Smart Affordable Composite Blades for Tidal Energy

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Abstract— The absence of reliable, high-performance affordable turbine-blades is an obstacle to the commercialisation of tidal-stream energy. This paper describes a novel, but commercially proven, manufacturing process for composites that can address this challenge and discusses the merits and limitations of the resulting blades. The process uses a ceramic, heated mould to process epoxy powder and glass fibre into blades and offers advantages over alternative techniques. The paper also outlines a sensor system for blades that reduces maintenance costs and increases reliability. Together, these technologies are set to play an important role in creating a new European industry – the production of tidal stream turbines. The research is being funded through the Smart Efficient Affordable Marine Energy Technology Exploitation using Composites (SEA*ME*TEC) project, within Horizon 2020 SME Instrument framework.

Keywords— Composites, low-carbon ocean energy, tidal turbine blades, fibre-crimping, fibre wet-out, manufacturing improvements.

I. INTRODUCTION

Tidal energy offers substantial potential to increase security of supply of electricity and reduce carbon emissions across many coastal regions of the EU and other countries (e.g. Canada, Chile, and Korea). Whereas tidal barrages are a fully commercial technology, tidal current turbines which allow more phased development of tidal resources are only now in the process of being demonstrated. Technological and commercial challenges have limited their success to date but many of these challenges are now being addressed and prototype commercial turbines are being built [1].

For tidal turbines, volume manufacturing of high-quality, cost-effective blades remains a challenge. Tidal turbine blades are shorter but need to be much stiffer and stronger when compared with equivalent power wind turbine blades due to the difference in density between water and air (approx. 800 times more dense) and the complex loads that tidal blades experience (combined tidal, wave and buoyancy loads).

This paper presents a new technology that can deliver high-performance, low-cost tidal turbine blades to the market using a manufacturing technique that is suitable for volume manufacturing (more than 20 blades). It also presents technology for SmartBlades, *i.e.* blades that capture data from sensors embedded within the blade and monitor strain and damage during operation. Information from the sensors will inform preventative maintenance and repair of turbines and increase up-times and revenues. Together, these technologies will remove an important obstacle to the commercialisation of tidal energy and will contribute to increased renewable electricity generation.

The paper is organised as follows. Section II provides a brief overview of the Tidal Energy Market and competing technologies before proceeding to outline the challenges facing the industry and the objectives of the research work described in this paper. Section III presents the different technologies used to manufacture tidal turbine blades and presents a new technology that will increase blade quality while also reducing cost. Sensor systems for monitoring and optimising tidal turbine blades are presented in Section IV, which is followed by a discussion of key results and a concluding summary of the paper.

II. OVERVIEW OF TIDAL ENERGY

This section argues that there is a real opportunity to make tidal energy a commercial reality but that key obstacles need to be overcome in order to make this opportunity a reality.

A. The Market

The European Ocean Energy Association has predicted that tidal stream energy capacity by 2050 could exceed 100GW globally [2], which if realised would correspond to a €200-300bn industry [3]. Other estimates for tidal energy capacity are shown in Table 2.1 below. Blades account for 15% of the cost of wind turbines [4]; if the cost breakdown for tidal turbines is similar, a €45bn market for tidal blades will result.

. TABLE I
DIFFERENT PROJECTIONS FOR TIDAL ENERGY

Source	**Year**	**Market Size**
EU-Ocean Energy Association [2]	2050	100 GW
International Energy Agency [3]	2050	1.200 TWh/year
MCT/Siemens [5]	Worldwide theoretical power	120 GW (Tidal Stream)

It is also worth noting that the cost of €2-3m/MW assumes commercial scale developments and that the first projects will be considerably more expensive. The MeyGen project for example has raised £51m, most of which will be spent on the first array of four 1.5MW tidal turbines, hence a gross capex of up to £8.5m/MW [6].

The UK is the most advanced tidal energy market due to a number of factors:

1. Leader in offshore wind which offers synergies for tidal energy;
2. Home of OEMs that have the most developed devices;
3. Government support;
4. Leading international position in terms of permits issued;
5. Home of the EMEC (European Marine Energy Centre) – a leading full-scale offshore energy test facility;
6. Has some of the best commercially accessible tidal resources in the world.

