

## Structural Health Monitoring in Previous Military R+D Projects, and as a Future Commercial Application

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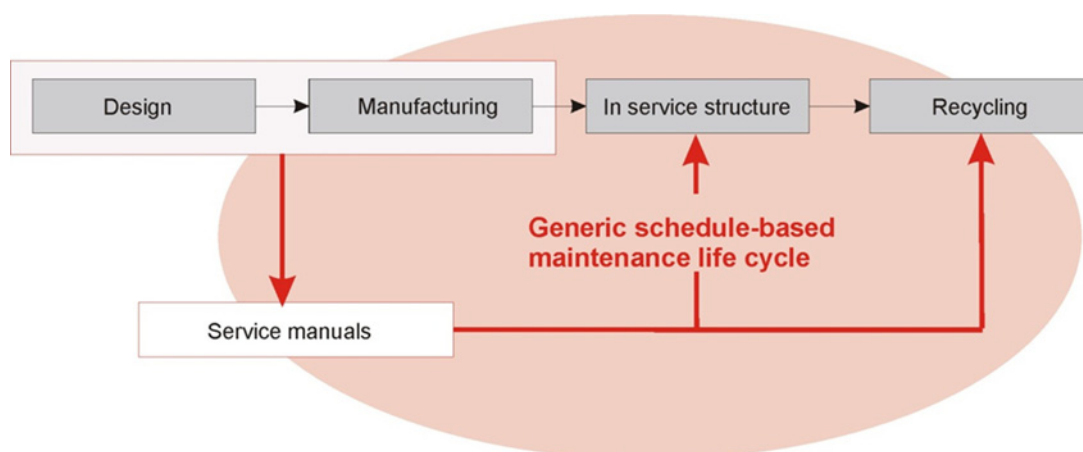
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### **ABSTRACT**

*The following text supports the lecture series AVT-220 on “Structural Health Monitoring of Military Vehicles” co-ordinated by STO-CSO. This lecture series is planned to run in Germany (BAM-Berlin) and Spain (Centro Convenciones MAPFRE –Madrid) during 2014, and Canada (Vancouver) in 2015. The author, Malcolm McGugan, is one of seven lecturers involved and this report accompanies his presentation. A summary of various military projects involving Structural Health Monitoring that the author has been directly involved in is given. It is then argued that successfully implementing the high capability Structural Health Monitoring Systems of interest to military applications first requires a successful implementation at a lower capability level, but at high (commercial) volumes. Offshore Wind Farms are suggested as the most obvious “enabling” application.*

### **1.0 STRUCTURAL HEALTH MONITORING (SHM)**

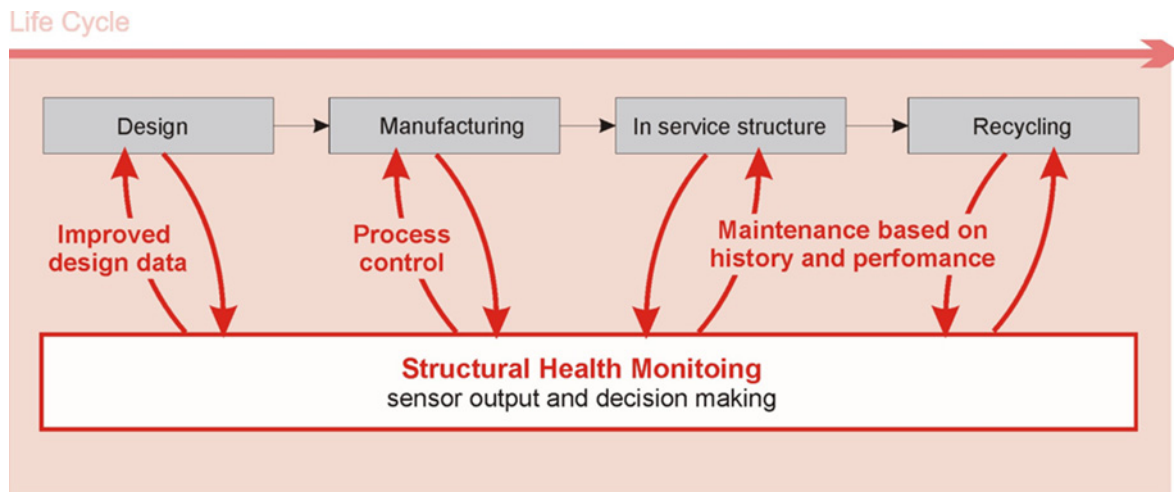
The design and manufacture process produces two items, a structure and a set of general instructions for how that structure is to be maintained and repaired during the prescribed service lifetime. These generic maintenance guidelines are then applied to each structure. The frequency of inspections is determined by the guidelines provided by the manufacturer, the occurrence of special loading conditions (such as severe storms for instance), and the requirements of insurance or certification bodies. The maintenance of many structural components are organised along principles similar to those shown in the figure below.



