Towards a Wireless Powering and Interrogation Strategy for Rotorcraft Health Monitoring

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ABSTRACT

Structural health monitoring is the implementation of a damage detection and condition assessment strategy for a structural system with goals of cost savings in maintenance and operations and/or life safety improvement. In rotorcraft applications, it is well-known that excessive rotor vibrations correlate well with fatigue and wear, which subsequently increase total life cycle costs. Monitoring rotor component (e.g., the pitch link) vibration levels in-situ could readily lead to mitigation strategies and better overall life cycle management. The cyclic rotor operating conditions in the rotating frame of reference present unique challenges that appear well-suited for a completely wireless solution. In this paper, we discuss how these challenges may be addressed by both wireless powering and interrogation.

1 INTRODUCTION

One of the primary costs associated with any engineering structure is that of repair and maintenance. Recent research has looked to structural health monitoring (SHM) to reduce these costs. The opportunities for reducing the expenditure fall into three categories:

- Longer scheduled maintenance intervals (maintenance costs and down time)
- Longer service life (where condition monitoring replaces time-based retirement policies)
- Fewer unscheduled failures and maintenance procedures

In addition, information available from the monitoring process allows better statistical evaluation of the factors affecting reliability, directing future developments.

This is particularly relevant in the aircraft industry, and specifically for rotorcraft. Helicopters contain large numbers of safety-critical parts and as such the maintenance schedule and part replacement regime is rigorous. It is unsurprising that many current research works are focusing on this industry. Factors affecting reliability include service time, vibration levels and frequencies, temperature cycles, load cycles and load levels, pressure, moisture, and contaminants.

SHM research falls into four broad categories:

- Sensing technology
- Telemetry

- Feature Extraction
- Power Supply

All four are necessary for a successful SHM implementation and each presents unique challenges on its own. The holistic integration of the components requires yet more endeavour and should form a focus for the individual fields.

This paper examines the motivations and demands of SHM research in an effort to identify beneficial directions for future work. The state of the art is reviewed and the bottlenecks in the development path are assessed. Discussions of current technologies and available expertise lead to suggestions for productive research efforts with an emphasis on producing a significant advance in SHM implementations in a short timeframe. In particular the analysis will be focused on developing technologies for use in rotorcraft applications, where the unique challenges presented encourage the development of wireless communication and power supply strategies. While wireless communication is a relatively mature technology, wireless power supply has received less attention. A detailed exploration of the technologies available for power delivery is provided and the benefits and drawbacks associated with different equipment are evaluated.

2 ROTORCRAFT LIFETIME COST ANALYSIS

The perceived benefits of SHM technology are primarily those of reduced operational cost and in some applications, increased life safety. In order to rationalise the cost benefit it is necessary to analyse the total costs of an engineering structure over its life span. These include not only the acquisition and standard operational costs, but also those of maintenance (scheduled and particularly unscheduled), part replacement, failure costs (these may be in terms of equipment or loss of life or loss or productivity during unexpected down-time) and disposal costs. To categorically determine the most critical subjects for health and prognostic monitoring it is necessary to consider all these factors and produce a figure for the true savings afforded by such equipment.

An important question when determining the cost is the cost to whom; generally in the aircraft industry the manufacturers are concerned with minimising the perceived costs for the purchaser who is also usually the operator. This provides some fairly clear cut measures but these lines will likely become blurred in the near future, when environmental considerations will exert greater pressures. These will be felt both in terms of marketing for the operating company and its clients (presenting a 'green' image) and in terms of regulatory restrictions and financial incentives. For example, taxes on environmentally damaging materials, procedures and consumables (e.g. fuel) are likely to increase in years to come, as are the disposal costs for parts and full assemblies.

Structural health monitoring can have a positive impact in most of these arenas: fewer unnecessary replacements will result in fewer disposal and acquisition costs; forewarning of imminent failure will allow procedures to be carried out at a convenient time and place, reducing transportation costs and down time; condition reports may allow preventative maintenance as well as offering opportunities for improving the efficiencies of worn systems and thereby reducing energy bills. Furthermore, as the complexity and number of subsystems included in aircraft increases, it becomes progressively more difficult to carry all the parts and equipment to maintain them, not to mention the skilled personnel to perform the servicing. SHM facilitates better planning and a reduced 'emergency repair kit'.

A comprehensive analysis is a daunting task; a comparable study into energy demands in the automotive industry required 5 years of data aggregation [1]. Moreover, the interests of parties holding critical information are often not in keeping with the impartial nature of such a study. Nonetheless, a comprehensive assessment of current and future cost breakdowns will allow effective focusing of research activities.

