Smart Structure Applications In Aircraft

CF PHOTO

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Introduction

The Canadian Air Force relies on relevant and dependable equipments operated by qualified and motivated airwomen and airmen in order to accomplish its mission both domestically and internationally. In order for this equipment to be completely efficient in today's complex operations, the Canadian Forces (CF) needs to bring into service some of the best and latest technologies available. One approach to optimize our aircraft is to deal with the maintenance process, which plays a major role in the availability and the use of these assets

Aircraft Maintenance

Traditionally, the method to schedule aircraft maintenance actions is based on records such as take-offs and landings, flight times, and torque events. These records are compared to a generic baseline with conservative margins. This conservative attitude is adopted by the authorities to guarantee safety, as well as reliability, availability, and to avoid disasters. Since not every aircraft is used in the same flight conditions, this method leads to inefficient timing of inspections and parts replacement, with operational negative impacts such as aircraft unavailability.

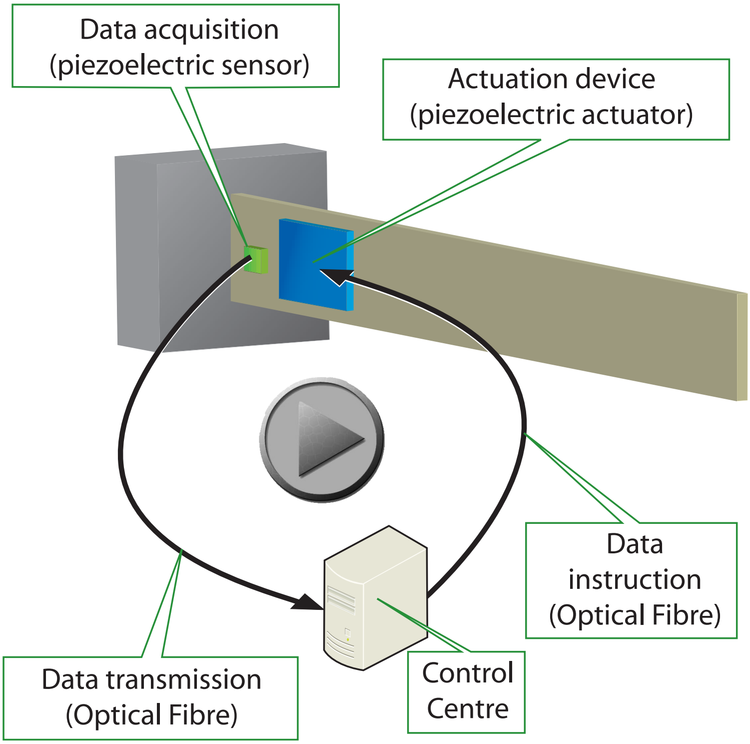
One way to close this gap is to use smart technologies to monitor closely the operational regime of the aircraft, improve its functioning, reduce its maintenance, and finally, enhance its life cycle. With advanced technology in sensors and signal processing, operators can now monitor parts and determine the exact time at which inspections and parts replacement is needed, based on the actual condition of these parts. This is currently possible with the Health Usage and Monitoring System (HUMS) and is called "condition-based maintenance".

The concept of continuous monitoring has been in use in the aerospace community for some time now. For example, in the United Kingdom it is mandatory that all civil registered helicopters carrying more than nine passengers be fitted with a HUMS. They also suggest that the benefits for the system have already surpassed its cost, and that it has eliminated potential fleet unavailability and prevented the potential loss of two Chinook[1] helicopters. Although HUMS is currently used mostly on helicopters, it is also used on some fixed-wing aircraft and unmanned aerial vehicles (UAVs). Typical HUMS are composed of sensors and processing algorithms that enable the monitoring of engine condition and performance, continuous performance, continuous vibrations, engine exceedance, and rotor track and balance[2].

In the CF, the Griffon helicopter is one of the aircraft fitted with a HUMS, which is used for diagnostics and monitoring of critical components. Some of the benefits to the CF are categorized as maintenance credits, and include: extension of main gearbox overhauls, rotor track and balance maintenance flights, drive train monitoring, and flight time logging.[3] However, it is not used for true condition-based maintenance. Maintenance actions timings are still largely based on records of flight hours, take-offs and landings, and so on. Even though the technology is now available to conduct condition-based maintenance, its acceptance by the operational communities—civilian and military—as to its benefits and airworthiness, is still faced with resistance in changing the traditional methods of maintenance.

The next step beyond condition-based maintenance is to exploit the information provided by the sensors that activate actuators dispersed on the aircraft's components, which alleviate loads and vibrations. The net result of this approach is an increase in performance and fatigue life of these components and of the aircraft. This is the essence of a paper on smart structures published in the Canadian Military Journal in 2000.[4]

Figure 1: Vibration suppression of a cantilever beam with the smart structure approach.



DEFINITIONS

In 1996, Spillman, Sirkis, and Gardiner established a definition of a smart structure from a wide variety of sources. It reads as follows: "a smart structure is a non-biological structure having the following attributes: 1) a definitive purpose, 2) means and imperative to achieve that purpose, and 3) a biological pattern of functioning."[5] This biological pattern of functioning has been broken down into five basic components by Akhras[6] (items in parentheses represent the equivalent within the human body):

1. Data acquisition (tactile sensing): collects the required raw data needed for an appropriate sensing and monitoring of the structure;
2. Data transmission (sensation nerves): forwards the raw data to the local and/or central command and control units;
3. Control centre (brain): manages and controls the whole system by analysing the data, reaching the appropriate conclusion, and determining actions required;
4. Data instructions (motion nerves): transmit the decisions and the associated instructions back to the members of the structures; and
5. Action devices (muscles): take action by triggering the controlling device/units.

Figure 1 shows a simple example of a smart structure in the form of a cantilever aluminum beam in which vibrations are suppressed systematically. The piezoelectric sensor converts the mechanical deformation into an electric signal. This signal is processed by the control centre, which in this simple case basically inverts the signal and amplifies it. The new signal is then sent to the actuation device, another piezoelectric material that converts electrical energy into mechanical form to reduce the vibration.

BENEFITS

Smart structures applications will provide benefits to the aviation industry and operators. Continuous monitoring, including monitoring of the health status, damages, and possibly mitigation and repair is not the only envisioned benefit. Other benefits include the following:[7]

1. increase passenger and crew comfort by reducing vibrations and noise;
2. increase systems and components structural life;
3. improve precision pointing and sensing of onboard electro-optics and infra-red sensors; and
4. enhance aircraft performance by optimizing aerodynamics and lifting surfaces to mission and flight profile.

All of these benefits will result in either a reduction in manufacturing and operating costs, or an increase in performance of the overall aircraft. It is noteworthy that other vehicles, including trains, trucks, and naval vessels could also benefit from these technologies.

AREAS OF APPLICATIONS

In aviation, the application of smart structure technologies can be divided into four distinct areas[8]: monitoring of composite materials, suppression of structural vibration, noise suppression, and control of surface morphing.

Monitoring of Composite Materials

Composite materials are now widely used in the aerospace industry. They offer great advantages compared to metal alloys, such as reduction in weight, increase in strength, and greater resistance to corrosion. However, composite materials react differently to loads and vibrations. Cracking of metallic components is gradual and predictable, whereas composite

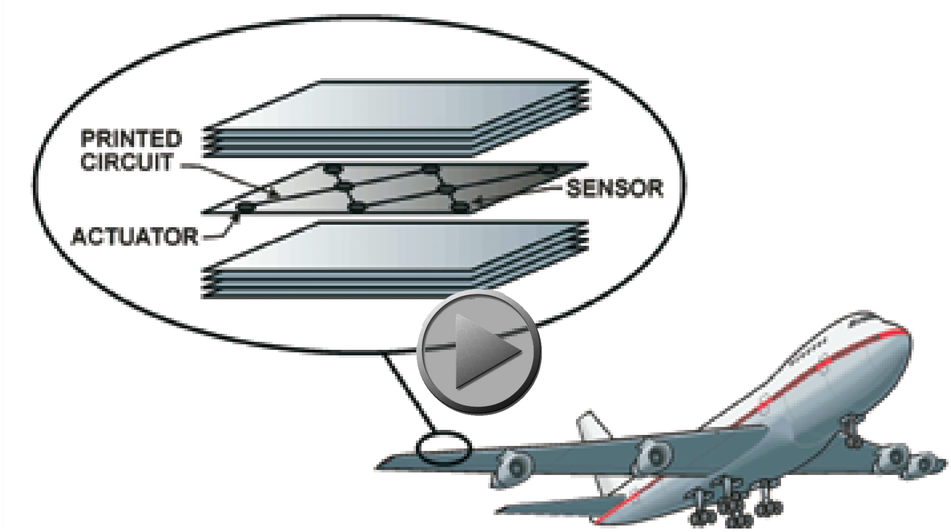


Figure 2: Embedding of smart materials in composite structure using printed circuit technology.

materials suffer from discrete traumas due to accidental damage of an unpredictable, random nature.[9] This suggests that monitoring of composite structures should be done differently than monitoring of alloys.

One method of monitoring a composite structure is to take advantage of its layered composition and of the recent advances in printed board techniques. This makes it possible to embed low-cost sensors[10] into a composite structure, with minimal impact on its overall integrity. Chang and Lin[11] proposed an example of this monitoring technique in the form of the SMART Layers®[12] shown in Figure 2. This method uses a combination of actuators and sensors to detect any modification in the composite material. By exciting the composite, the actuator will generate waves and the sensor will detect any changes to the original structure. When a new crack appears, or an existing crack grows, it modifies the pattern of propagation of the waves and reports this change. In 2006, this method was demonstrated in a few experiments and showed that embedded piezoelectric sensors could detect cracks as small as 0.1mm.[13]

Suppression of Structural Vibration

A second area of application is the use of actuators on components to alleviate the loads and vibrations imposed on these components. Helicopters are probably the type of aircraft that is subjected most to vibrations. This is due to the requirement for helicopters to perform both hover and forward flight. The result is "high vibration and noise, limited payload and speed, high maintenance, and limited component life."[14]

The direct active approach suppresses vibrations at their source, which in a helicopter is the main rotor. The Smart Material Actuated Rotor Technology (SMART) is a project led by Boeing with design goals to achieve 80 per cent reduction in vibrations, 10 decibel (dB) reduction in blade vortex interaction while landing, 10 per cent gain in rotor performance, and automatic in-flight blade tracking. This project is divided into two parts. The first part, the flap actuator, uses a piezoelectric-driven trailing edge flap for high bandwidth vibration, noise, and aerodynamic performance improvements. The second part, the tab actuator, uses a trailing edge trim tab driven by shape memory alloy (SMA) for quasi-static in-flight blade tracking.[15] The key design factors for this project include actuator weight, size, and power requirement,[16] with all of them having a minimum impact on the dimensions and weight of the existing rotor blades.

Results on simulation and bench testing on the flap actuator led to design changes, resulting in significantly improved performance. The use of high-voltage stacks of piezoelectric materials, recently made available, is projected to enable the flap actuator to meet all performance requirements. Tests on the tab actuator, under static and dynamic loading, meet all requirements, with the exception of bandwidth. Forecast is that bandwidth requirements could be met with improved control algorithms or cooling of the SMA elements.[17] The project underwent whirl tower testing in 2004, shown in Figure 3 and 4, with promising results.

Other organizations were also successful in suppressing structural vibration. A successful demonstration flight of a piezoelectric-actuator-driven main rotor trailing edge flaps was done in 2005 by Eurocopter on a BK117


Courtesy of BOEING

Figure 3: Whirl tower testing of smart rotor.[18]

helicopter.[19] Current implementation dates forecast for these types of systems are as early as 2012.[20]

Another approach is the incorporation of special devices for the adaptive vibration control. These devices use piezoelectric materials to vary the stiffness, the damping, and/or the mass of a dynamic system. A good example is the smart spring of the National Research Council of Canada (NRC), which was tested in a helicopter for the vibration control of the main rotor. However, it has many other potential applications in both helicopters and fixed-wing aircraft, including adaptive engine or gearbox mounts, isolation of cargo floor from fuselage in cargo aircraft,[21] and adaptive seat vibration suppression.[22] Results from wind tunnel tests showed that the adaptive controller of a main helicopter's rotor was able to obtain an overall reduction of 11.9dB[23] under varying wind speed.

Noise Suppression

The third application deals with the comfort and well being of the users. By interacting properly with the structure, the noise produced from engines, propellers, and helicopter rotors in the cabin can be suppressed. The Active Structural Acoustic Control (ASAC) approach uses speakers embedded within the structure to counter noise with noise.

Microphones distributed throughout the cabin will monitor the noise, and actuators attached to the fuselage at strategic locations will modulate the structural response and reduce the low frequency noise.[24] The Ultraquiet Cabin, developed by Ultraquiet Technologies is already used on several aircraft.[25]

An alternative approach is to suppress the noise by interacting directly with the structure. This was developed and tested by NRC and the setup at their laboratory is shown in figure 5. The sensors in this smart structure, consisting of accelerometers, are attached at various locations along the fuselage, while the actuators are stacked piezoelectric ceramics bonded to the fuselage. The largest reduction of almost 28dB was obtained on the aisle seat in the third row. Results show that the noise reduction was essentially global, with greater reductions occurring in the noisiest areas of the cabin. This approach has the added benefit of diminishing the vibrations on other components of the structure, thereby reducing wear and increasing fatigue life of these components.[26]

Another approach is to deal with noise at one of its main sources – the turbine engines. The Boeing 747-8 may be the first commercial aircraft to fly with an integrated smart component. Figure 6 shows a variable-area engine where the shape memory alloy attached to the chevrons is used to modify the shape of the exhaust, controlling the noise from the engine in the take-off phase. At low altitude and low airspeed, the increase in temperature in the SMA forces the chevrons inward. This operation mixes the fan and core exhaust streams together, and bypasses the flow of the engine with the effect of reducing shear and noise. However, it will decrease engine performance.


Courtesy of BOEING

Figure 4: Whirl tower testing of smart rotor.


Courtesy of BOEING

Figure 5: NRC Active noise suppression on Dash 8.[27]

On the other hand, at high speed and high altitude, the low temperatures in the SMA will straighten the chevrons and bring them back to their original shape, and consequently improve engine performance.[28] This noise reduction requirement from aircraft comes from more stringent noise abatement procedures found in most airports in large cities around the world.[29]

Courtesy of BOEING

Figure 6: Noise control on Boeing 777-300ER.[30]

Control of Surface Morphing

The last area of application is the control of surface morphing. The objective is to exploit the technologies of smartness to control, optimize, or rearrange the shape of the surface wing to improve the efficiency of the aircraft. A few projects are looking at the concept of using SMAs to change the shape of the wing for flapping in manners similar to birds or bats. This area is not likely to see any applications in commercial aircraft soon; however, research projects are under way, particularly focusing on applications with high potential such as UAVs.

The DARPA Smart Wing Project is one of these efforts. The goal is to evaluate a SMA-based hingeless trailing edge control surface concept through several series of wind tunnel testing, including some at Mach speeds. Results indicate that deflections over 20 degrees at rates over 80 degrees/second can be achieved. Results also demonstrated improvements in system performance. For example, the rolling coefficient improved approximately by 17 per cent at 15 degrees of control surface deflection. This project also identified the key issues to be addressed before smart wings are implemented into operation aircraft. These issues include long-term fatigue life of the structure, development of feedback-control laws, assessment of aero servo elastic behaviour, development of compact power supplies, and system optimization.[31] Further developments followed in 2006, with the flight tests of the MFX-1, a 100-pound UAV that enables in-flight changes from the wing. Area change of 40 per cent, span change of 30 per cent, and wing sweep varying from 15 to 35 degrees were demonstrated in flight at speeds around 100 knots. In September 2007, flight tests of the MFX-2, a 300-pound, twin-powered UAV, demonstrated area changes of 40 per cent, span change of 73 per cent, and aspect ratio change of 177 per cent.[32] These demonstrations show that the technology to implement such capabilities in operational aircraft, especially UAVs, might not be as distant in time as envisaged a few years ago.

Other types of control of surface morphing are being researched. The control of missile trajectory is studied by a team of scientists from Defence Research and Development Canada – Valcartier. They have conducted simulations as well as wind tunnel testing for this application.[33] Another project worth mentioning is an adaptive spoiler to control the transonic shock using SMA. By changing the aerofoil shape of a wing, the SMA alleviates the impact of shock waves when the aircraft is flying at transonic or supersonic speeds.[34]

IMPLEMENTATION OF SMART TECHNOLOGIES IN AVIATION

Even though a diversity of research projects has successfully demonstrated the viability of using smart technologies in aviation, they are still not implemented in practical applications. This technology is still in its infancy. Many technical issues still need to be addressed, finalized, and fine-tuned to satisfy the stringent and very rigorous standards of the aviation field. On the other hand, while some existing standards could be applied to smart structures, they do not address properly all the particularities of this emerging technology,[35] such as the characteristics of smart materials and their reliability, as well as all the technological aspects of fabrication of smart composites. Any inclusion of these new technologies should satisfy first the airworthiness, followed by specific aircraft certification. Many more theoretical, technological, and numerical, as well as experimental tests are needed before this technology could satisfy all the requirements of safety.

Moreover, three main non-technical issues are delaying this implementation. The first one is the nature of these smart structures, which encompasses many science and engineering fields, and leads implicitly to the second problem of integrating of all these novelties requiring cooperation and time. The grouping of experts to share their knowledge and particular expertise and operate jointly could be a challenge. Established in 1997, the Canadian Smart Materials and Structures Group (CANSMART)[36] mandate is to offer the opportunity for researchers and scientists from academia, government, and industry to exchange views on the common aspects of smart materials and structures, as well as try to alleviate this complexity in general. The third issue is related to the cost of incorporating these smart structure technologies into aircraft production, which currently makes the system more expensive,[37] and therefore less attractive to prospective operators.

Finally, overall acceptance of this new technology by everyday operators will take some time. Some parallels with the implementation of other technologies have been drawn. For example, the introduction of composite materials into the aerospace industry, which is now widely embraced, took about 50 years.

CONCLUSION

With the expansion of demonstration projects on the capabilities of smart structures in aerospace in general and in aviation in particular, industry and government will realize their benefits and a growing demand for their use will follow. In the meantime, more research, development, and engineering on smart materials and their inclusion in smart aircraft structures need to be pursued. Similarly, particular effort is also required to develop appropriate standards and regulations to deal with their specific characteristics.

There is no doubt that smart structure is a seriously emerging technology in the aviation industry. In a few years we are likely to have aircraft that will tell us their health status, what loads and constraints they are subjected to, and what measures are implemented to alleviate them. In military applications, this would also include damage assessment, as well as corrective action, with capacity for mission delivery. ■

Notes

1. Knight, P., Cook, J. and Azzam, H. "Intelligent management of helicopter health and usage management systems data," Vol. 3, Part G, Proceedings ImechE: J. Aerospace Engineering, (2005), 507-24.

2. Scandura, P.A. Jr. "Vehicle Health Management Systems". Digital Avionics Handbook, Second Edition, Avionics, elements, software and functions. Edited by C.R. Spitzer (Boca Raton, FL: Taylor & Francis Group, 2007), Chapter 22.

3. Augustin, M. and Bradley, S.J. "Achieving HUMS Benefits in the Military Environment – HUMS Developments on the CH-146 Griffon Fleet," American Helicopter Society 60th Annual Forum, Baltimore, Maryland (2004).

4. Akhras, G. 2000. "Smart Materials and Smart Systems for the Future," Canadian Military Journal, (Autumn 2000), 25-31.

5. Spillman, W.B. Jr., Sirkis, J.S. and Gardiner, P.T. "Smart Materials and Structures: What are they?" Smart Materials and Structures, number 5, (1996). 247-254.

6. Akhras.

7. Sater, J.M., Lesieutre, G. and Martin, C. 2006. "A Smarter Transition for Smart Technologies." www.aiaa.org/aerospace/images/articleimages/pdf/AA_June06_PP.pdf. Accessed 17 August 2007.

8. Capt F. Dufault did this classification as part of a technical paper prepared for the Aerospace Systems Course (ASC) 59: "Application of Smart Structures in Aerospace." CFSAS, Winnipeg (2007).

9. Bartelds, G., Heida, J.H., McFeat, J. and Boller, C. "Introduction". Health Monitoring of Aerospace Structures. IOP Publishing, Staszewski, W., Boller, C., Tomlinson, G., Ed. John Wiley & Sons Ltd, West Sussex, England, (2007). 29-73.

10. Such as fibre optic sensors, piezoelectric, or shape memory alloys.

11. Ihn, J-B. and Chang, F.K., "Detection and Monitoring of Hidden Fatigue Crack Growth Using a Built-in Piezoelectric Sensor/Actuator Network: II. Validation Using Riveted Joints and Repair Patches." Smart Materials and Structures, 13 (2004), 621-630.

12. SMART Layer® is a registered trademark of Acellent Technologies Inc. www.acellent.com.

13. Zhongqing S. et al., "A built-in active sensor network for health monitoring of composite structures". Smart Materials and Structures, 15, 1939-49.

14. Straub, F.K. et al., "Smart Material Actuated Rotor Technology – SMART". Journal of Intelligent Material Systems and Structures, Vol. 15, (2004). 249-260.

15. Ibid.

16. Sater.

17. Straub.

18. http://www.boeing.com/ids/news/2004/q2/nr_040518t.html.

19. Strecker, R. 2005. "Piezo Flaps Counter Noise," Flug Review (2005), www.flug-revue.rotor.com/FRheft/FRHeft05/FRH0511/FR0511f.htm. Accessed 17 August 2007.

20. Sater.

21. Wickramasinghe, V. et al., "Smart Spring: A Novel Adaptive Impedance Control Approach for Active Vibration Suppression Applications". SPIE 11th Annual Conference on Smart Structures and Materials, San Diego (2004). Available at http://rotorcraft.mae.carleton.ca/php/people/fn_papers/SPIE2004.pdf.

22. Chen, Y., Wickramasinghe, V. and Zimcik, D.G. 2006. "Development of Adaptive Seat Mounts for Helicopter Vibration Suppression". Cansmart 2006, Proceedings: International Workshop Smart Materials and Structures, (Toronto, ON, 2006), 9-19.

23. Wickramasinghe.

24. Wickramasinghe, V., Zimcik, D. and Chen, Y. 2004. "A Novel Adaptive Structural Impedance Control Approach to Suppress Aircraft Vibration and Noise." RTO AVT Symposium on "Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion." Prague, Czech Republic, published in RTO-MP-AVT-110, (2005), 16-1 to 16-13.

25. The Ultraquiet cabin system developed by Ultra Electronics Ltd. can be found on the following platforms: Saab 340 A, B, Bplus, and 2000; Bombardier Dash 8 Q100, Q200, Q300, and Q400; King Air 350, 90, 200, and 300; Challenger 640; and Air Commander.

26. Zimcik, D.G., "Active Control of Aircraft Cabin Noise". *RTO AVT Symposium* on "Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion," (RTO-MP-AVT-110, Prague, Czech Republic, October 2004), 20-1 to 20-16.

27. Ibid.

28. Hartl, D.J. and Lagoudas, D.C., "Aerospace Applications of Shape Memory Alloys". *Proceedings, ImechE: J. Aerospace Engineering*. Vol 221, Part G, (2007), 535-52.

29. The noise situation around major airports in high-density urban areas is managed by the International Civil Aviation Organization (ICAO) through the Committee for Aviation Environmental Protection (CAEP). In 2004, it proposed three goals for ICAO, one of which is "to limit or reduce the number of people affected by significant aircraft noise." Noise level at airport is legislated by states. However, aircraft design is standardized by ICAO. Working Paper, Assembly –35th Session. 2004. Agenda Item 15: Environmental protection. http://www.icao.int/icao/en/assembl/a36/wp/wp116_en.pdf. Accessed 20 Feb 2008.

30. http://www.boeing.com/news/frontiers/archive/2006/march/i_tt.html.

31. Kudva, J.N. 2004. "Overview of the DARPA Smart Wing Project." *Journal of Intelligent Material Systems and Structures*, Vol 15. (2004), 261-67.

32. www.nextgenaero.com/success_mfx2.html.

33. Wong, F.C., Rabbath, C.A., Léchevin, N. and Buissonneault, O., "Closed-Loop Performance of a Shape Memory Alloy-Based Micro-Flow Effector for Missile Flight Control." *Cansmart 2006, Proceedings: International Workshop Smart Materials and Structures*, (Toronto, ON, 2006), 41-56.

34. Bein, T., Hanselka, H. and Breitback, "An Adaptive Spoiler to Control the Transonic Shock." *Smart Materials and Structures*, 9, (IOP Publishing, UK, 2000), 141-48.

35. A review of existing standards and specifications for the inclusion of smart structures is described by Kessler, S.S., Amaratunga, S. and Wardle, B.L., "An assessment for durability requirement for aircraft structural health monitoring sensors." (2005). Available at http://web.mit.edu/sskess/www/papers/SHM05.pdf.

36. www.cansmart.com.

37. