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McGugan, Malcolm

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Chapter 2
Design of Wind Turbine Blades

Malcolm McGugan

Abstract In this section the research program framework for European PhD network MARE-WINT is presented, particularly the technology development work focussing on reliability/maintenance and the models describing multi-body fluid structure interaction for the Rotor Blade structure. In order to give a context for the effort undertaken by the individual researchers this section gives a general background for Wind Turbine blades identifying the trends and issues of importance for these structures as well as concepts for "smarter" blades that address these issues.

2.1 Rotor Blades as a Common Research Topic

In order to meet its objective of strengthening the fundamental scientific work within the multi-disciplinary engineering field of hydro-aero-mechanical coupling in the wind energy conversion process, the MARE-WINT project was organised as five cross-linked work packages in a common research programme. The first three research work packages focus on the major structural components of the Offshore Wind Turbine; Blade, Drive train, and Support structure. In addition to these independent structure based work packages, there were two consolidating technology based work packages focussing on Reliability and Predictive maintenance, and Fluid–Structure interaction. In this way the goal of integrating multiple disciplines was to be achieved. This concept is visualised in Fig. 2.1 where the three vertical, structure-based Work Packages, are connected by the two horizontal technology-based Work Packages.

Work Package 1 is the focus of this chapter and concerns the challenges for offshore wind turbines with regard to the rotor blades, as well as proposing an innovative response to address these. Within the network two researchers were allocated within Work Package 1; Gilmar Pereira, based at the Technical University of Denmark (DTU) and Vladimir Leble, based initially at the University of Liverpool, and later at the University of Glasgow. In addition three researchers in the network allocated within Work Packages 4 and 5 conducted work at the nexus

M. McGugan (✉)
Department of Wind Energy, Technical University of Denmark (DTU), DTU Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark
e-mail: mamc@dtu.dk

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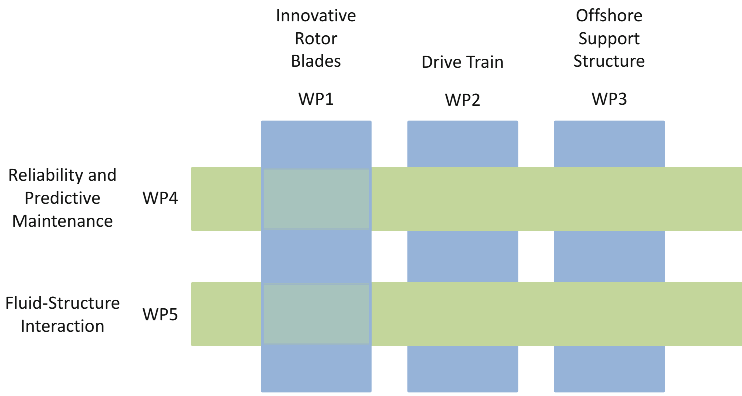

Fig. 2.1 Diagram showing the cross-linked MARE-WINT Work Packages

between their technology area and the blade structure. Borja Hernandez Crespo, based at The Welding Institute in Cambridge, worked on Reliability and Predictive Maintenance for the blades, and Alexander Stäblein worked with wind turbine blade Fluid–Structure Interaction models at DTU Wind Energy, as Javier Martinez Suarez did at the Institute of Fluid-Flow Machinery in the Polish Academy of Sciences.

In Work Package 1 the structural and fluid dynamic investigations on the rotor blade are approached by numerical and experimental methods. Within the work package individual projects were developed, the first considering the behaviour of the composite material (particularly when in damaged condition) within the blade structure and the use of embedded sensors to detect this behaviour, and the second describing structural behaviour and rotor performance in Computational Fluid Dynamics models, including the use of leading and trailing edge flaps to modify this.

These activities cross-link with the combinatory horizontal work packages (4 and 5) by providing, among other things, structural health information to the reliability and predictive maintenance work package, and input to the fluid–structure interaction models developed for the entire turbine.

In Work Package 4 the prime consideration is the economic efficiency of an offshore wind farm as depending upon the individual turbines availability and reliability. For the blades this involves the study of the various damages observed in service, and understanding their root causes and criticality with respect to operational lifetime. Detecting damages that initiate and propagate during service is not straightforward and developing inspection technologies alongside remote sensing systems is a key part of the future optimisation in this area.

In Work Package 5 the structural description of the various Offshore Wind Turbine components are combined with flow models in a fluid–structure interaction description of the complete system. The key task involves identifying and integrating the various aero/hydro loadings and their effect on the structural responses, particularly any coupled effects. Of the three researchers in Work Package 5, two worked specifically on the complex blade structure. The areas of interest here include the use of twist-coupled aeroelastic blades to achieve structural load reduction at high wind loads, and the development of flow control technology for advanced blades.

In order to provide a common platform for the different Work Packages, a reference model was agreed as one of the first deliverables within the project. Described by Bak et al. (2013), the DTU 10 MW reference wind turbine was developed by DTU Wind Energy together with Vestas Wind Systems as part of a collaborative research intended to create the design basis for the next generation of wind turbines. As such it is an ideal, publically available reference for MARE-WINT to work on the optimisation of large offshore wind installations; and indeed many of the inputs within this chapter use this shared reference.

2.2 General Background for WT Blades

Access to affordable, reliable, sustainable and modern energy is one of the 2030 targets for the United Nations (UN 2016). This requires a substantial increase in the share of renewable energy within the global energy mix, and wind is a prominent part of the solution if the world is to achieve such a target. The potential for offshore wind energy is enormous with industry projections in Europe showing an increase from 5 GW in 2012 to 150 GW in 2030 (European Wind Energy Association, Fig. 2.2 (EWEA 2016)). By moving to offshore sites the Industry can establish larger wind farms with turbines of a size that would not be easily accepted onshore where land use is at a premium. In addition to this, the quality of the wind resource is greatly improved away from the effect of land contours, forests, and so on.

However, moving such a large portion of the industrial production capacity offshore is a major challenge. The environment offshore can be extreme and requires a more robust and durable design for all components, access is expensive for establishing and maintaining production offshore, and support structure designs for deep water sites are yet to be proven commercially. At the European Wind Energy Association conference in 2014, the delegates were warned that without a reduction in energy costs corresponding to at least 40 %, offshore wind could not persist in the current energy market beyond 2020 (EWEA 2014). While costs for onshore wind are already competitive, targeting a reduction in the cost of energy offshore was vital if the ambitious political and industrial targets are to be achieved. It was further observed that initial offshore developments were based on technology from the offshore oil and gas supply chain which is driven by a need to maximise production, rather than by cost reduction. The solution agreed was for a more focussed investment in research and development that produces innovations in logistics, transport and operation.

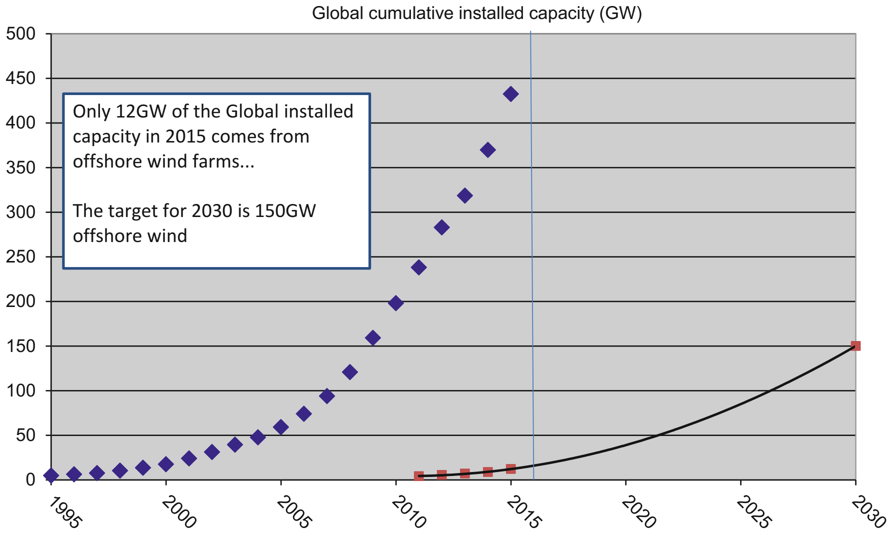

Fig. 2.2 Growth in Wind Energy capacity from 1995 to 2015 (data available on www.gwec.net)

Table 2.1 Comparison example between commercial turbines developed by Vestas in 2000 and 2015

Year	Manufacturer (rotor diameter)	Effect	Tip height
2000	Vestas Wind Systems V52	2.5 MW	70 m
2014	Vestas Wind Systems V164	8.0 MW	222 m

One of the most eye-catching developments in the wind energy industry over the last 15 years has been the increase in the size of the turbines being manufactured with new turbine designs consistently providing larger turbines with higher power ratings, as shown in Table 2.1.

