate (Fig. 15). An Agilent Technologies digital oscilloscope
 286 type MSO-X 302A was used to generate a constant sine wave voltage, up to a maximum of
 287 5V peak-to-peak, over a range of frequencies from the Hz into MHz ranges. 5V peak to peak
 288 was found to be adequate for most of the experimental work here, though a 10V output Instek
 289 sine wave generator type 8216A was also used to give higher voltages. The sine wave
 290 generator was connected to an EIN RF power amplifier type 240L to generate the voltage
 291 amplitudes necessary to drive the shear actuators. These voltages ranged from 50V to 200V
 292 peak-to-peak.



293

294 Fig. 15: Typical experimental set-up
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297 To create ice on the surfaces of the plate, plates were placed inside a domestic freezer
 298 (Fig. 16a).



299
 300 Fig. 16: The test plate in experiment, a) Ice patches created in freezer; b) Standing SH wave patterns
 301 in iron oxide powder

302 Validation of the numerical models of ice debonding experimentally from the substrate
 303 with Shear-Horizontal (SH) guided ultrasonic waves proved to be impossible. The time it
 304 took to remove the ice was a determining variable and this varied according to the thickness
 305 of the ice, its distance from the actuator, the nature of the substrate and even the ambient
 306 temperature. Moreover, the actuators generate heat and it was not always possible to
 307 determine whether or not this was causing the ice to melt, rather than SH-waves causing the
 308 ice to substrate bond to break. A real-time metric was needed.

309 One discovery was that fine black iron oxide particles, used in magnetic particle
 310 inspection, could visualize SH standing waves in the plates. This was a very useful
 311 phenomenon, because the patterns would only appear when resonances occurred in the plate,
 312 and the distances between the nodes and anti-nodes could be measured to provide
 313 measurements of wavelength. The particles move in response to the shear stresses on the
 314 plate surfaces, which, in the presence of standing waves, give rise to patterns in the powder
 315 distribution (Fig. 16b). To apply the powder evenly, a dry powder puffer bulb was used.

316 Another metric was to measure the displacement at the surface with a shear wave sensor.
 317 Transducers from the commercially available Teletest Long Range Ultrasonic Testing
 318 (LRUT) system were used for this purpose. These have shear wave elements that are highly
 319 damped, in order to give short pulses of ultrasound with minimum ‘ringing’ that are needed
 320 in pulse-echo ultrasonics. The damping gives the transducers very broad band receiver
 321 response. The Teletest transducer was connected to the same oscilloscope as the actuators so
 322 that both the transmitted and received sine waves could be observed and phase shifts and
 323 amplitude changes could be observed in response to changes in frequency.

324 The Teletest shear transducer is designed for pulse-echo ultrasonic testing. It is therefore
 325 heavily damped and of low power output. A range of alternative high-power shear wave
 326 actuators including Lead Zirconium Titanate piezoelectric (PZT) and resonating Macro-
 327 Fibre-Composites (MFCs) were investigated (Fig. 17).

328 MFCs were first investigated as these give relatively large displacements (>10microns)
 329 with moderate applied voltages (<200 V). However, the shear actuation is complicated by the
 330 bipolar nature of the motion, where the ends of the MFC element move in and out in unison
 331 and the middle element is stationary. This in effect creates two SH waves.