Several hundred MW of tidal stream energy projects are already either in planning or under development in the UK. Bloomberg predicts that 148MW of tidal stream power will be installed by 2020 [7].

France has become much more interested in tidal energy in recent years with major companies such as DCNS and Alstom taking majority stakes in tidal turbine OEMs. Ireland, the USA and Canada as well as Korea and Japan, and possibly Spain and Norway, are also poised to become important players in tidal energy markets.

The tidal industry has seen numerous initiatives (equity, grants etc.) implemented by the EU/European governments designed to build and improve their ocean energy potential for the future [8]. These include SI Ocean (Strategic Initiative for Ocean Energy) and the EU Ocean Energy Forum. Private investment has also increased: over €700m flowed into tidal and wave energy in the 10 years to 2014 [8].

B. *Tidal Technologies*

The Tidal Energy Conversion (TEC) market has not yet fully converged on a preferred option in terms of technology or maintenance strategy and many companies are competing for market share.

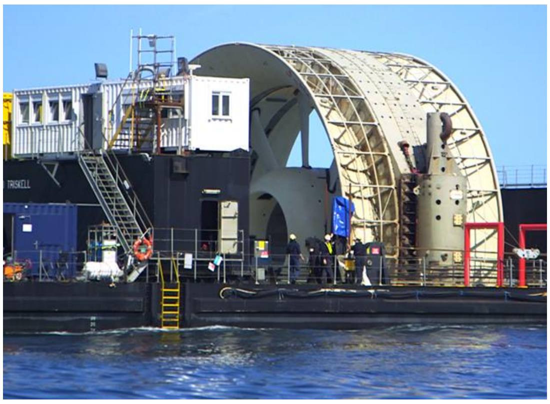

Fig. 1. OpenHydro's 16m Diameter Tidal Device

Many tidal turbines are conceptually similar to wind turbines but typically with shorter, stiffer blades. Such designs have been built by several OEMs including Andritz. OpenHydro, in contrast, have manufactured an "open-centred" design (Fig 1).

Most devices so far have been designed for installation on bottom-fixed foundation, but some are suspended from a floating structure (e.g. ScotRenewables SR2000). Tidal currents are usually strongest near the surface but wave interactions can make the near-surface tidal stream less attractive and floating structures must be made to resist storm damage etc. Various approaches are used to optimise energy capture as the tide reverses, from reverse-pitching the blades to turning the whole turbine, to using fixed symmetrical blades to extract energy regardless of the current direction. Device scale varies, but the most prominent turbines are 1MW+ in capacity.

Recently, tidal stream energy has made significant progress towards becoming a commercial reality – in addition to the MeyGen project mentioned above [6], EDF and, Alstom together with GDF SUEZ, are committed to projects in France [9, 10] and projects are also being considered in the Bay of Fundy in Canada [11] and elsewhere.

C. *The Challenges*

To date, blade manufacturing has focused on high-cost, low-volume, prototype blades because this has been sufficient for industry's needs. Now, however, OEMs require higher volumes of low-cost reliable blades to generate competitive, clean electricity. Design and manufacture of tidal turbine blades that are sufficiently robust for harsh marine environments is not straightforward and blade failures have been reported for commercial projects [12, 13]. This has resulted in cost and schedule overruns.

Blade failures are a major barrier to full-scale commercialisation of tidal energy, and the cost of over-engineering currently limits the viability of much of the available tidal energy resource. The current trend to deploy small scale arrays of tidal turbines – seen as indispensable on the way to "the first GW" of installed tidal stream power – depends critically on drastic improvements in tidal blade reliability and predictability.

Efficient design methodologies for composite tidal turbine blades are still being developed [14] but it is clear that the forces and torques involved are equivalent to those carried by much larger wind turbine blades. This results in high stresses, in particular at the root end of the blades, which will necessitate the use of higher performance fibres (e.g. carbon) and much thicker laminates. Both of these factors will serve to increase the per MW cost of tidal turbine blades, when compared to wind turbine blades, especially if traditional manufacturing processes are used (e.g. vacuum resin infusion followed by slow cures and adhesive bonding of blade sections).

Efficient design and maintenance of turbines is a challenge because of the absence of intelligent condition monitoring – there are no sensors in place to warn turbine operators about blade degradation (such as crack initiation). Deployment of suitable sensor technology will allow a move from reactive to proactive maintenance, including repairs and replacements of blades. This will reduce maintenance cost and increase turbine availability, thus enhancing profit margins.