**Figure 1: Traditional lifecycle paradigm.**

A structure lifecycle controlled by a SHM system involves information feedback loops at every stage in the structure lifecycle. This structure response data, which is not available in traditional systems, is the means by

which optimisation at each stage is made possible. A further key difference is that as all structures are sensorised, the data obtained is specific for each. This allows decision making based on the particular status of the structure, taking into account the manufacture, service life, repair history, and so on.



**Figure 2: An SHM based lifecycle paradigm.**

Through the use of a successful SHM system it becomes possible to closely control the lifecycle of each individual structure. The user interface presents all the information necessary to make qualified decisions.

The in-service SHMS should:

- remotely identify the presence of damage within a structure,
- locate the damage within the structure,
- assess the “severity” of the defect (perhaps after gathering new input via on-site inspection?),
- and issue a prognosis of the damage development (perhaps after separate analysis and modelling?).

People have been building structures for thousands of years, and it can be seen that SHM, as the term is defined above, has only become technologically feasible fairly recently due to remarkable advances in sensor development, data handling, networking, communication systems, computing power and by establishing a deeper understanding of the mechanisms involved in material degradation and failure. The adoption of a SHM approach to physical asset management however, is not dependent on an innovation within any single one of these technological disciplines, rather it is dependent on an exploitation of a set combination of them all with respect to a particular monitoring challenge. These technologies could therefore be said to represent the platforms upon which SHM systems can be created.

It is important to realise that these technology platforms are most often independent of each other and valuable to Industry (and research) in and of themselves. The job of combining a multi-disciplinary network in order to solve a specific SHM challenge becomes therefore a management/co-ordination activity, where the different technology experts must be aligned.

## **2.0 SOME EXAMPLES OF MILITARY SHM PROJECTS**

In this section of the report an overview of the types of SHM projects that the author has been involved in is given. By summarising the ambition and extent of these various projects, in a roughly chronological manner, it is possible to establish the key areas of interest for the technology as well as the technical challenges

involved. It also shows the areas where progress has been made and conversely where breakthrough is still needed.

### 2.1 Active Health Monitoring System (AHMOS)

The Active Health Monitoring System (AHMOS) project ran from July 2000 to July 2003 as part of the EUCLID CEPA 3 RTP 3.20 agreement. The project budget was 9.5 MEUR distributed between 17 companies and research institutes from 8 countries; Belgium, Denmark, Germany, Finland, Italy, Netherlands, Spain, and the UK. The full title of the project was, “Structural Health Monitoring Systems for Military Platforms - Requirements, Design and Demonstration” [1].

The motivation for AHMOS was to enhance current state of the art usage and loads monitoring technology with dedicated damage detection systems in order to reduce cost of ownership of military aircraft or other military platforms by saving inspection and maintenance costs (including repair), and to extend the life of a wide range of existing and new military platforms.

Specific objectives were to define, develop, and demonstrate practical Structural Health Monitoring Systems (SHMS) with sensors, signal processing, data logging, analysis, and presentation; but also to incorporate these sensors within the structure, and consider the integration of the monitoring systems into the platform operation.