The task must be conducted in close collaboration with industrial partners, and standard approaches to information collection and assessment must be employed. A toolbox for this economic analysis would ideally be developed, following equivalent methods to those proposed for environmental assessment and monitoring by Bonaffini [2].

Results from such studies may be counterintuitive, as was found in the automotive study where the environmental advantages of hybrid cars were found to be strongly offset by the energy-intensive processes used in their manufacture and the difficulty in disposing of or recycling their constituent parts. The holistic consideration of the economic factors affecting rotorcraft, including the effects of structural health prognostic deployment, will put the benefits into clear context while highlighting the research topics requiring attention.

3 FACTORS AFFECTING RELIABILITY

Factors which can influence the life of rotorcraft components include:

- temperature
- loading
- vibration
- pressure
- environment (moisture, dust, sand, etc.)

SHM analysis consists primarily of two techniques: condition assessment and usage monitoring. The condition assessment may be performed through straightforward measurements (for example wear levels and pressure changes), or through intelligent feature extraction and modelling. Usage monitoring relies on empirical stochastic data to relate usage cycles (loading, vibration, temperature etc.) to life span. Studies of this nature are currently under way and will form a complimentary facet to feature extraction, modelling and prognostic efforts.

An influential report with regard to helicopter vibration and reliability was made by Sikorwsky in 1973 [3]. The report detailed a field study combined with laboratory vibration testing of a USAF-CH3 helicopter fleet. The experiments sought to determine the influence of vibrations on the reliability and maintenance costs of the rotorcraft components, in light of the addition of a new bifilar vibration absorber to the fleet. A control group without the new absorber was compared with the group with the absorber installed over a period of months to determine the difference in component reliabilities. This was related to vibration levels by means of laboratory tests to determine the difference in response amplitudes for the case of a helicopter fitted with the absorber and one without.

The study concluded that the majority of the components exhibited significantly greater reliability under lower vibrational loads. It was also concluded that the confidence in the quantitative results was low on account of the small numbers of helicopters included in the study, the gaps in the available operational data and non-trivial differences in the operative conditions in the two groups of helicopters. Suggestions for improving on the study included individual component testing under laboratory conditions, and testing of a larger group of aircraft, in addition to the inclusion of a control group with the same operating regime as the test group.

Fundamentally, it was found that far more data was required to draw meaningful conclusions. With the advent of modern health and usage monitoring systems (HUMS), access to the necessary data for a full analysis becomes a realisable possibility. The integration of these sensors in aircraft fleets is already underway, notably with the installation of Integrated Mechanical Diagnostic devices for Health and Usage Monitoring Systems (IMD-HUMS) on fleets of US Army UH-60 Blackhawks at a cost of $150k per aircraft, for which congress allocated $56m million throughout 2005. Similarly, Built-In Test Equipment (BITE) is supported in the US Army Future Combat System (FCS) project. Twenty-eight sensors are incorporated into IMD-HUMS to measure a broad range of usage data. The system is touted as being capable of recognising regime profiles, allowing informed usage and remaining life estimates to be made. A control study of the Black Hawk deployment indicated that the IMD-equipped unit flew 27% more missions and had a higher readiness rate than the unequipped unit [4]. A novel development coming out of the IMD programme was that of rotor balancing based on cabin vibration data, without the need for an additional tracker [5]. The concept has been proven on Sea Stallions, Black Hawks, Seahawks, Chinooks, Cobras and Hueys and has been said to function more reliably than a purpose-built tracker.

Other craft which may have HUMS equipment fitted include the Agusta-Westland AW-139, Sikorwsky S-92, Sikorwsky S76C+ and the Eurocopter EC-135. The Agusta-Westland EH101 is fitted as standard with sensors primarily in the engines and transmission train structure. They measure torque, vibration, temperature and debris in lubricant. The rotating parts of the structure, for example in the rotor assembly, form a challenging location for sensor deployment due to the challenges of supplying power and taking measurements from the devices in flight. The critical path for achieving a full prognostic system lies in expediting the deployment of sensors and data acquisition throughout all of the critical components, including those in the rotating assemblies.