As the rotors become larger, the industry has relied on improvements in blade structural design, manufacturing processes and material properties in order to meet the requirements for ever longer blades that remain light-weight, strong and stiff. It can be argued that the blades present the most challenging materials, design and engineering problems being a complex, anisotropic material in an aerodynamic structure that is subjected to continuous dynamic loadings of a combined and non-uniform nature over long periods of time. These operational requirements and conditions lead to materials that must exhibit a high stiffness, a low density, and long fatigue life.

Material performance criteria therefore identify fibre reinforced polymer composites as the prime candidate for rotor blades. Here the stiff fibres (usually glass, sometimes carbon) are aligned in the primary load directions within a cured matrix of resin (usually thermosetting polyester or epoxy). The processing technology for such material (whether pre-preg, resin infusion, or wet layup) involves considering the material properties, design approach and manufacturing process as an integrated issue as already at this stage the characteristics of the material (and hence the behaviour of the final structure) are determined. For example, in longer rotor blades the reinforcing (stiffening) fibres must be aligned along the length of the blade, but with sufficient understanding of the out-of-plane properties and weak laminate interfaces and bond lines so as not to generate problems with durability when the complex combined loads are encountered.

Blade design combines a relatively thin shelled aerodynamic profile supported by a longitudinal beam or webs which carry the bulk of the structural load. The blades are heavier at the root section and taper towards the tip to match the load distribution in a cantilever beam structure and maintain the allowed material strain levels. Industry demands have spurred improvements in design with an optimised aerodynamic profile, relative reduction in weight for longer blades and integrated bend-twist coupling into the structural response.

For much more on material and structure requirements for wind turbine blades see Brøndsted and Nijssen (2013).

The design philosophy for rotor blades (as with all fibre reinforced polymer structures) began with large safety factors and addressing simple issues of linear elastic behaviour. With time, as knowledge about the materials, structural behaviour and manufacturing approaches increased (coupled with the pressure to make more daring multi-MW designs) it became possible to adopt more advanced structural design approaches. The development in light weight structure design is nicely illustrated in a general way by Braga et al. (2014) and here we see that an implementation of "smart" structure technology is the anticipated innovation to supersede the current state of the art not only for offshore wind turbine blades, but also in other industries where polymer composites are utilised.

Recent trends in the wind energy industry can be summarized as follows:

- A rapid increase in the level of installed capacity world-wide
- An increase in the physical size (dimensions) of the structures
- An increase in the size (number of multi-MW turbines) of individual wind farms
- A tendency to place these wind farms offshore
- Higher industry requirements for reliability, safety and easy maintenance
- A strong focus on a reduction in the cost per "unit" of energy produced
- New materials, designs, and production methods continuously adopted

2.3 Innovative Blade Concept

As the most effective way to increase the power produced per turbine is to make each turbine bigger, we now have an industry that manufactures extremely large rotor blades using low-cost fibre composite material and low-cost manufacturing methods. A consequence of the components in a wind turbine blade being so large (in some companies almost the entire structure is manufactured in one piece via resin infusion of dry laminate layers), is that there is little scope for improving the performance of a finished blade by rejecting parts that do not meet very high quality standards. This is because the low-cost manufacturing approach demanded by the industry makes manufacturing a "perfect" blade challenging, and parts thus rejected would be too costly to simply discard.

Instead the situation is that each blade has a unique set of "variations" (we might call then defects) from the intended "perfect" design; these are then more or less mitigated with repair technology before leaving the factory. And in operation the specific load profile will also vary for each turbine. Without detailed information about the distribution of structural/material defects and repairs present, combined with detailed loading and response history for each blade, it will be impossible to make accurate predictions about the lifetime performance of these blades individually; only a generalised probability analysis is possible. And prescribing regular manual inspection is neither an economical nor technically efficient solution to control the health of the structures as for large offshore farms this would be both costly and difficult.

Having an isolated understanding of the individual stages in the wind turbine blade operational life, such as manufacturing, operational, emergency situations, repairing, etc., is therefore not enough to achieve a smart wind turbine blade concept. Rather knowledge of how each stage interconnects with the processor and successor, and the impact of a change in any of the properties to the individual wind turbine blades operational life is required. The traditional Mono-Stage design and methodology, as shown in Fig. 2.3, is no longer applicable to match this requirement; especially as blades become larger, more complex and expensive to manufacture, more information feedback is required to maximise their lifetime and improve processes.

Thus, methods to measure and evaluate structural integrity and operational parameters through all the wind turbine blade life stages need to be implemented from the design stage (McGugan et al. 2015).

The smart blade design and methodology is shown in Fig. 2.4. The presence of sensors integrated in the structure since manufacture will provide feedback at each stage of the structure life time. For example, if during an extreme load a change in

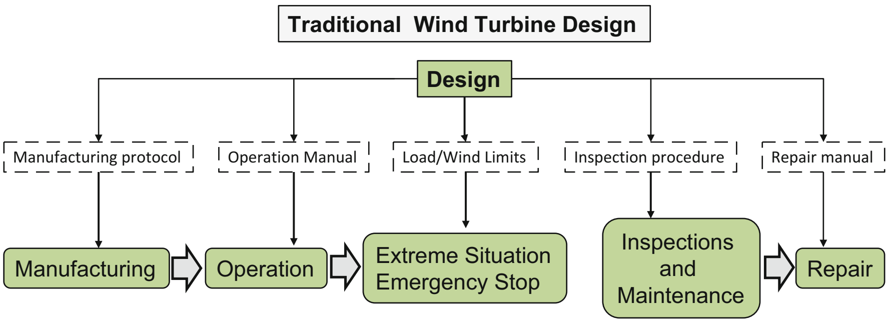

Fig. 2.3 Life stages of a wind turbine blade: traditional design methodology

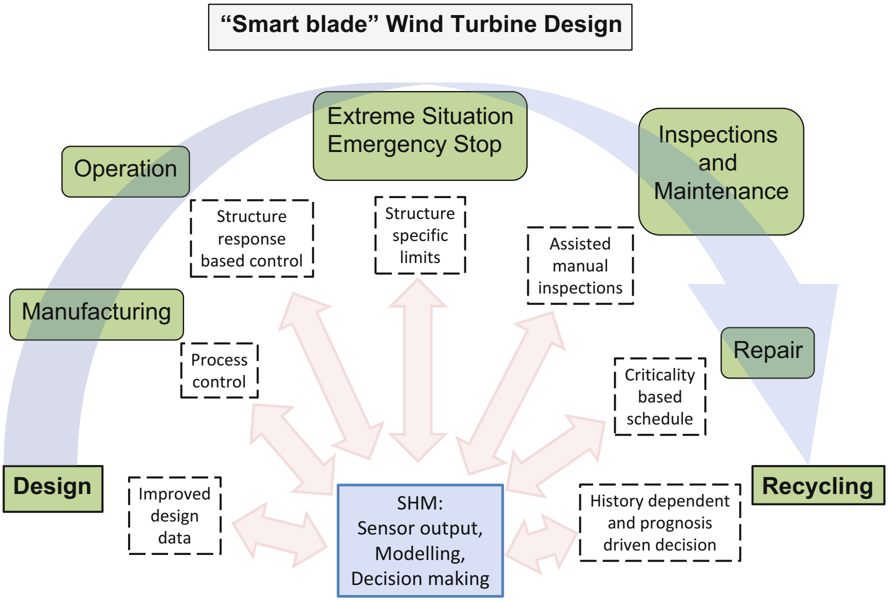

Fig. 2.4 Life stages of a wind turbine blade: "smart-blade" design methodology

the material stiffness is detected, caused by delamination or a crack in the adhesive joint, the wind turbine operation limit can be decreased based on this information. This will enable the structure to operate safely until the next repair action, continue to generate energy, and minimise monetary loses.

Structural Health Monitoring is a well-known engineering area concerned with assessing the current state of a specific asset in order to ensure proper performance. It has the perspective to function both as an automated (and remote) maintenance and inspection process, as well as a "smart" structure feedback allowing activation and response based on condition and environment.

The novel approach proposed is thus that blades are allowed to contain defects and develop stable damage under operation as under the current "passive" damage tolerant design philosophy. But the implementation of structural feedback from the embedded sensors and active response is combined with improved damage tolerant materials and design methods in order to expand the current design philosophy and include SHM and applied fracture mechanics from the initial concept. This allows a design that ensures any defects present cannot develop into unstable damage that leads to blade failure. Furthermore, a full life-time perspective is given that enables a holistic optimisation of the structural resources.