A major outcome was the definition of a modular, “toolkit” approach suitable for tackling a wide variety of different structures and damage combinations. Agreement between the project participants allowed the group to establish a common data handling platform that could support and integrate input from different sensor types. Crucially the sensor data would be analysed within the individual modules, but then combined and presented as clear structural damage condition information for the front-line user of the system. The information rich data from the sensors was also available for detailed analysis and cross-correlation with different sensors and parametric information, in order to improve confidence in the outputs and develop prognostic tools, but this was not the graphic output for the operator who needed only the location and extent of any detected damage.

Technical assessment of a large number of different sensor approaches for damage detection was also undertaken, but only 5 were identified by the consortium as “ready” for integration in the kind of modular system envisioned by AHMOS; Acoustic Emission (AE), Fibre-optic Bragg- gratings (FOBG), Strain Gauges (SG), Lamb Waves (LW), and Smart Wide area Imaging System (SWISS).

At the end of AHMOS I it was considered within the consortium that the most promising of the individual sensor types had been raised from a Technological Readiness Level around 2 or 3 (proof of concept) to 4 or 5 (laboratory validation) via the assessment process. However, despite reaching agreement on the way a modular system integration of different sensors could be achieved (sensor fusion) this had not been demonstrated and the objective of a practical application demonstration was in no way achieved.

### 2.2 Active Health Monitoring System II (AHMOS II)

Despite the failure of the initial project to achieve its key objective, the promise of demonstrating an operating prototype of the modular “toolkit” SHMS led to a follow-up project involving the same consortium members. The Active Health Monitoring System II project ran from 2004 to 2008 under the ERG103.015 Agreement, Contract No 04/103.015/028. The full title for the project was, “Prototype Demonstration of Modular Structural Health Monitoring System for Military Platforms” [2].

In this case the primary motivation for the project was to demonstrate an operating system. The specific objectives were to develop the most practical sensors (and extend capability) within a modular network

SHMS; to demonstrate the operational capability of this prototype SHMS in flight; to demonstrate the functionality of this prototype SHMS via independent full-scale on-ground damage detection tests, and to assess the operational reliability, cost benefit, and possibility to replace conventional inspection procedures.

The effort within AHMOS II was divided between two paths; the Flight path, and the Technology path. The flight path focussed on establishing the system architecture and design, and implementing this prototype system in a flight test (operational capability) and in a ground test (functional capability). The Technology path focussed on challenging the individual sensing techniques and improving the modular system architecture. As the technology path was less critical for the project it was also possible to express a higher degree of innovation and technology forecasting in the reporting of the consortium activity.

The prototype SHMS developed in the AHMOS collaboration was flown seven times within an underwing pod of a TMK1 Hawk Training fighter (tests organised by BAE UK). The first two flights were able to carry and demonstrate the full suite of sensor technologies on-board. During flights three to seven a reduced suite of technologies (Strain Gauge and Swiss removed) flew. Data was successfully downloaded after each flight, which has shown to reflect both the crack propagation of the mini-specimen within the Pod, and aircraft manoeuvres. The Strain Gauge and SWISS components of the AHMOS SHMS flew within an underwing pod of an F18 (tests organised by Patria, Finland) detecting cracks in a specimen mounted within the pod.

As well as these operational trials of the system running within an aircraft sub-structure, it was also necessary to demonstrate the functionality of the entire system via Ground Tests where a variety of damage types could be generated and propagated in a controlled way using mechanical testing on relevant structural sub-sections.

**Table 1: Ground test demonstration test specimens.**

Sub-component	Material	Dimensions	Damage type	Sensors	Procurement
Sub-com 1a	Thin metal – Riveted stringer	<1.5mm x 0.95m x 0.4m	Cracking at rivets	AE + SGI	Fokker ✓
Sub-com 1b	Thin metal – Bonded stringer	<1.5mm x 1.15m x 0.5m	Stringer Disbond	FO, AE, SGI, + Lamb	Fokker ✓
Sub-com 2	Composite – Bonded stringer	4-7mm x 0.8m x 0.15m	Stringer Disbond	FO, AE + Lamb	QinetiQ ✓
Sub-com 3	Aluminium tensile test specimen	~3mm x ~50mm x ~250mm	Cracking at centre hole	SWISS	EADS-G ✓