4 STRUCTURAL HEALTH MONITORING

4.1 Introduction

Most complex engineering systems today are designed-using a combination of experience, analysis, and code or regulation constraints-for a fixed life cycle. The system is designed, built, deployed, maintained (almost always on some fixed, very conservative schedule), and retired (in many cases, with actual useful life remaining). This is entirely a uni-directional process that, in many circumstances, is unadaptable to a number of complex issues that arise during its life cycle. Such issues could include unexpected operational/environmental conditions or design function/performance retasking, which may strongly increase the likelihood of damage initiation and accumulation that can lead to failure, performance degradation, and subsequent severe economic or life-safety consequences. As an example in the United States Air Force air fleet, the C/KC-135, B-52H, C-5A, and C-130 aircraft platforms were originally designed for service lives of 20-30 years, but the average service life on this fleet is now approaching 50 years with further service being demanded. These aircraft are now known to be highly susceptible to corrosion, so the actual service life will be reduced significantly by corrosion and stress corrosion-induced fatigue. Annual maintenance for this damage, which relies on conservatively scheduled (based on fleet averages) visual inspections that require significant downtime, cost the Air Force $185,000 per aircraft in 1990 alone. It is clear that a life-cycle management strategy here would be beneficial as these aircraft are pushed beyond their design life in the presence of degradation mechanisms (corrosion, fatigue, mechanical wear, etc.). Furthermore, if rapidly damaged during flight, adaptability and control could combat degradation even up to onset of catastrophic failure by shifting loads through flight control or even suggesting alternate pilot handling strategies. In another industrial example, semiconductor manufacturers have indicated that the cost associated with unscheduled production line downtime caused by unexpected equipment failures can result in losses to the company of up to $10M per hour [6]. Here, a strategy for predicting in a quantified way the time to failure could provide a mitigating manufacturing strategy feedback for reconfiguring operations that prevent such costly downtime. As a third example, a recent report [7] indicates that out of 1200 accidents in a fleet of 11000 civil helicopters, 35 were caused by rotor system failure which could have been averted with the use of structural health monitoring (SHM), which will be more formally defined shortly. The focus of current helicopter Health and Usage Monitoring Systems (HUMS) research, currently centered on the drive train and gearbox components, needs to be extended to the rotor assembly. In particular, industrial studies of HUMS benefits [8, 9] call for better damage localisation in order to provide clear 'go/no-go' flight indicators. (Current techniques may detect that a problem exists without necessarily determining the location or severity of the damage.)

For these examples, generally damage initiates at microstructural levels in materials, accumulates under service and environmental loading, manifests itself at macroscopic scales in some way (such as a change in measured dynamic behaviour), and eventually may lead to a component or system failure. 'Failure' in this context may be defined very generally as the point at which the damage accumulation no longer allows the component or system to reliably perform its intended functions. Structural health monitoring (SHM) is the process of making an assessment, based on analyses of measured data (usually in an online fashion), about the current ability of the component or system to successfully perform its design functions. Damage prognosis (DP) extends this SHM process by considering how this current state assessment, when combined with a probabilistic model of future loading conditions and uncertainty quantification due to environmental and other sources of variability, may be used to forecast metrics of system performance useful to the owner/operators, e.g., remaining life, time to next service, etc. It is this DP capability that potentially gives owner/operators the ability to implement condition-based maintenance as well as to manage system planning and evaluation more efficiently, either of which can provide large economic and/or life safety benefits.

Implementing an SHM/DP strategy is obviously a challenging task, and much of this may have to do with scale: even though damage initiates at the microstructural level, it is generally not observable at that level (at least in an online, near real-time manner). Practically speaking, it is at the macroscopic levels that we have mature technologies (strain gages, accelerometers) to make measurements of structural response, which indirectly reflect the realization of damage in the system performance. Furthermore, in some applications it may be that some amount of microstructural-level damage per se is not even relevant, as it may have little functional effect on the system performance level, which is typically what the system owner most cares about.

The first line of attack in any SHM implementation is clearly the establishment of an appropriate sensor network that can adequately observe the system dynamics for suitable signal processing and feature extraction at the observable scales. The challenges posed in rotorcraft are manifold: high vibration levels require robust equipment, certification procedures are rigorous and require complimentary sensor deployments, and the large numbers of critical rotating parts need a power source and communication link with a central monitoring station. HUMS have been in operation on helicopters for many years overcoming many of the difficulties, but the rotating parts have largely been neglected on account of the unique challenges of power supply and data transmission in these locations. Slip rings are commonly employed for such purposes; these are already present in many helicopters, for example the EH101, for supplying power to de-icing matting on the rotor blades. The electro-thermal matting demands 45 kW of power from the generator and this is passed through a slip ring assembly. The substantial power levels result in arcing of the power supply, with large power spikes and electro-magnetic interference. These features are not conducive to the operation of sensitive measurement equipment, where power spikes will disrupt measurements and damage sensors, and interference will cause problems with data communications. As an alternative, wireless energy supply is proposed in conjunction with wireless data communication as a solution to the difficulties in monitoring these components.

An overview of SHM technology is provided below for reference.