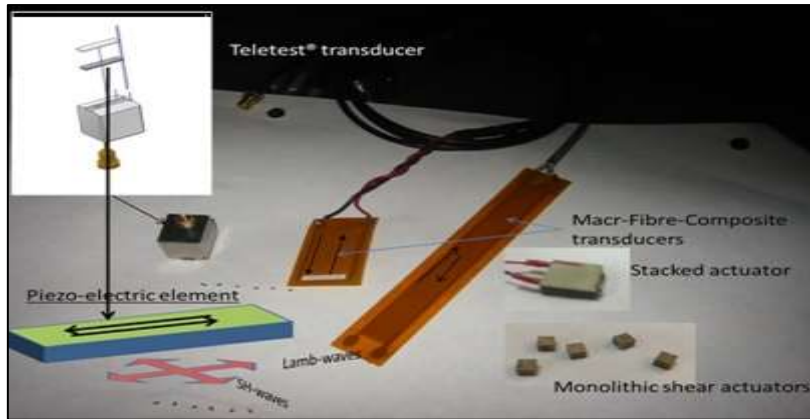


Fig. 17: Actuators used in the experiments

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334 A range of 6mm x 6mm and 10mm x 10mm PZT actuators, 1.7mm and 3.4mm thick with
 335 either single (X or Y direction) or dual (X and Y direction) motion were acquired. It was
 336 found that the thickness of the shear actuator determined the amount of displacement with
 337 each stroke of the applied voltage - the thicker the element, the greater the voltage needed to
 338 power it. To increase the magnitude of the actuator displacement, it is possible to stack two or
 339 more elements together separated by electrodes. The experiments conducted here used two-
 340 element stacked actuators.

341 The actuator was placed close to one end of the plate, and the shear wave sensor at the
 342 other. For the de-icing experiments, after the ice had formed, the plate was held vertical in the
 343 ice box or freezer. For the visualization experiments, the plate surface, which had been
 344 carefully dried, was held horizontal.

345 The initial experiments with the available PZT shear actuators attempting to break the ice
 346 to substrate bond did show some debonding of the ice from the substrate, but this could have
 347 been a thermal effect rather than a mechanical one. A new study of standing SH-waves in the
 348 plates using the iron oxide powder as the detecting medium and the LRUT shear transducer
 349 as the SH-wave sensor was performed. A parametric study was set up to find the influencing
 350 factors on the amplitude of standing SH waves (Table 3). In this study, the temperature of
 351 both ambient and freezer were changed to see their effects on the performance of the waves.
 352 Likewise actuators of different orientations for propagating waves, different positions and
 353 different resonating pressure were examined. Also the orientations of receivers were being
 354 varied to ensure the reception of maximum wave amplitude.