Over the course of the Ground Tests, an operational Structural Health Monitoring System (SHMS) was established using prototype hardware from seven different suppliers. Three structural sub-components were instrumented with four different sensor types, and subsequently tested to destruction with all sensor data handled by the SHMS. The main objective of the AHMOSII Ground Test was to increase confidence in the SHM systems technological readiness level by providing the hardware suppliers with an experimental configuration corresponding to a relatively “high fidelity” laboratory integration of components. Hence, damage types and structural sub-components reflecting those of interest in “real-life” aerospace application, but where a high level of technical access and support was available. A secondary objective was the

opportunity to assess the development of the system as a single entity, from the perspective of an eventual “end-user” of an aerospace SHMS.

The results of the Workshop/Ground test can be summarised as follows:

A preparational workshop was held in Denmark (DTU Wind) during September 11th- 15th 2006. All sub-component instrumentation was completed at this workshop. During the Workshop an operational AHMOS SHMS was established consisting of the Central Computer, Ethernet switch, Fibre Optic sub-system, Acoustic Emission sub-system, Lamb wave sub-system, Strain gauge sub-system, and Notebook.

Over the following three weeks (18th September - 6th October 2006) the sub-components were tested to destruction with all sensor data obtained by the SHMS uploaded each day to a shared website for analysis by the sensor suppliers.

1. *Loading period* (simulated “flight”) - During which time all the sub-components were simultaneously fatigue loaded in the test machines
2. *Maintenance period* - During which time the notebook is connected to the AHMOS Central Computer, all SHM sensor responses are downloaded, a SWISS image is obtained, visual inspections are completed, etc.
3. *Report period* - In which the test machine output, SHMS output, inspection output, etc. are all uploaded to a shared website

A separate test was conducted on a SWISS instrumented test component (22nd September 2006).

As well as the technical (data) output from the sensor modules and comparison with the observed (measured) damage progression, the Ground Trial also included evaluation statements focussing on the experience of using the SHMS at this early stage of its development and is summarised here.

### 2.2.1 Fibre Optic Sub-System (FOSS) Performance

The fibre optic hardware used in the Ground Test was not the system intended for use in the final SHMS. Of all the sensor sub-systems (SS), the FOSS required the least attention during the Ground Test. It provided no live information to the Central Computer status monitor beyond indicating its presence on or absence from the network. However it was very noticeable during data downloads as the FOSS flooded the Central Computer (CC) and Notebook with high information content, unanalysed data continuously, regardless of the state (healthy or damaged) of the sub-components instrumented.

### 2.2.2 Acoustic Emission Sub-System (AESS) Performance

The AESS module appeared well advanced in terms of hardware development. The acoustic emission sub-systems higher functionality with respect to configuration files for different structural materials and sensor distributions was however not integrated with the user interface (Notebook) and required a direct connection to be made to the module with software tools provided by the sensor supplier. During the Ground Test the AESS displayed an occasional “sensor damaged” warning on the Central Computer status monitor. These warnings were inaccurate and were generated by an automatic sub-system diagnostic routine.

### 2.2.3 Strain Gauge Sub-System (SGSS) Performance

The SGSS appeared very well advanced in terms of hardware development. In addition this sub-system included a local LED “status indication” display for the eight sensor channels (similar to the live status indication provided for all the sub-systems by the Central Computer status monitor). It was possible for the 8-channel SGSS to monitor different sub-components (structural sections) that were being tested simultaneously. However, it was noted that the user was required to manually set “warning” and “damage”

limits via direct connection to the sub-system and using unique software tools. Also noted was the fact that any changes in loading condition must also be reflected in a change to the user input limits, in order to continue to obtain good damage information from the sub-system. Furthermore, the SGI sensors are vulnerable to “zero-drift” if the sub-component is placed in an unloaded state or handled for whatever reason, requiring manual connection/correction again to ensure channels are still giving valid data. The manual supplied to assist in using the SGI interrogator was excellent, and after being guided through the set-up once, it was then a simple (if time consuming and manual) process to subsequently tune the channels.