4.2 Sensors

A wide array of sensors is available for SHM purposes, and after consideration of the sensor properties (sensitivity, bandwidth etc.), the possibilities are bounded primarily by cost, size, and power demands. All of these form a focus for current research, and in particular, the move towards wireless remote sensors has prompted novel research into low-power sensing technologies. For example, surface acoustic waves have been used to good effect in a passive wireless pressure-measurement transponder [10] which requires minimal power and also produces a fully wireless solution.

Piezoelectric sensors can measure acceleration, force and pressure and typically require in the range of 0.1-1.0 W of power when combined with the appropriate amplification and signal processing units. Some acceleration sensors also take advantage of micro-electromechanical systems (MEMS), which are discussed further in the context of power supplies below.

Strain is commonly measured with bonded foil gauges, as well as with thin film, diffused semiconductor and piezoresistive gauges. The latter have the benefit of being much smaller than standard foil gauges but at the expense of a nonlinear response. Power consumption across the range is typically around 1W for a 4 channel setup.

Where greater strain resolution is required, fibre-optic methods may be employed; sensing of the order of tens of nanostrain is reported using these techniques [11]. These systems are, however, expensive and have large power requirements: the most demanding component is the thermoelectric cooler needed for regulating a Fabry-Perot filter for voltage-to-wavelength conversion. This typically uses 3-5W.

Active methods commonly employ piezoelectric actuators, which may double as sensors. The capacity to generate known excitation patterns permits advanced analysis using, for example, Lamb wave propagation [12–14] and impedance-based [15] SHM methods. Typical Lamb wave actuation methods will require 300mW of average power, with even higher peak demands, in addition to the power required by the waveform generator, the D/A converter and the piezoelectric sensing measurement equipment.

4.3 Data Interrogation and Statistical Modelling

The scope of SHM encompasses a wide range of data processing methods with varying analytical sophistication, including:

- low-level condition monitoring (pressures, wear indicators, temperatures etc.)
- usage monitoring and empirical remaining life prediction
- damage / wear indications through response profile changes
- damage identification and localisation through feature extraction
- health prognosis through advanced modelling

Condition monitoring has been widely employed in many sectors for years now, conspicuously in the automotive industry (with oil pressure, brake pad and tyre pressure indicators on the dashboard), and similarly in the aircraft industry.

Usage monitoring is a primary area of current development in the aerospace industry, aided by the expanding implementations of HUMS sensor networks throughout rotorcraft. Success has already been achieved with such methods although not yet to the extent that is ultimately hoped for [8, 9].

Damage indications, localisation, identification and prognosis all rely to varying extents on feature extraction and modelling of a system. This puts higher processing demands on an SHM deployment than the simpler measurement procedures described above. The processing may be performed at a central unit, or performed locally at the sensor. In the latter case the power available for processing will determine the permissible analysis sophistication.

4.4 Telemetry and Power Supply

Regardless of where the raw data are processed, some data must ultimately be relayed away from the sensing locality. The simplest approach is to use a wired network. With such a network the problems of power supply and communication are effectively solved; bandwidth is unlikely to be a concern in this configuration, and continuous data may be relayed.

Specific problems associated with wired networks are the prohibitive cable routing, particularly for large numbers of sensors or networks covering large regions, and the difficulty in maintaining wired contacts for moving parts. Retro-fitting of sensor networks further exacerbates these difficulties. In helicopters, the rotor parts have been identified as an important area for SHM, to date largely overlooked. This application has the further constraint of airworthiness certifications, where connection to existing electrical systems may compromise the appraisal.

In rotorcraft the problem of supplying power to the rotor blades using sliprings has already been tackled for the purpose of deicing the blades. As discussed, this necessity compromises the potential for exploiting the same approach for sensor measurements; arcing in the 45kW slipring supply produces potentially damaging power spikes for sensitive equipment and will interfere with data transmissions. One possibility would be to develop robust power conditioning hardware and research carefully modulated digital signal transmissions to withstand interference. In the absence of such equipment, however, the only solution is a wireless implementation.

Wireless communications standards are plentiful, with low-power solutions such as Zigbee well-suited to these applications. Even these, however, place a much higher power demand on the sensing device than the sensor hardware itself. One approach to this conundrum is to perform data processing and/or compression on board the sensing device, transmitting only the necessary information. Careful optimisation can produce reduced energy requirements [16]. The more sophisticated the processing requirements, however, the greater will be the energy demands.

In the absence of a wired power supply, the prime candidates for energy delivery are batteries, scavenging, and wireless delivery. Batteries provide only a short-term solution and are an inconvenient compromise, as they themselves require changing (maintenance) on time scales that often are exceeded by the life cycle of their host system.