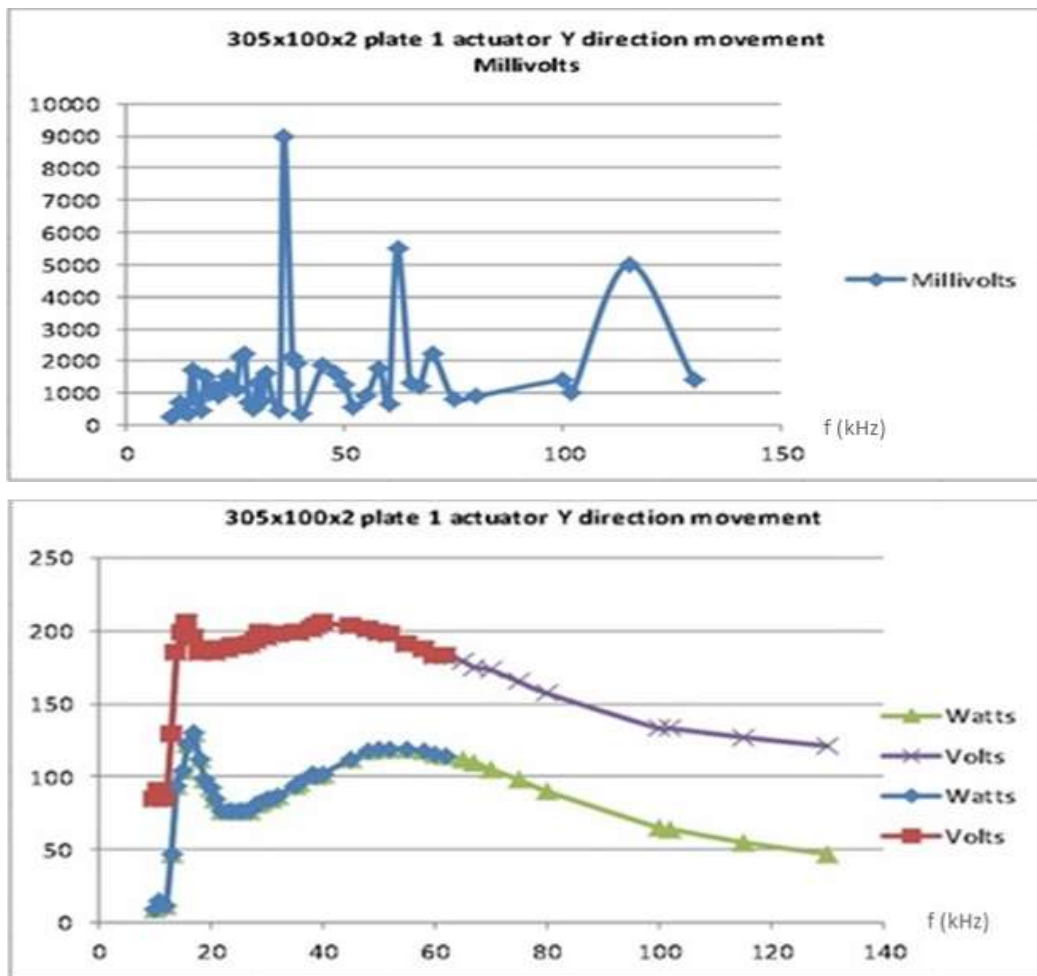
355 Table 3: Matrix of parameters

Temperature		Actuator										Receiver		
Ambient	Freezer	Orientation		Position						Pressure (per unit area)			Orientation	
20C	-10C	X	Y	15.5/ 5	15.5/ 6	15.5/7.5	25/5	27/5	29/5	0.3 N	0.4 N	0.5 N	X	Y

356

357 For each experiment a frequency sweep was conducted, starting at just within the audible
 358 frequency range (15 kHz) and ending at about 350 kHz, according to whether or not a voltage

359 could be detected at the sensor. A typical data record is shown in Fig. 18, the peaks in the
360 voltages at the sensors occurring at the plate SH-wave resonances.