D. Objectives of this Research

The main goal of the developments described in this paper is to develop high-performance, low-cost tidal turbine blades using a manufacturing technique that is suitable for volume manufacturing. This removes an important obstacle to the full-scale commercialisation of tidal energy and contributes to increased renewable electricity generation.

The research also aims to create 'SmartBlades' by embedding sensors into the tidal blades to monitor strain and damage during operation. Information from the sensors can inform preventative maintenance and repair of turbines and increase up-times and revenues.

III. Towards Efficient Affordable blades

The vast majority of tidal turbine blades are made from glass fibre or hybrid glass/carbon fibre composites and some also use composites for other parts of the turbine structure. To date, blade manufacturing has focused on high-cost, low-volume prototype blades. Now, however, OEMs need high volumes of low-cost reliable blades to generate competitive, low-carbon electricity.

Composites manufacturing is a knowledge-intensive industry: it is difficult and time-consuming for a new company to manufacture complex composite products such as turbine blades. In practice, this limits manufacturing of tidal blades to a handful of companies because successful designs are heavily reliant on the tacit, in-house knowledge of composite materials. These include Gurit, Airborne, Aviation Enterprises Ltd (AEL), and Shetland Composites. Most companies use techniques that are derived from wind turbine blade manufacturing or aerospace. High-volume manufacturing of affordable tidal blades is especially challenging because it demands very high quality but ideally at a cost similar to that of wind energy.

This section describes an innovative but commercially proven technology for manufacturing smart, low-cost, high-quality blades that are better aligned to market needs. The technology presented is capable of addressing this market need and hence accelerating the commercialisation of tidal energy.

A. Traditional Composites Manufacturing

Currently the majority of composites used in the renewable sector are manufactured Out-of-Autoclave (OOA) using vacuum infusion of dry glass fibre (Vacuum Assisted Resin Transfer Moulding - VARTM) or by vacuum forming pre-impregnated (pre-preg) material. In order to manufacture complex products using these technologies, individual parts are usually bonded together to form the final product (notwithstanding that Airborne and Siemens have developed processes that reduce\eliminate the need to glue parts). A typical wind turbine blade is manufactured by bonding together at least 6 individually manufactured glass or carbon fibre parts (top and bottom skins, spars, 2-part root section). Gluing these parts together results in glue-lines that are weaker than the sub-assemblies they join together and also adds weight and cost to the blade. (The weight of the adhesive itself impacts the overall weight of the blade).

Traditional cure processes of the thick section laminates required to withstand the higher stresses in tidal turbine blades require very slow cure cycles (over 8 hours) in order to avoid exothermic damage. This adds considerable costs and barriers to high volume production of blades.

Aerospace parts, in contrast, are usually manufactured in autoclaves (large pressurised "ovens") that allow the use of more advanced materials and high curing temperatures and pressures. The resulting parts are typically higher quality than the composite materials used in the wind-energy sector but they are significantly more expensive.

B. An Innovative Composites Manufacturing Technology

An innovative Out-of-Autoclave (OOA) technology has been developed by ÉireComposites [15,16], based on its experience in manufacturing composites for the Aerospace and Renewable sectors and technology transfer from research and development work performed for the European Space Agency. The key to this OOA technology is a reliably heated, ceramic mould that operates at temperatures above 200°C.

The possibility of having reliable heated tooling opens the possibility of using novel thermoset systems, particularly the type of heat-activated epoxy and polyester systems. The features of these VOC-free thermosets are as follows:

- Polyester and epoxy powders – base materials currently used by the painting and powder coating industries.
- Heat activated at 200°C or above. No heating exotherm seen in the reaction.
- No VOC (Volatile Organic Compound) emissions.
- Solid powder material at room temperature.
- No special storage requirements, indefinite shelf life.
- Polymerization not sensitive to moisture.
- No dwell time necessary at processing temperature.

The combined use of powder epoxy and ceramic, heated tooling allows one-shot consolidation of large composite structures such as wind- and tidal turbine blades. This technology has been patented by EireComposites [17].