Energy scavenging techniques for rotorcraft are generally focused on vibration scavenging [17] and ambient radio-frequency radiation scavenging, and the possibility of thermoelectric generation also exists, for example if deicing equipment is in operation on rotor blades. The problems with RF energy scavenging are associated with the broadband nature of the ambient radiation, although some steps towards tackling this problem have been made, primarily with the intention of permitting broadband power supply from a base station (as opposed to ambient scavenging) [18].

Vibration-based energy harvesting may be achieved using piezoelectric devices [19], or with mechanical electromagnetic devices [20]. These techniques are fundamentally limited by the mass of the device, as this is where the energy is derived from. Piezoelectric devices may incorporate the mass of the structure to which they are attached but once more the power production is ultimately limited by their scale. Mechanical devices have the added complication of reliability problems with the resonant moving parts. Despite these drawbacks, piezoelectric power has been successfully demonstrated in low power sensing applications on a helicopter pitch link by Arms et al. [21].

Micro-electromechanical systems (MEMS) are allowing development of advanced mechanisms, such as those required for vibration energy scavenging, on small scales. Techniques for fabricating three-dimensional structures have even been developed [22]. Concerns may be raised once more about the reliability of MEMS subject to vibration, particularly in rotorcraft where such forces are high. A study of 22 microengines found only 2 to suffer from vibration-related failures, while 3 suffered non-vibration-related electrical failures [23] in the same period. The study concluded that vibration related failure is not a big concern compared to other failure modes, but it is noted that the overall failure rate was high. A SHM implementation needs to be more reliable than the system it is monitoring by several orders of magnitude, suggesting that this technology is not ready for exploiting yet.

In light of the power limitations and reliability issues of energy scavenging techniques, combined with the high power demands of existing advanced sensor technologies, wireless power delivery presents the most promising option for sourcing the required power to enable radical sensing and processing improvements in rotating parts. This technology is reviewed in detail in a subsequent section.

5 WIRELESS POWER DELIVERY

5.1 Introduction

The wireless delivery of power has been a subject of interest since the late 19th century when Maxwell predicted the possibility in his “Treatise on Electricity and Magnetism” and Hertz later demonstrated the ability experimentally. In subsequent decades, Tesla experimented with the transmission of electromagnetic power but interest subsided with the advent of large-scale wired power supply grids. Development was abandoned until the advent of radar during World War II, whereupon the production of high-power microwave radiation facilitated the focusing of useful radio frequency (RF) beams and brought the power transmission goals within reach. Current technological developments now warrant the exploitation of such techniques in the short- to medium-range. Modern wireless power transmission falls broadly into three categories:

- Induction
- RF radiation
- Laser radiation

All three are forms of electromagnetic power distribution, with the first two differing in their utilisation of the near- and far- field effects of inductive antennae and the last two differing in the wavelengths of the radiative electromagnetic waves. These superficially small differences result in markedly different methodologies and equipment, reviewed below.

5.2 Induction

Magnetic induction has long been used to great effect in electrical devices. A notable example is that of the transformer which allows electrical isolation and the stepping up or down of voltages and currents. Such devices typically employ ferrous cores and permit extremely high efficiencies through containment of the induced field and restriction of the inductive load. The technology has been adapted, removing the continuous ferrous core but maintaining as small a gap as is practical, to allow the transfer of power between two separate devices. This method is commonly employed in the charging of batteries in portable devices without the need for a direct electrical connection. The technique has been employed extensively in electric toothbrush chargers, surgically implanted cardiac equipment, and cellular phone chargers [24]. The success of such implementations has led to the proposal of a universal battery charging platform for use with a range of household devices [25]. These contactless electrical energy transmission (CEET) [26] devices may suffer from large leakage inductance, increased proximity-effect winding losses and increased conduction losses due to reduced magnetising inductance. Electromagnetic radiation from the air gap may also be problematic in terms of both efficiency and interference with nearby electronics or communication devices. Some of these issues are tackled by Jang and Jovanovic [27] but they remain reliant on the close proximity of the transmitter and receiver.

The efficiency of the near-field electromagnetic inductive methods has led to a recent analytic study into the distance limitations [28]. In contrast to the more common non-resonant inductive schemes, the study considers tuned coupling to excite resonant electromagnetic states. The findings are supported by an experimental demonstration which reports the transfer of 60 Watts with 40% efficiencies over distances in excess of 2 meters [29], with relatively little power dissipated in radiative RF emissions.

An emerging technology that commonly utilises near-field signals is that of radio frequency identification (RFID). Finkenzeller [30] gives a comprehensive review of the technology. The principles of RFID were first employed on a large scale by the British Air Force in World War II to identify their aircraft and differentiate them from enemy fighters. Many modern RFID implementations focus on stock tracking as an improvement to the current industry standard bar codes, where passive devices which scavenge their energy from the RF signal are the only practical solution.