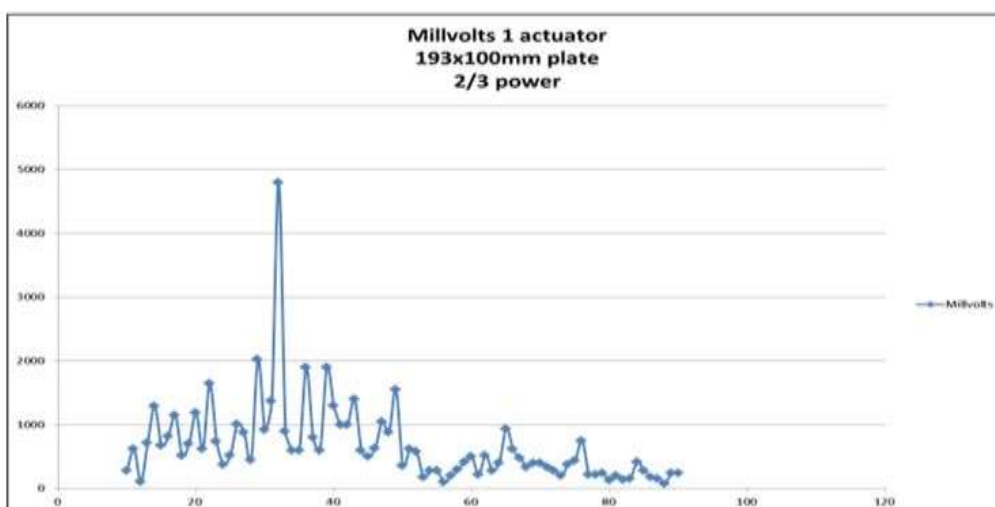


361

362

Fig. 18: Example experiment data set

363 The parametric study showed that the dominant influence on plate resonance was plate
364 width.



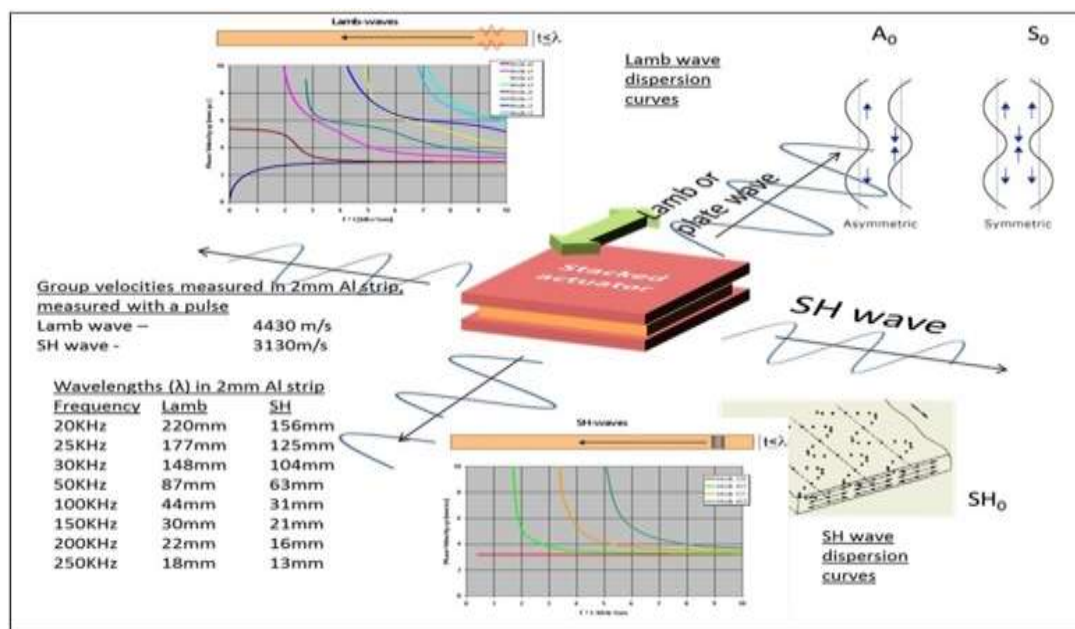
365

366

Fig. 19: Peak resonance in 100mm wide Al plate

367 With the actuator placed in the middle of the plate, the first resonance would occur when
 368 the plate width was equal to $\frac{1}{2}$ wavelength of the S0 wave (Fig. 19). This is due to the shear
 369 wave actuator propagating a Lamb wave orthogonal to the SH wave (Fig. 20). The Lamb
 370 wave component is shown in the upper part of the figure, the SH wave component in the
 371 lower part. The graphs show the respective Dispersion curves, from which values for
 372 wavelength of Lamb waves and SH-waves at different frequencies in a 2mm thick Al strip
 373 have been derived. Lamb waves are made more complicated than SH waves by the presence
 374 of symmetric and anti-symmetric motions.

375 The parametric study also concluded that shear horizontal waves (SH waves) are
 376 attenuated too strongly in GFRP to be used for de-icing the leading edge of a wind turbine
 377 blade. Therefore, as an innovative solution, it was proposed to use an aluminium strip
 378 mounted on leading edge of the blade, to which the SH-wave actuators were attached. A
 379 schematic of the shield and its dimension details along with an ultrasonic actuator array
 380 placed along its centre-line is shown in Fig. 21.