C. Benefits of the Proposed Technology

ÉireComposites has manufactured 13meter wind turbine blades for the Vestas V27 using this technology. These blades have demonstrated the advantages of the technology, such as faster cure times, lower tooling cost, lower energy cost, and safer, more environmentally friendly production [18]. The 13meter wind turbine blades and the heated tooling used to manufacture the blades are depicted in Figures 2 and 3.

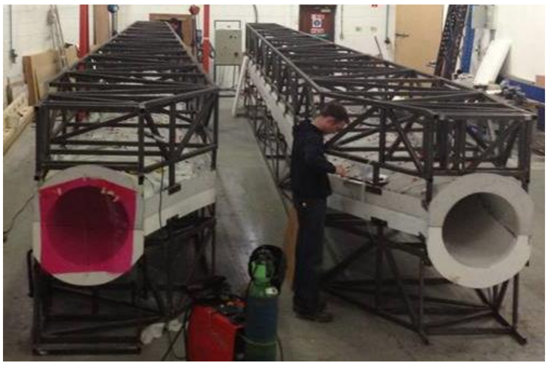

Fig. 2. Ceramic Mould used to make 13m Wind Turbine Blades

Fig. 3. 13m wind turbine blades made using epoxy powder

The one-shot method eliminates glue lines, increases fibre-straightness, increases fibre-volumes and reduces the void content in comparison to traditional methods. It also offers the possibility of complex overlapping of ply joints in a way that is not practical with traditional methods where glue is used.

The ÉireComposites tooling and manufacturing process results in many of the thermal and materials advantages of an autoclave but at a cost competitive with wind turbine blades. Advantages include:

1. Lighter, more-robust blades due to higher fibre volume fractions and straighter fibres.
2. Manufacturing technique suitable for high-volume, high-quality production.
3. Blade is cured as one piece hence avoiding the need for adhesives.
4. cost reduction as compared to conventional blade-manufacturing process.

Based on the above advantages, the epoxy powder technology is well suited to the manufacture of tidal blades. Material properties for laminates produced from powder epoxy are presented below.

D. Key Results: Mechanical Properties

Testing was carried out on material samples in order to compare materials manufactured using different manufacturing processes. The results obtained for powder epoxy are presented for comparison with published results for Vacuum Assisted Resin Transfer Moulding (VARTM) and prepreg in the below table.

. TABLE II
MATERIAL PROPERTIES

	Infused	**Prepreg***	**Powder****
Tensile Strength (MPa)	821	952	957
Compressive Strength (MPa)	511	687	666
Tensile Modulus (GPa)	37.8	42	39.2

**Comparative data from Gurit – www.gurit.com*
***Normalised to 53% fibre volume fraction*

The results show that:

- Powder epoxy glass fibre laminates achieve better mechanical properties than equivalent VARTM laminates
- Powder epoxy laminates can achieve similar performance to prepreg laminates at lower cost

Powder epoxy is also much easier to store than prepreg which must be refrigerated. This is challenging, especially in warm countries if factories are not air-conditioned and also results in increased transportation costs.

Currently, most wind turbine blades are manufactured using VARTM processes but some manufacturers are using prepregs to reduce weight despite the increased cost. Powder epoxy is being used by EireComposites to manufacture wind turbine blades and is ideally suited to the tidal industry where high quality blades at an affordable cost are essential in allowing the industry to blossom.

E. Detailed Results for Materials Processing

Work has begun on developing a material processing window for glass-fibre reinforced powder epoxy. This will provide greater knowledge of the material's flexibility with respect to the manufacture of thick composites laminates using ÉireComposites OOA technology.

Developing the process window amounts to a combination of different material characterisation techniques including thermal and physical testing.

Dynamic mechanical analysis (DMA) of both glass-fibre reinforced powder epoxy samples and neat powder epoxy samples have been carried out with some success. The DMA results for the composite samples have shown that the material can achieve a glass transition temperature (T_g) of 114°C, while a crosslink density of $9\text{x}10^{-4}$ mol/cm^3 was calculated from the results of the neat resin samples. The crosslink density calculation was based on the rubber elasticity theory [19]:

$$\nu = E/3RT \tag{1}$$

Where E is the storage modulus (MPa) value approx. 30-40°C above the T_g, R is the universal gas constant (8.314 J/mol.K), and T is the temperature in Kelvin.