Any device that creates an electric field will inevitably produce the magnetic field required for inductive excitation, but by far the most common hardware used in RFID is a simple conductive coil. These are sized according to the range requirements: larger coils produce weaker fields at zero distance but the field strength also drops off at a lesser rate. The receiver coils may be smaller, according to the amount of power required; it is noted that in RFID the power transfer efficiency is not a primary design driver and the principles vary in that regard to those used by Karalis et al., described above.

Where an RF signal is used to transmit energy, it is desirable that the same signal may be modulated to facilitate communication between devices. While this is trivial for communication from the source (transmitter) to the device (receiver), the reverse requires further consideration. One advantage of near-field methods is that they permit such reverse communication from a device to the source by means of load modulation. This technique applies a modulated load to the receiving coil, disturbing the magnetic field and creating equivalent fluctuations in the source coil current. This is used to encode the data, adopting amplitude shift keying (ASK), frequency shift keying (FSK) or phase shift keying (PSK).

Early RFID employed this technique almost exclusively [31] but as the bandwidth requirements increased with greater amounts of data, limitations were recognized: the useful range of magnetic induction shows an approximately inverse relationship to the frequency. Thus for greater bandwidth in the subcarrier it is necessary to increase the power supply frequency and sacrifice the already limited range of the devices.

5.3 RF radiation

Where distances from the source are large in comparison to the signal wavelength, far-field effects must be utilised. Under these conditions the two devices are no longer electromagnetically coupled but rely on the propagation of electromagnetic waves from source to receiver. This is a radiative phenomenon, with the power dissipated from the source regardless of the loading at the receiver. As such any energy that is not collected by the receiver is lost, with the associated efficiency penalty. This means that the energy density harvestable from an isotropic radiator will diminish in proportion to the square of the distance. While not ideal, this is an improvement on the cubic relationship seen in the field strength of inductive schemes, permitting greater ranges to be covered. A further advantage is that the size of a radiative antenna is broadly governed by the wavelength, such that smaller devices are better suited to higher frequencies, which in turn allow higher data transmission bandwidth. The disadvantage of high frequencies is the associated lower permissivities which reduce efficiency.

The loss of RF radiation to the environment may be lessened through the use of directional antennae; these have a gain measured as the ratio of the maximum intensity to the theoretical intensity of an isotropic antenna at the same distance. With such devices the radiation may be focused into a beam; as a rule of thumb, the larger the device, the better the beam can be focused. At the receiving end, the overall efficiency of the energy transmission is governed by the area of the receiving antenna array in comparison to the beam area. Once again, larger devices will permit greater efficiency.

One of the simplest antennae in popular use is the dipole antenna. The maximum gain for such an antenna is 2.2dBi (dB relative to an isotropic radiator). Yagi-Uda antennae [32] increase this gain by supplementing the dipole with a reflector and a series of director antennae, respectively slightly longer and slightly shorter than the driven antenna. These antennae are recognisable as those commonly used for television reception. The element lengths and spacing are determined by the wavelength of the RF transmissions, with each element approximately half a wavelength long and spaced approximately a third of a wavelength apart. The gain is roughly proportional to the number of elements so that, for example, a 15 element Yagi antenna has a gain of around 14dBi.

Another approach is to focus the RF emissions using a parabolic reflector. Solid reflectors produce the best results but weight and wind-loading penalties often lead to the use of mesh instead, producing comparable results as long as the gaps remain less than 10% of the wavelength. The RF source may be a simple dipole-reflector combination for large wavelengths but is better served by a horn antenna for high frequencies. These are generally connected to signal lines by means of a waveguide to effectuate the transition. More complicated source (or 'feed') arrangements may call for the implementation of Cassegrain reflectors, where a secondary reflector permits the relocation of the feed from the focal point of the main reflector to a more convenient mounting behind the main reflector.

In some circumstances it is necessary to change the direction of the RF beam, for example to track a moving object or to switch between two receivers. The simplest option is to mechanically change the orientation of one of the devices discussed above. This will have a time lag associated with it, and will not be suitable for rapid changes of direction or erratic motion. It may also require prohibitive amounts of energy for large equipment and have other pragmatic restrictions. An alternative is to use phased arrays of antennae to create a directional beam. With this arrangement the direction of the beam is controlled by adjusting the relative phase of all of the antennae. The direction may be changed almost instantaneously with no physical movement of the device.