381
 382 Fig. 20: Orthogonal SH and Lamb waves from actuator

383 The power required for protecting the Al strip shown in Fig. 21 was almost 400 W
 384 consumed by the 4-transducer array to be used for a single blade. This means that the total
 385 power consumption for a three-blade wind turbine would be 1200 W, 1.6% of the turbine's
 386 nominal power output (as the modelled blade is pertinent to a 75-kW wind turbine). This
 387 amount of power is a considerable reduction compared to the power consumed by thermal de-
 388 icing techniques which usually reaches up to 15% [2].

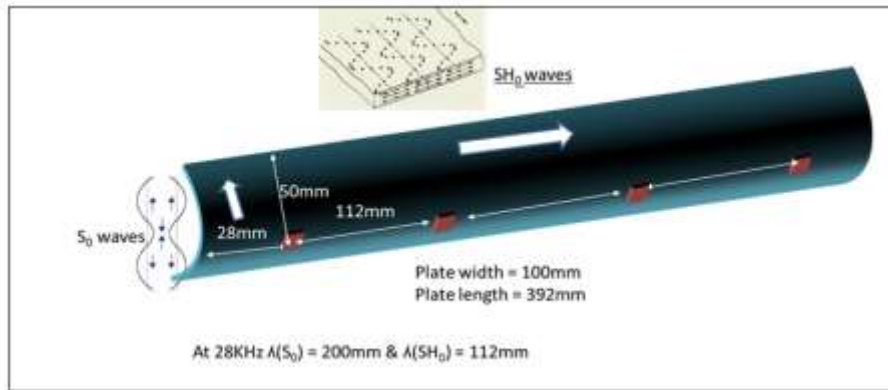


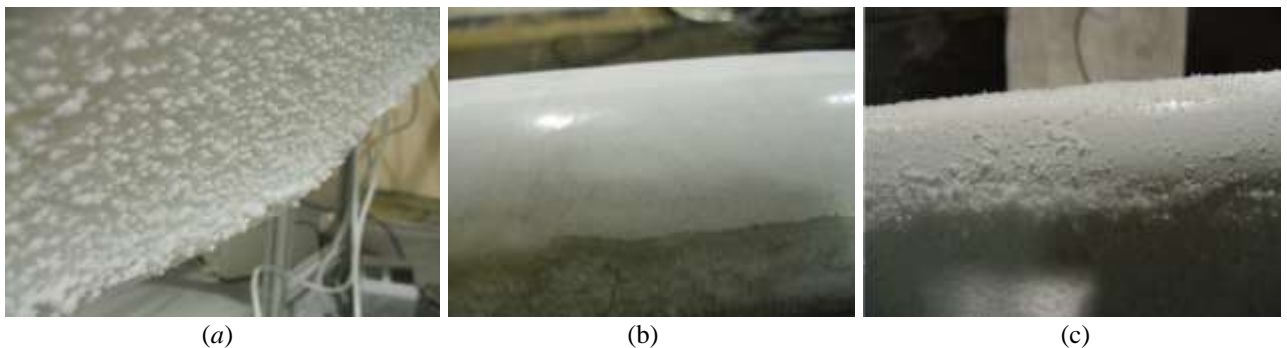
Fig. 21: Design for de-icing shield along leading edge of turbine blade

389
390

391 3.2. Wind tunnel testing

392 Once reliability and performance of both the UGW and LFV techniques were verified in
 393 the laboratory experiments, the approach was tested in a climatic chamber with interior
 394 dimensions of 3300mm x 3555mm x 7000mm. The tunnel air temperature could reach down
 395 to -40°C with possibility to apply different relative humidity ranging from 5% to 95%. The
 396 chamber had fully enclosed support building with a circuit type of vertical return. It was
 397 provided by two airflow nozzles and a cooling system of 765kW capacity supplied by twin
 398 rotary-screw compressors and heat exchangers.