Differential Scanning Analysis (DSC) of uncured powder epoxy was used to investigate the effect of cure temperature on the rate of cure. As is evident from Figure 4, the time required to achieve full cure reduces rapidly for relatively small increases in temperature.

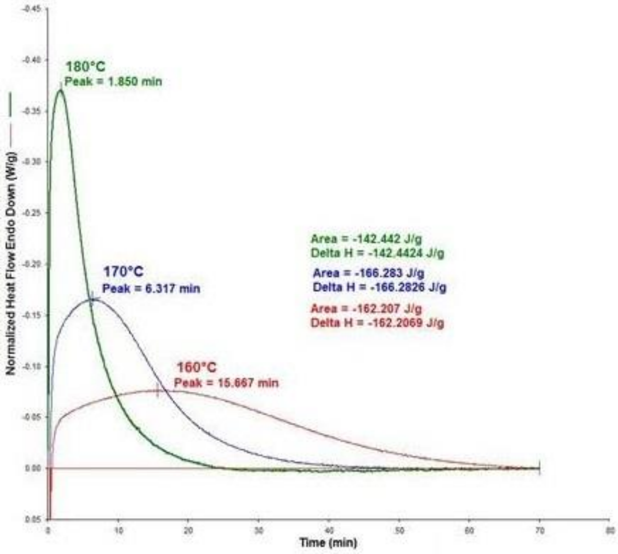

Fig. 4 Isothermal DSC curves at 3 cure temperatures

Transverse flexure testing of uni-directional glass-fibre material was used extensively for investigating process conditions. This test indicates the quality of the interfacial strength between matrix and fibre, and therefore provides a more clear reflection of any changes in the process [20].

Figure 5 shows the normalised transverse (90°) flexure strengths for some different processing conditions. The data is normalised against a mean value of 153.2 MPa for processing condition 1, which used the optimal cure cycle. The effects of decreasing and increasing the final cure temperature are shown by conditions 2 and 3, respectively. The significant drop in strength for condition 2 shows that under-curing must be avoided during manufacturing. Condition 4 shows the effect of increasing the dwell time for the final cure stage, while condition 5 indicates the drop in strength that occurs when the drying stage is taken out of an otherwise normal cure cycle.

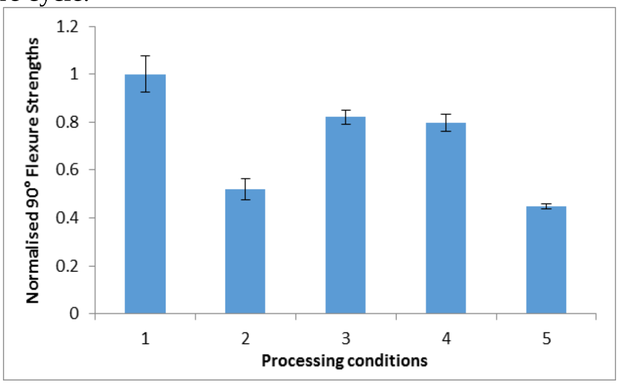

Fig. 5 Normalised transverse flexure strengths for various processing conditions

The result of removing the drying stage is clearly visible in Figure 6; SEM images of the failure surfaces of two transverse flexure specimens. Trapped moisture creates macroscopic voids throughout the material, almost tripling the overall void content.

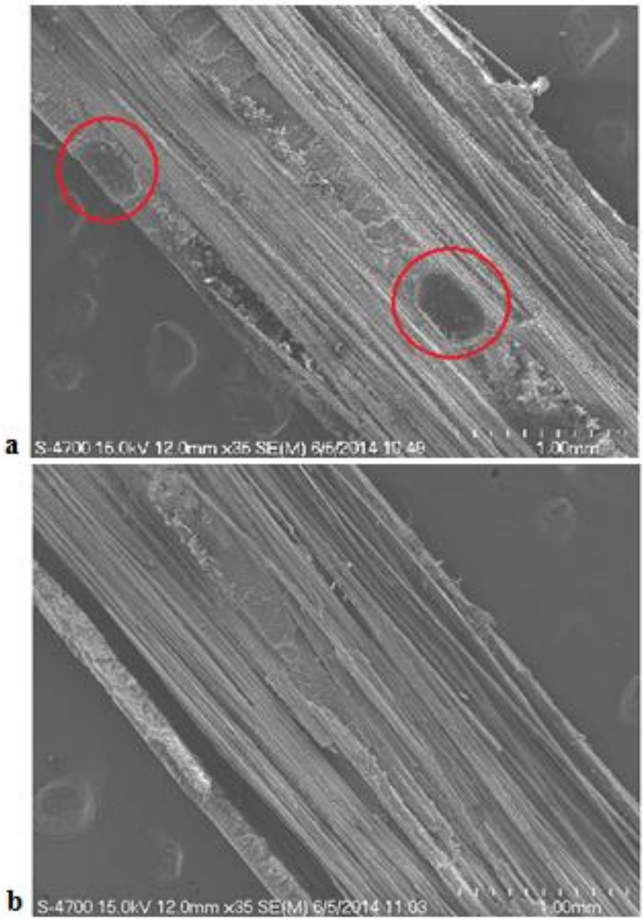

Fig. 6 SEM images of the failure surface for two separate tranverse flexure specimens; (a) shows the macroscopic voids that form from trapped moisture, (b) shows a fully wetted out specimen that has been processed normally

These preliminary results show that:

- The powder epoxy reacts well to both elevated cure temperatures and extended cure durations outside the recommended cure cycle
- An insufficient degree-of-cure will result in a significant drop-off in the material properties
- Removing the drying stage results in a higher moisture content, and subsequently a much higher void content

For conventional blade manufacture techniques, such as VARTM, the key processing challenges are around ensuring full wet-out of the fibres, avoiding resin-rich areas and ensuring fibre alignment (especially for carbon fibres). For powder epoxy, the key processing parameters are temperature, dwell-time and drying time but overall the quality of the laminates is more consistent when powder epoxy is used instead of VARTM.

Development of a full processing window is currently progressing towards an advanced stage in conjunction with the MaREI Spoke 2.1 Project. This project will include full static and fatigue testing for both dry and immersed conditions, in addition to further material characterisation using techniques such as modulated DSC, TGA and parallel-plate rheology.

IV. TOWARDS SMART BLADES

In Section 2, the research objective of creating a Smart Blade technology using sensors and micro-processors was stated based on a review of the tidal energy market and the challenges facing tidal OEMs. Significant work has been carried out by EnerOcean to meet this objective [21]. EnerOcean is a Spanish SME with extensive IP in relation to sensor systems and the processing of digital signals from composite structures.

Condition Monitoring is one of the critical aspects of successful deployment of Marine Energy devices. EnerOcean has led the FP7 Tidalsense and FP7 Tidalsense Demo projects dedicated to monitoring of composite elements in such devices [21]. It has also participated in the National Project SEAMAR where it is responsible for the monitoring of floating foundations for Wind Turbines.

EnerOcean has used its skills in Marine Energy construction, instrumentation, sea-trials and data analysis of composite elements to lead development of "Smart" capacity for tidal blades in conjunction with TWI. It is also carrying out work on integration of data from condition monitoring equipment into SCADA systems of marine renewable energy devices and has performed sensor testing on prototypes.

The SmartBlades work by sending an ultrasonic Lamb wave signal through the composite material [22]. The SmartBlade system is derived from Long Range Ultrasonic Technology (LRUT) used in Oil and Gas pipeline inspection for the detection of cracks, material losses etc. In applications relating to composite Tidal Energy Converters, the same technology is used to detect debonding, delamination, cracks or buckling.

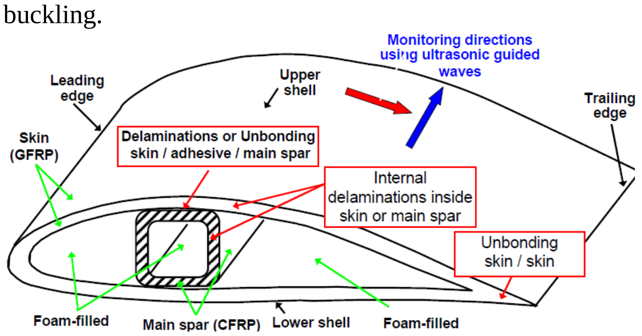

Fig. 7. SmartBlade Cut-away

At least 2 sensors are required – one to emit the signal and one to receive it. However, 4 or more sensors are typically deployed so that triangulation can be performed to identify the location of a defect.

A. Smart Blade Condition Monitoring

The factors that determine the particular mode of Lamb waves and operating frequency to be used are as follows: dispersion, attenuation, sensitivity, excitability, detectability, selectivity and sensitivity to defects [22]. If there are defects in the propagation path of the Lamb waves, the waves are reflected, scattered and converted into other modes. Also, the attenuation of the guided waves in composites is higher than in metals. Hence, the analysis of the received multi-mode signal affected by the internal non-homogeneities becomes complicated. In order to avoid or mitigate these problems the measurements are performed in low frequency ranges where only two primary fundamental modes A0 and S0 propagate [23, 24].

The propagation of guided waves is very sensitive to many parameters of the composite (the structure, the geometry, thickness of the layer, orientation of the fibres, the material and etc.). As a result, even small changes in the structure or parameters of the composite component can lead to measurable changes in the parameters of the propagating guided waves. Hence, the inspection or monitoring technique should be developed and tested on samples which are as close as possible to the real structure of the component under investigation. On the positive side, however, high sensitivity to changes in structure means that low levels of damage to the composite can be detected. The sensor system could also be developed to identify manufacturing deviations.

The disbond between a blade spar cap and the skin, using SmartBlade technology, has been detected and described by Makaya et al [25]. To this end, an array of 4 transmitters and 4 receiver sensors were symmetrically placed at either side of the disbond across the width of the sample.

Results are presented in Figure 8 below. The disbond was successfully detected and the scan image shows that the disbond is not uniform across the spar cap. The scale in colour in Figure 8 represents the signal amplitude in mV. For tests No 14 through to 31, full-coverage of the disbond by the array was achieved and partial disbond is detected in tests No. 7 through to 13, and tests No. 32 through to 38.

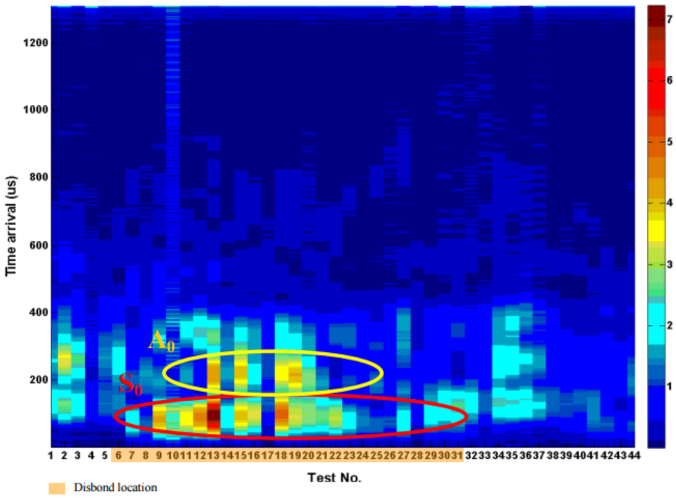

Fig.8 Image of disbond skin and spar cap

One limitation of the technique at present is that some false-positives are detected –there are no known defects prior to test at location No. 6 and beyond test location No. 31 but indications of a "defect" (other than the disbond) are observed in the scan (although with very small signal amplitudes).

Hence, further refinement of the technique is needed to eliminate these errors and perfect the technique.

Nonetheless, the results clearly demonstrate the success of the sensors in picking up the defect. Subsequent to this work, a similar system has been used to identify damage to wind-turbine blades during destructive testing and the technique can also be used to identify other manufacturing defects or in-service damage to blades.

Further work is also needed to develop the sensor system from a research demonstrator into a low-cost, high-volume manufacturing technology and to establish a cost\benefit model for the technology in a mass-production context.

B. Results - Benefits of Smart Blades

The resulting SmartBlades offer the following benefits:

- Enhanced Quality: Manufacturers can quality-check and non-destructively test their components prior to release, reducing risk and improving customer warranty confidence.
- Advanced Failure Warning: Operators can pre-empt component failure (by detecting damage before it causes failure), decide whether to shut down the machine, and plan to replace parts rather than being forced to adopt a reactive approach to component degradation\failure.
- Reduced Onsite Maintenance: Operators can reduce the frequency of machine inspection reducing risk and cost by providing this ability remotely. Tests can be run from the safety of the shore, and more frequently.
- Enhanced design: Designers are provided with valuable data service degradation of structures and design weak points, about opportunities for blade optimisation based on in-service performance.