#### **2.2.4 Lamb Wave Sub-System (LWSS) Performance**

The Lamb Wave module appeared to be the least developed hardware prototype used during the Ground Tests, and required the most technician attention during the workshop to prepare it for the testing. During the Ground Test however, this sub-system performed very well and supplied the most useful information to the status monitor allowing a good correlation between the damage growth and the sensor response to be displayed “live” during the testing. The Lamb Wave sub-system higher functionality, with respect to configuration files for different structural material and tests, was not integrated with the user interface (Notebook) and required a direct connection to be made to the module with software tools provided by the sensor supplier.

#### **2.2.5 Smart Wide Area Imaging System (SWISS) Performance**

Unfortunately it was not possible to integrate the SWISS sub-system during the workshop, and the hurried testing of sub-component 3 did not give good results, apart from highlighting the importance of a correct sensor bonding procedure. It was also noted that the SWISS system is operated entirely separately from the rest of the SHMS and (at the time of the Ground Test) shows no data fusion capability.

#### **2.2.6 Data Network Performance**

Occasionally the network would become inaccessible and it was necessary to power cycle all the components (turn on/turn off) and let the system reboot. The network environment was not robust and problems occurred if sub-systems (and other IP addresses) were disappearing and reappearing on the network. It was necessary to maintain the strict IP allocations at all times in order to have a moderately stable network.

#### **2.2.7 Central Computer Performance**

The Central Computer appeared well advanced in terms of hardware development. The status monitor provided for use during Ground Test turned out to be absolutely vital, supplying “live” information of the composition of the network, the state of the system, and the operational condition of each sub-system. It was also the preferred control interface for effecting system mode changes. The amount of data transferred to the Central Computer (especially by the Fibre Optic sub-system) seemed to be excessive and necessitated very long download times after loading periods. Unexpected power outages (due to network inaccessibility for example) and data download without first changing operating modes could result in corrupted or improperly “closed/truncated” data files. The Central Computer higher functionality with respect to configuration files, data directories, log file access, etc. was not integrated with the user interface (Notebook) requiring a direct connection to make any changes.

#### **2.2.8 Notebook Performance**

The notebook program was not successfully installed on a local DTU Wind supplied laptop, and the system was accessed via a computer supplied by the developer and with the Graphic User Interface (GUI) program pre-installed. This system was used only to connect to the network and download data for analysis elsewhere

(directly by the sensor suppliers and by the Notebook program integrated evaluation tool). Occasionally it was not possible to make a Notebook connection to the network, and this necessitated a direct File Transfer Protocol (FTP) from the Central Computer data directory. None of the higher function data evaluation tools were used during the ground test.

### **2.2.9 Prototype “End-User” Assessment**

The DTU Wind Mechanical Test Hal is highly experienced in the use of mechanical testing measurement and inspection systems. The use of experimental or prototype hardware is also a common requirement here. However it should be clear that any SHMS product must be intended for a broader end-user group than experimental test/measurement specialists with full technical facilities available. The prototype system developed by the AHMOS consortium did not display the level of integration, robustness, development or completeness intended in the final system. Examples of this lack include the necessity for unique software to connect directly with each sub-system in turn, the fragility of the communications network, the lack of facilities in the de jure interface, the lack of local data handling, etc. During the concept planning of the Ground Test there was an expectation that the sub-component testing would take place simultaneously, with the combined SHMS capable of detecting all damage types of interest. Despite the hardware limitations this would have been possible if the sensor suppliers had co-operated in distributing the available sensors across the different sub-components and damage types with the objective of providing an integrated SHMS response to damage generation. However, the strong need for individual suppliers to validate their particular sub-system, meant the focus of the Ground Test changed from being a trial of a system comprising several damage sensor types, to being a test of various sensor sub-systems that shared a common data storage and download tool.

And this is symptomatic of the challenge in applied SHMS. Despite the ability of individual sensor techniques to detect structural/material changes of interest, the sensor fusion (synergy) effect of combining differing techniques is often missing. Focus on robust data systems and a separation of the deep, data heavy, raw, research-level output, from the operational, user-interface, pre-analysed structure condition information is also lacking.

### **2.3 Assessment of Lightweight Low Cost Carbon Fibre Composite Materials and Structures for Armoured Fighting Vehicle Platforms (CAFV)**

The CAFV project “Assessment of Lightweight Low Cost Carbon Fibre Composite Materials and Structures for Armoured Fighting Vehicle Platforms” was part of the EUROPA contract number 04/103.014/09 running from 2005 to 2008. The objective of the project was to strengthen the technology basis for the large-scale application of carbon fibre reinforced composite materials to military structures by developing and demonstrating technologies for the replacement of conventional metallic materials with carbon fibre structural systems incorporating efficient armour system. As part of this assessment a review of the Structural Health Monitoring concept was conducted (Work Element 4.4).

This review did not only include the (usual) list of sensor techniques of interest, but also considered the fact that although there was a desire to implement SHM on military platforms and access the anticipated benefits, this was unlikely to occur until technological advances moved the hardware from developmental items to Commercial Off-the-shelf (COTS) technology. This developmental effort was not anticipated to come via directly funded military consortia.

SHM is a future technology that has potential for a profound and wide-ranging effect on the asset management strategies of many industries, not least in revolutionising military support concepts [3]. However, before implementation of such technology could take place, the following requirements would need to be demonstrated. Reliable sensor or monitoring systems to characterise condition or state of the structure; methods for interpreting sensor data and converting it to usable information about structural

integrity in a consistently fast and reliable manner; and developed support concept and maintenance architecture that effectively uses these technology gains.

The recommendations of the review included establishing a watching brief on the development of technologies identified as supporting future SHM; supporting common maturation of SHM approaches in other applications to promote a COTS environment for SHM; and defining specific goals for SHM implementation on military platforms and developing the support concepts and maintenance architecture that can most effectively use these technology gains.

## **2.4 Inspection and Repair of Sandwich Structures in Naval Ships (saNDI)**

The research project saNDI, “Inspection and Repair of Sandwich Structures in Naval Ships” was part of the joint defence funded THALES JP3.23. A key objective here was to develop usable damage tolerance prediction tools for forth-coming production control and in-service inspection/repair manuals for the Nordic/Anglo navies [4].

As part of this extensive project there was the opportunity to investigate active (Acoustoultrasonic) and passive (Acoustic emission) stress wave measurements on board Danish Patrol Vessels P555 Støren (Sturgeon) and P563 Søløven (Sealion).

P555 Støren is a 450-ton, multi-role vessel (patrol ship, missile platform or mine-layer/sweeper) of the first series Flyvefisker (flying fish) class. The area of interest was a section of debonded deck surface which was scheduled for repair during an imminent refit period (February 2004). Prior to the repair a series of Acoustoultrasonic measurements were taken using a piezoelectric transducer and sensor pair. The stress wave energy generated by the transducer is detected by the sensor; and by scanning the pair across the debond area it was possible to generate a “map” of the extent of the defect as good material transmits the stress wave energy more effectively than damaged. Following the repair the measurements were repeated to confirm that the newly repaired deck sections now matched the condition of the undamaged deck. This inspection gives a qualitative assessment of the success of the repair that would not otherwise be available.

The Standard Flex 300 vessel, P563 Søløven, was made available for an eight-hour trial by the Danish Defence Acquisition and Logistics Organization and the Army Operational Command in February 2007. During this time Acoustic emission sensors positioned at various locations on the ship’s composite hull recorded measurements whilst the vessel was operated at various speeds and manoeuvres. The measurements showed that the AE profile varies with the operating environment and furthermore with the measurement location (hull section), which indicates that it is possible to “map” the AE (background) profile of a vessel. This suggests that it is possible to identify structural damage through an “exception analysis”, i.e. changes in the AE profile. For example:

- Exception 1: The structure starts responding heavily to normal operation loads (the learned sensor response changes)
- Exception 2: Identical sensor positions give different response (e.g. port and starboard position response differently)
- Exception 3: Cross ship exception (you expect two identical ships to respond in the same way)

However, the trial was not carried out with the purpose of showing that damage signals can be extracted from operational signals.

This combination of “passive” sensing information (from the Søløven trial) where the activity is generated within the structure by operational loading, and “active” sensing information (from the Støren trial) where the monitoring system “pulses” a signal through the structure and compares the response with a template is a powerful advantage of the embedded piezoelectric wafer technique.