Often the exact receiver location will be unknown or may be moving relative to the source. Several options are available for dealing with this scenario. The most straightforward is to use a wide beam that will encompass the receiver despite small variability in the alignment. This approach will be inefficient, however. A better- focused beam will give the potential for greater efficiency but requires the determination of the receiver's location. This may be achieved by one of two means, both requiring a signal from the receiver. The first method is simply to triangulate the position using an omnidirectional signal broadcast from the power receiving device. The second method is for the device to digitally transmit a signal to the source concerning its whereabouts. One possibility is for this to be determined from variations in the received power levels; the transmitter could calculate this based on readings from multiple sensors or a continuous scanning technique could be used instead. A further possibility is presented by Brown [33], who successfully demonstrated the guiding of a helicopter using a single RF beam. Similar principles would allow the device to determine its orientation with respect to the beam and transmit this information back to the source.

With the uncoupled nature of the source and receiver, it is not possible to use the load modulation techniques used in inductive supply. A common method used in RFID is that of backscatter: the impedance of the receiver's antenna is deliberately mistuned to reflect some of the RF radiation, and digital communication is possible through binary modulation of this detuning. With the higher frequencies adopted for far-field techniques the bandwidth is increased over that of near-field methods. In RFID the current limits are typically around 3m [31] with current receivers able to detect signals with power levels of -100dBm in the 2.4GHz band. A further possibility is to implement a separate communications channel on a different frequency using one of the established low-power wireless protocols such as Zigbee.

The efficiency of the overall transmission is strongly influenced by the receiving antenna, particularly as the design restrictions on the sensor device are likely to be more stringent than at the RF source. It is envisaged that future implementations will be strongly focused on this part of the design. To maximise efficiency, the antenna must be large enough to absorb energy from the entire beam cross section, and tuned so as not to reflect or re-emit any of the signal. Where polarisation is uncertain, quadrapole antennae may be employed. In metallic structures, resonant cavities [34] form the most appropriate antennae. The structural consequences of the cavities must be considered carefully.

An important development in RF power transmission is the highly efficient rectenna [35–37]: a rectifying antenna. These devices in their simplest form consist of a diode connected to an antenna, allowing direct rectification of the RF signal to provide a DC current. Here the efficiency is directly related to the matching of the antenna and diode, and the diode characteristics (voltage drop and switching speed). Schottky diodes are favoured for these applications, and rectenna efficiencies of 91% have been reported [38]. Arrays of these rectenna elements are arranged in parallel or series to provide high current or voltage, respectively. Generally the requirement for sensor technologies lies in achieving the 3.3V required for CMOS devices. Rectenna arrays are commonly comprised of planar antennae, and have the advantage of being relatively non-directional. Much research has gone into the development of flexible planar arrays, suitable for application to curved and non-stationary surfaces [39]. Many research works have focused on the use of such arrays to power sensing devices, for example [40].

The overall efficiency at the receiving device will be governed to a large extent by impedance matching of the antenna and circuitry. Meeting this objective requires sophisticated modelling for proper antenna design; such modelling is well encompassed by finite difference time domain (FDTD) method [41]. Precise tuning produces the required efficiency at the expense of broadband versatility; electronic tuning through the use of varactor diodes [42] offers the best of both worlds, although the active circuitry will consume some of the limited power supply and the additional semiconductors in the supply line will dissipate further energy. Similarly, phased arrays may be used in a receiver to compensate for highly directional non-stationary sources, with the same drawbacks.

Health concerns regarding concentrated microwave beams have been raised in many fora. These can be divided into two categories: thermal and non-thermal effects. The latter concern does not have a firm scientific basis, and is not generally taken into account by regulatory bodies. Thermal effects are well understood and have been exploited in non-lethal weapons such as the Active Denial System [43]. While such applications are designed to have no lasting effects, many studies (e.g. [44]) have investigated the long-term health implications across the microwave spectrum and these have contributed to the standards contained in BSR/IEEE C95.1a-1998. The regulations are based on averaging times of 6 or 30 minutes for controlled or uncontrolled exposure respectively. Thus the power densities specified may be endured indefinitely, and where the power density is doubled the exposure should be limited to three minutes in any six minute period (or 15 in any 30 for uncontrolled exposure). In the gigahertz bandwidth the power density is limited to 5mW/cm2 for controlled and 1.0mW/cm2 for uncontrolled exposure [45].

The frequency bands available for RFID, which could likely be utilised for similar RF energy transmission schemes, are 0-135 kHz, and the ISM frequencies around 6.78 MHz, 13.56 MHz, 27.125 MHz, 40.68 MHz, 433.92 MHz, 869.0MHz, 2.45 GHz, 5.8 GHz and 24.125 GHz. Far field applications generally use frequencies above 100MHz, typically in the UHF spectrum (eg. 2.45 GHz) [30].