2.4 Operational Concept

Many industrial sectors share similar ambitions regarding polymer composite structural materials, structural diagnosis, and development of prognostic approaches. However each one differs in how they intend to exploit the new technology and apply the new developments. The different expectations and priorities across the sectors will influence the entire design, processing, and maintenance line. For example, the aerospace sector can be characterised by polymer composite structures that are high cost material and high value structures, whereas the wind energy sector considers the rotor blades as low cost material and high value structure.

In practice this means that a common "toolkit" of deliverables and work areas exist for defining a physics-based polymer composite structural component life analysis that can be investigated by researchers and industry across different sectors. However from this "open-source" framework, sector specific implementations will then be developed.

The upper part of Fig. 2.5 shows the concept of a blade structure operational lifetime being "consumed" during its' use in a more or less controlled and progressive manner throughout the planned service life. The usage depends on a loading input which is monitored and understood and in some cases controlled (active management) to a greater or lesser extent.

This control could be in the form of a simple measurement of wind speeds and a calculation of the resulting aerodynamic loads on the structure which provide a "cut off" wind speed above which the turbine should not be permitted run (in part to avoid overload situations). Progressively more advanced turbine control systems can include passive bend-twist blade designs, an active control of pitch and leading/trailing edge settings combined with turbine specific in-flow measurements

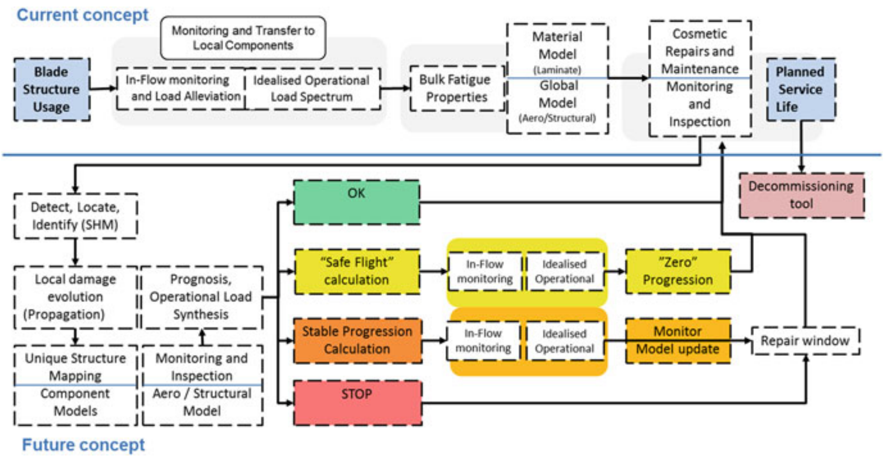

Fig. 2.5 Health Management Concept for future Innovative Rotor Blades

to allow for load alleviation from tower shadow effects, shear loads, turbulence, and so on. The degree of structure control available will define the quality of the load spectra applied and specify the risk of stochastic peak loads that can progress (or initiate) damage. The greater the degree of control, the more availability a damaged structure can exhibit. The availability of a distributed in-situ load monitoring capability will enhance aerodynamic load control options.

Moreover, combining Structural Health Monitoring with other inspection technology will detect and characterise localised damage for each structure, generating a "damage map" for each wind turbine blade with local and global damage models communicating to define critical (and sub-critical) failure criteria. A prognosis tool based on the local forecast of operation can propose the suitable structural sustainment action:

- an unaltered operation (exploiting the passive/designed damage tolerance capability of the material/structure)
- a modification of the structure control settings to limit load conditions that risk progressing damage (a "safe flight" operation)
- an operation of the structure that will allow a progression of damage but in a stable regime allowing repair to be scheduled for the next available maintenance period
- or an immediate stop pending critical repair

In all cases the target for the individual structures is to meet the planned service life whereupon "problem" structures can be decommissioned and the remainder assessed for the feasibility of an extended operational lifetime. The updated database of structural integrity information generated by this process improves the decision making regarding which structures can be safely licensed for continued operation and those that need to go to refit, resale, or recycling.