V. Implications of Results

The results presented in this paper constitute a step-change in tidal turbine blade manufacture. By reducing the cost and increasing the quality of blades, they will help make tidal stream energy a commercial reality and ensure that the cost of tidal energy is competitive on a long-term basis. In the absence of such technologies, tidal stream energy may not achieve sustainable penetration of the renewable energy market or such market penetration may be delayed.

The use of sensor systems and epoxy powder in combination will reduce the cost of constructing and maintaining tidal turbines and increase their reliability. It will hence reduce the cost of tidal energy and mitigate the need for heavy subsidies. This will stimulate investments in projects in new countries/regions where tidal energy is not yet viable. Hence, the technologies described in this paper will reduce the levelised cost of green electricity from tidal energy and thus reduce carbon emissions.

At a technical level, our innovative solutions address several barriers to the more widespread deployment of tidal and offshore wind:

1. Poor quality of blades ➜ common quality problems eliminated.
2. Damage and failure of blades ➜ proactive maintenance using SmartBlade technology.
3. High cost of Tidal Energy ➜ significant cost reduction for tidal turbine blades achieved by reduced material cost, reduced labour cost during manufacture and elimination of rework.
4. Weight of tidal turbine blades ➜ 20% weight saving reduces costs on other turbine components
5. Rework and scrappage of spars for offshore wind-blades ➜ rework and waste eliminated.

The research work described above has created new knowledge regarding manufacturing and monitoring of large composite structures and this will also benefit other industries, especially wind energy and aerospace.

VI. Future Work

Future work focuses on transforming the technologies presented in this paper into commercial products for the tidal sector. Currently, the sensor system and epoxy powder technologies both have Technology Readiness Levels (TRL) of 6 w.r.t applications on tidal turbines (technology demonstrated in relevant environment) [26,13]. This needs to be increased to TRL 9 (actual system proven in operational environment). This will involve:

1. Further materials qualification
2. Full-scale tidal-blade design, manufacture and testing
3. Smart blade design and data interrogation
4. Technology show-casing and commercialisation of results

It is anticipated that funding to carry out the above tasks will be provided through the Horizon2020 SME instrument. EireComposites and EnerOcean have been successful in Phase 1 of their joint application to the SME Instrument funding.

In addition, the technologies described in this paper could be used in other applications. EnerOcean is exploring applications in wind and wave energy in addition to tidal. EireComposites is initially focusing on wind turbine blades, but also currently manufacturing products for the marine sector (catamaran hulls) and considering applications in civil engineering (bridges) and ultimately hoping to use powder epoxy manufacturing for large aerospace components.

VII. Concluding summary

This paper first provided an overview of tidal stream energy. It showed that tens of millions of Euros are already being spent on tidal array projects and argued that the industry is set to grow to provide 100GW of carbon-free electricity at a cost of about €300bn by 2050.

Several different tidal turbine concepts are being developed by different OEMs but, regardless of which concepts ultimately capture large market share, high volumes of cost-effective, reliable blades will be required. Manufacturing such blades is challenging: blade failures have resulted in delays and poor PR for at least two leading tidal OEMs and traditional manufacturing techniques cannot provide sufficient volumes of quality blades at affordable prices. Full-scale commercialisation of tidal energy could be delayed unless these issues are addressed.

In response to this challenge, a novel, patented manufacturing technique for composite tidal blades was presented. The approach uses a heated ceramic mould to process epoxy powder coated over dry glass fibres. The resulting composite structures offer improved performance in terms of weight and strength over alternative manufacturing techniques. Microscopy results visually highlight the importance of correctly curing the material and testing has demonstrated the advantages of the technology in terms of mechanical properties.

A second technology was also presented: the use of a sensor system to monitor blade damage over time and hence inform preventative maintenance and more efficient blade design. The same sensors are also used to monitor strain in the blades and hence provide the turbine OEM with valuable information on the loads being exerted on the blades and other parts of the device. This information allows the development of more efficient tidal stream turbines.

The results presented in this paper are potentially significant in so far as they remove a key obstacle to the commercialisation of tidal arrays. Future work focuses on manufacturing and testing blades for commercial tidal devices and on applying the technologies to other markets, initially wind energy but eventually also aerospace.

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