A popular source of microwave emissions around the 2.4 GHz band is the magnetron; several magnetrons are often combined into a phased array by phase-locking the oscillator. For some applications the transmitting antenna at this frequency may be considered prohibitively large and the development of the gyrotron has led to research into collecting power in the 35 GHz band. Rectenna designs for these frequencies emerged in 1992 with reported efficiencies of 50-70% [46].

Notable historical demonstrations of RF power delivery include the remote powering of a remote control helicopter [47] and the transmission of 30kW of power over a distance of a mile [48], both of which focused the microwave radiation with an ellipsoidal reflector and collected it with a rectenna array.

5.4 Laser radiation

Laser radiation is another type of far-field electromagnetism, operating at optical frequencies rather than radio frequencies. The much shorter wavelength offers advantages in the size of generating, focusing, directing and collecting equipment. With the current state of the art, however, the disadvantages are more numerous than the benefits.

A significant limitation of short wavelength emissions for use within the Earth's atmosphere is the lower permissivity of air at these frequencies. Thus a popular application for laser energy transfer is in extra-terrestrial use. Landis [49] discusses some of the challenges presented by the transmission of power from the Earth's surface to moon- or satellite-based photovoltaic arrays. Atmospheric transmittance is higher in some frequency bands than others (notably that of visible light), and may be deemed acceptable, particularly in short-range applications.

The generation of laser radiation can be achieved through a variety of processes, commonly electrical or chemical. It is a very inefficient process, typically lower than 10%. Quantum Cascade Lasers [50] have improved on these figures, with recent demonstrations [51] reported to have achieved 22% efficiencies at room temperature and 34% at 160 Kelvin. This is still far below the efficiencies available with longer wavelength apparatus and will be prohibitive wherever power at the source is not in abundance. That said, many applications will have an unrestricted supply at the source and this consideration may be negligible.

Conversion of optical waves to electrical energy is performed by photovoltaic arrays; these can achieve 40-50% efficiencies but still fall short of the levels attainable with RF equipment. They are most commonly employed in the scavenging of solar energy but are in fact better suited to conversion of narrow-band radiation. With the advent of modern nanotechnology an alternative to the semiconductor-based photovoltaic devices is being investigated: nano-scale rectenna arrays [52] using the same principles as those used in RF power harvesting. While these devices are theoretically capable of operating to the same efficiencies as their RF counterparts, the smaller scales offer unique challenges which remain to be resolved.

6 CONCLUSIONS

Lifetime costs associated with an airframe from design through manufacture and operation to disposal are difficult to quantify. There is no doubt that maintenance and unplanned failures contribute significantly to the expense but it remains difficult to attach numerical figures to these costs. While the perceived wisdom points towards structural health monitoring and prognostics as a valuable area of research, it is difficult to justify the resources contributed to this field, and more importantly the priority assigned to each facet of the research, without a comprehensive study. This is a daunting undertaking but results from related industries have sometimes proved counterintuitive and such a report could help direct efforts towards the most productive endeavours.

Existing reliability studies of rotorcraft parts have provided meaningful assessments of the factors leading to component failure but, historically, the relatively small data sets available for analysis have hampered definitive conclusions. The current trends in HUMS data collection have paved the way for more detailed studies and this opportunity should be capitalised upon through the deployment of extensive sensor networks. In addition to the direct benefits of condition monitoring, the data will allow identification of critical operating and failure regimes, facilitating better focused development efforts. In particular, a largely neglected but crucial area for monitoring is on the rotating parts of rotorcraft.

The unique problems presented by such deployments make them prime candidates for wireless implementations. The long life-cycles of these structures make the prospect of easy retro-fitting enticing. Electrical isolation makes certification easier, and the wireless approach offers the prospect of simplified installation on the rotating assemblies in addition to that of remote data acquisition at ground stations. Furthermore, the efficiency limitations of wireless power delivery are not a significant concern in such environments, where power at the source is plentiful.

The installation of large sensor arrays and empirical studies of failure and fatigue modes will be aided by the incorporation of advanced sensor techniques, including active sensing; technologies that are ready for implementation but currently limited by power availability. These studies also form a natural precursor to intelligent prognostic implementations, where again the state of the art is in advance of current sensor deployments. For these reasons, and because of the shortcomings of current energy scavenging methods, the critical path in the development of SHM technology points towards the implementation of wireless power delivery in rotorcraft applications.

The technologies presented herein provide many avenues for research, and while several advanced methods show significant promise (for example, nano-scale rectennae), the technologies which have produced the best results to date and which should be available for immediate implementation are the inductive and RF radiative methods. Further feasibility studies on the specific needs of rotorcraft applications are recommended to determine the most appropriate of these two options and to optimise the choice of equipment from that presented here.

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