399 The procedure in the icing tunnel was application of the integrated setup to investigate the
 400 synergistic effects of this approach. The mock-up wind turbine blade provided by the shaker
 401 setup and ultrasonic transducer array was then subjected to ice formation in the wind tunnel
 402 under freezing conditions. The temperature during the experiment was kept in a constant
 403 domain between -18°C to -21°C . Also, the relative humidity was always near to saturation
 404 ranging from about 80% to 95%. Forming the ice was carried out using a special water
 405 sprayer/gun driven by high pressure air. Since the type of ice built up depends on a few
 406 factors such as water droplet size, chamber humidity, temperature and airflow velocity,
 407 various types of ice were formed under certain conditions. Fig. 22 shows the three types of ice
 408 created on the blade during trials in the wind tunnel.



409
410
411

Fig. 22: Different types of ice formed in icing wind tunnel; a) hard rime ice, b) clear glaze ice, c) soft frost (snow-looking ice)

412 The performance of the approach to tackle ice accumulation depends on the ice type. Since
413 humidity and temperature in the chamber were changing in a narrow domain, the type of
414 formed ice was highly dependent on the way water sprayed on the blade surface. In fact, it is
415 important that how far the water gun is operated from the target surface. This factor
416 determines the size and instant temperature of water droplets as well as the speed of their
417 impingement to the blade. The major ice shape built up was *hard rime* ice which is a milky-
418 looking ice with a comb-like appearance that usually forms with high velocities. This type,
419 shown in Fig. 22a, is a very hard ice found in nature. In the wind tunnel, this type appeared to
420 accrete mostly when water sprayed on the blade surface from a distance of approximately
421 0.6m to 0.7m. The height of the teeth of a rime ice layer, on average reached up to about
422 10mm within roughly one hour constant spraying.

423 The closer the water gun is to target surface, the higher is speed of impingement of water
424 droplets. On the other hand, when water was sprayed from a further distance, the droplets
425 became more scattered and finer with more chance for heat transfer with ambient. Once the
426 water spray jet was approaching to the blade, the ice became clearer and smoother so that in a
427 distance less than 20cm away, a transparent and quite homogenous ice coating so called clear
428 glaze ice (shown in Fig. 22b) was built up. It took around 60 minutes to form a 5mm thick
429 layer glaze ice. This type normally forms due to the impact of water droplets at temperatures
430 near freezing [13].

431 In addition to the high hardness of rime ice, it is mentionable that the characteristics
432 assumed for the theoretical studies and modelling procedures were not correlated to this type
433 but rather to the properties of glaze ice. For these reasons, although the developed strategy
434 was able to cause some cracks of up to almost 10 cm long in the layers of rime ice, it was
435 unable to achieve complete ice removal. On the contrary, as shown in Fig. 23, the transducer
436 array with the complementary effects of shaker setup could cope with removal of the glaze
437 ice. This removal occurred first for about a 20-cm long patch of the 5-mm thick ice layer
438 (around half of the Al bent plate representing the leading edge) almost instantly after the ice
439 protection system was switched on. The other half of ice patch was shed off within two
440 seconds after start-up. Except two very narrow strips hooked on the edges of the bent plate,
441 there were no even tiny spots remaining on the entire leading edge. This observation was
442 verified through two more attempts under same conditions while similar results were
443 achieved each time.



444
445 Fig. 23: A de-bonded layer of glaze ice formed on the Al strip mounted on the blade leading edge

446 In terms of the third type of ice i.e. snow-like, soft frost, the integrated setup could cope
447 with it as shown in Fig. 22c. Although there were a few small ice patches of about 8mm
448 thickness remaining on the lower parts of the blade, but the most crucial area i.e. the top strip
449 of the leading edge became entirely ice-free within 2-sec of the system operation. This soft
450 form appeared when the water spray was used more than a meter away from the blade
451 surface. Under this condition, the airflow was much slower and the water droplets became
452 even finer compared to the other two forms. In such a long range that droplets hit the surface,
453 they have more chance for heat transfer with ambient and therefore becoming cooler. Since
454 the bond of this type is not very firm and its density is very low compared to the other two
455 types, the performance of the shaker setup was understandably more effective than the UGW
456 transducer array.