2.5 Research and Development Work Supporting the Concept

The work carried out by the MARE-WINT researchers associated with Work Package 1 supports the implementation of this new operating concept for wind turbine blades across a broad area of material and structural advances. Each area of research and development is a valuable and acknowledged area of technology in and of itself and includes failure and damage mechanics, new sensing techniques, load spectra monitoring, characterisation of structural damages, data acquisition and analysis, handling environmental effects and other sources of uncertainties, residual properties prognosis, and the assessment of various maintenance and damage mitigation actions. The challenge for the adoption of innovative blade concepts is to combine the many fields into a multi-disciplinary technology within the minds of the next generation of designers and engineers.

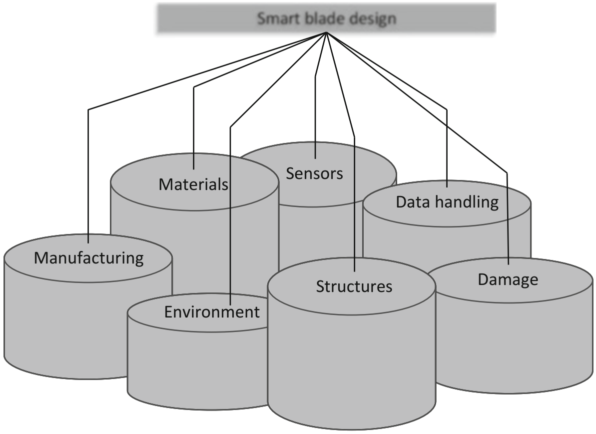

Fig. 2.6 Independent technology platforms supporting a "Smart" blade design concept

This idea of a set of independent technology platforms that can be combined to support a specific "smart" design concept is illustrated in Fig. 2.6. Note that the names of the technology platforms are illustrative only and far from exhaustive.

In Chap. 3 the topic of damage in composite materials and structural failures in the blades is discussed. In conjunction with the deepening understanding of the causes and effects of these, technology developments are also underway to provide remote sensing solutions and release the pressure on manual inspection procedure. Monitoring this degradation of structural material via manual Non-Destructive Inspection (NDI) during the service lifetime is an expensive, hazardous, and inefficient proposal for offshore wind farms. Therefore, integrating various robust and inexpensive remote sensing technologies and developing them to detect the most common and/or most critical of in-service failures is a clear target for research groups. The demands for improved material performance to achieve the structural designs for extremely long multi-Megawatt blades has propelled research in composite material fabrication, minimising imperfections and improving understanding of the behaviour especially in damaged condition. Crack propagation sensing techniques using embedded fibre optics are described in Chap. 4 and these offer a tool for optimising structural bondlines, and the remote monitoring of known damages (active damage tolerance).

In Chap. 5 the potential for blade design tailored to twist upon deflection and thus enjoy a passive load reduction capacity is explored; and the analysis and design of such blades that can safely exploit this effect at regions along their length whilst maintaining required structural stiffness is proposed. In Chap. 6 the development of flow control devices is described as designers seek to optimise performance for the rotor and researchers deepen the understanding of complex flow control cases. And in Chap. 7 the modelling of active flaps on the leading and trailing edges of the blades is described suggesting that a localised effect on the load distribution can be effected in-service, possibly eliminating adverse effects caused by tower shadow without generating any additional pitching moment.

Each area of research contains innovative aspects involving new approaches that improve on existing blade design procedures in a sustaining manner. Improving the sensor implementation via more robust and price competitive systems, better analysis tools, a deeper understanding of material and structural behaviour and degradation processes, ameliorating flow control devices, and providing assessment of designs for passive and active load alleviation.

These are all advances that are welcomed by an industry working to reduce Cost of Energy for offshore wind farms in the short term. However the greatest advance possible comes from a disruptive implementation of the new technology in a fully realised concept for structural sustainment. This essentially establishes a new relationship between the owner and their assets. This concept involves using permanent on-board health monitoring systems within a holistic management/control approach. It is a complex and multi-disciplinary field that has not been (and in fact cannot be) addressed by advancements in research alone.

Its realisation faces numerous training and research challenges; the main training challenge is the lack of young research scientists and engineers possessing the skills, research experience, and multi-disciplinary background required for undertaking the demanding research tasks of integrating, supporting and maintaining the innovative holistic structural health management systems and to propel their application in wind energy and other industries. The main research challenge is to focus and coordinate research in the previously mentioned fields to address technical voids which hinder the integration of the envisioned holistic approach. Training networks like MARE-WINT are successful in overcoming such challenges.

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