A SHMS for use in composite ship hulls could be applied to monitor known hot spots to achieve early indication of damage, generate a global structural AE profile of the vessel, i.e. mapping of the vessels structural response under normal conditions, identifying heavily loaded zones, give advanced information of likely problems prior to scheduled dock and inspection, and provide confirmation of the effect of repair/refit on the structure performance in service.

The final marine SHM application should be tough, clever and cheap (simple). It should preferably be a modular system allowing other sensor types (e.g. fibre optics and accelerometers) to match technological requirements and interface into a common display and decision making software.

### 2.5 Hunt Class Mine Countermeasure Vessel (MCMV) Hull Mid-Life Update

Between 1980 and 1989, 13 Hunt Class minesweepers and minehunters of the UK's Royal Navy were commissioned. These ships have glass reinforced plastic (GRP) hulls in order to reduce magnetic signature and were developed from a successful prototype, HMS Wilton, commissioned in 1972. The Hunt class Mine Countermeasure Vessels (MCMV) were designed for deployment in the North Atlantic with a specific function in mind. However, the end of the Cold War meant that from the 1990's these vessels were carrying out various functions for the Royal Navy at locations all over the world. Expanding their role in this way necessitated a structural assessment of the entire fleet.

Between 1996 and 2001, the author was employed at Rosyth Dockyard as a Research Scientist working with materials and Naval Structures experts to document the structural and material condition of these ships, establish load levels in extreme operational conditions, test various repair strategies (standard and emergency), determine the effect of temperature on material and structural properties, map thermal conditions in the structure during tropical deployment, establish damage tolerance limits, and update Naval Engineering Standards.

This represented a considerable application of resources in order to gather the kind of material and structural condition information that is generated automatically by a SHMS. One of the issues with investing in life cycle monitoring is that the cost is added to the initial (acquisition) budget, with the benefits then available throughout the service life and mitigating costs on general maintenance, mid-life assessments such as the Hunt class MCMV, extended operational capacity, or extended service life. A challenge for any implementation is to convincingly present the cost-benefit analysis for ownership, and/or to combine the sensing with actuation (smart structure) and in this way also enhance the platforms operational capability.

### 3.0 “ENABLING” STRUCTURAL HEALTH MONITORING TECHNOLOGY

There are some key challenges for technology transition of SHMS to military (high-capability) applications including; defining clear goals and criteria for the research projects to aim for, minimising the cost and technical risk of implementation by optimising vehicle design, production, and maintenance with SHM in mind, and developing a roadmap/timeline that transitions implementation in a manner that preserves safety and maintenance credibility but realises cost savings over an acceptable period of time.

In addition there are key developments in the reliability of available sensors and data tools, improved analysis and prediction models, and improved support concepts and maintenance architectures to exploit the technology gains. Enabling the maturation of this complex set of component and system level advances is challenging.

One way to approach this challenge is with reference to ideas first put forward by Christensen in the Innovators Dilemma [5]. Here one can read about the possible need for an “enabling application” which successfully uses a new technology on a lower capability application. This promotes (matures) the State of

the Art for the technology in such a way that it thereafter becomes competitive to apply on progressively higher technology capability levels.

Key terms in Christiansen's thesis include:

- Sustaining technologies – which improve product performance
- Disruptive technologies – which provide a “different value proposition”
- Enabling applications – which “pilot” the technology, demonstrate reliability, validate cost benefits, and reduce “program” risks prior to wide-scale application on an emerging program

Sustaining technologies are those that improve the performance of an established product or procedure. The improvement can be large, but it is always evolutionary in nature (doing something “better”). The vast majority of all technological improvements (also in the aerospace structural maintenance industry) are sustaining in nature. Disruptive technologies, on the other hand, bring to the market a very different value proposition than had been available previously. Generally, “disruptive technologies underperform established products in mainstream markets, but they have other features that a few fringe (and generally new) customers value.”

Christiansen goes on to suggest that once established in a few fringe or niche markets, disruptive technologies can then quickly go on to become fully performance competitive in the wider market, where initially they underperformed with respect to established procedures and/or products. The question could then be asked, is SHM disruptive with respect to current Non-destructive testing and inspection? If so, then in assessing technological possibilities for SHMS on military platforms (high capability applications), we can use Christensen's findings to help find a low-capability enabling application for SHM.

There are difficulties in successfully identifying Christensen's enabling and disruptive type applications before the fact, but a good case can be made for offshore wind turbine blade monitoring currently being one of the best candidates for an SHM enabling application. An enabling application will always involve mass production and associated economies of scale, and the politically driven targets for extensive adoption of offshore wind in Europe over the next few decades ensure that would be the case [6].

Across Europe and the World, huge wind farm developments have been planned. The towers, turbines and blades themselves are all becoming larger (to catch more wind) as modern materials permit more ambitious designs to become reality. The locations of these new farms are increasingly remote (offshore) dramatically increasing the Cost of Energy if standard approaches are maintained, and this in turn promotes the strong interest in Structural Health Monitoring (SHM) technology within the industry.

Trends in the Wind Energy Industry:

- an increase in installed capacity world-wide
- an increase in the physical size of the structures
- new materials and designs
- an increase in the size of proposed wind farms
- a tendency to place wind farms offshore
- higher requirements of reliability and easier maintenance
- A focus on the reduction of costs per “unit” of energy produced

The operation and maintenance of wind farms today is presenting an increasing challenge due to the trends summarised in the list above. It is a set of practical problems that have increased the relative cost of

maintenance within the industry, problems encountered when employing traditional scheduled-based inspection maintenance of turbines placed inconveniently on many tall towers located in remote/inaccessible areas. A growing problem particularly exists with the maintenance of offshore wind turbines and the operation of a centralised maintenance group covering wind farms located in several countries.

The solution to this problem involves the use of remote sensing to reliably report equipment faults and structural health information. This has the potential to hugely improve maintenance performance under these difficult conditions and so affect the profitability of the farm. Sensor and communication technology have advanced rapidly over the last decade allowing this ambition to become a realistic goal for the offshore wind farm operator.

Wind energy can be an important industry for establishing SHM as an applied technology as the industry is growing rapidly and is under pressure to adopt remote sensing. The prospect for the extensive use of sensor technology is apparent. And a further important factor in identifying the wind energy sector as the best prospect for adoption of monitoring technology lies in the pioneering culture that exists within this young industry, in contrast to that which exists in more traditional areas of structural engineering. All stages in the rapid development of the wind turbine structure design have required new approaches to solve challenging engineering problems. This is a sector that encourages the rapid integration of new ideas and approaches. A far more conservative point of view exists among civil sector engineers due to the greater emphasis on minimising risks, generally tighter constraints on budgets, and a huge reserve of good engineering practice and already established material and design information.

Adoption of SHM technology within the European wind energy industry would create a great demand for the hardware manufacturers and create a network of supporting industry and consultants on this continent. This concentration of expertise would form the base for the expansion of the technology into other sectors in Europe and around the world, re-exporting the “know-how” into diverse applications. The economies of scale would reduce hardware costs and the confidence from a successful application would win over more cautious engineers (in civil sectors for example).

Industries poised to follow the example of a pioneering European wind energy sector and embrace SHM technology include, Aerospace, Transport, Civil infrastructure, Earthquake construction, Historical building preservation and more.

A breakthrough application (“enabling application”) is necessary in order to stimulate a more general adoption and development of SHM ideas and techniques throughout industry. The rapid manufacturing growth within the wind energy sector, and the trend towards large offshore farms, make this the most promising global candidate for fulfilling the requirements of an SHM enabling application.

Wind turbine blade sensing systems most commonly used in the industry at present are fibre optic (Bragg-grating) strain measurement, e.g. MOOG ([www.moog.com](http://www.moog.com)), Fibersensing ([w3.fibersensing.com](http://w3.fibersensing.com)), Smartfibres ([www.smartfibres.com](http://www.smartfibres.com)), etc.; or natural vibration measurement (accelerometers), IGUS, Brüel and Kjær, etc. These are almost always post production instrumentations with the output handled by dedicated control software for Wind Farm Management.

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