457 It should also be noted that, in the wind tunnel, it was not feasible to take into account the
458 effects of centrifugal force arising from rotation of the wind turbine propeller. While the wind
459 hitting the blade was simulated in the chamber, this force acting on the ice layers could
460 obviously be helpful in stripping off the ice. For this reason, it can be stated that the approach
461 performance could have been even more effective in presence of centrifugal forces.
462 According to some preliminary simulation, this force is even stronger than the force caused
463 by LFV but since it applies as in-plane direction, it is not as effective as the normal-to-plane
464 LFV forces. Therefore, the approach is recommended to be tested under real conditions as
465 field trials where the turbine propeller spins.

466 **4. Concluding remarks**

467 In this study, a new approach to protect wind turbine blades against icing problems was
468 presented. The strategy is based on the superimposition of ultrasonic guided waves (UGW)
469 with low frequency vibrations (LFV) in such a way that the UGW shortcomings are
470 compensated by LFV. In fact, UGW has already been applied to ice protection systems but
471 has been never combined with any other type of vibration to improve its efficiency. In this
472 work, while the UGW technique was adapted for an anti/de-icing system for a mock-up wind
473 turbine blade, its functionality with the supplementary effects of LFV was enhanced further.
474 In fact, as the UGW approach takes care of the main action in generating shear stresses to de-
475 bond the ice layer accreted on the blade, the LFV shaker setup applies excessive stress
476 through high accelerations within a short period of operation to complement UGW's
477 performance and shed the ice.

478 The initial challenge was to characterise the optimum parameters of the UGW technique
479 through FEM modelling and post-processing analysis: best wave mode, excitation frequency,
480 excitation direction, number and geometry of transducer array to propagate the ultrasonic
481 waves using a minimal power were determined. At the same time, an FEM model of the full-
482 scale blade was developed for modal and harmonic analyses from which the optimum
483 characteristics of the shaker setup were evaluated. Then, laboratory trials to validate
484 modelling results obtained for LFV performance were implemented on the blade. The trials
485 included a strain gauge setup, to measure displacements, and operational modal analysis,
486 through an accelerometer setup, to characterise mode shapes. The data obtained by

487 experimental post-processed data and modelling results were in reasonable agreement.
488 Regarding the UGW experimental tests, as expected according to the modelling results, the
489 waves were strongly attenuated in the composite test pieces. Hence, as a novel solution, the
490 tests were carried out for an aluminium strip to be bent and mounted on the leading edge of
491 the blade as a shield in order to conduct the waves efficiently for ice removal. The required
492 power turned out to be very low compared to thermal ice protection systems making it an
493 efficient technique.

494 As the final phase, the blade was tested in an icing wind tunnel using the final setup
495 integrating LFV and UGW strategies. Different forms of ice were developed on the blade in a
496 climatic chamber. Since the technique development has been based on considering glaze ice
497 properties, the approach could cope with removing the clear glaze ice and soft frost when
498 both UGW and LFV are applied in a synergistic way as planned. Although the approach was
499 not entirely successful in the case of hard rime ice, there were some promising indications
500 that the approach could work even for hard rime ice, if the properties of this ice form were
501 considered in developing the technique.

502

503 **Acknowledgements**

504 This paper is a technical summary extracted from a project called DeICE-UT. The DeICE-
505 UT project is co-founded by the European Commission through the Seventh Framework
506 Programme (FP7/2007-2013) managed by REA-Research Executive Agency through the
507 funding scheme “Research for the Benefit of SMEs” under Grant Agreement No.605138.
508 DeICE-UT is collaboration between the following organisations: TWI, Brunel University
509 London, ZUT, BS Rotor, DTK Electronics, Selftech, Smart Material, Floteks and Tureb.

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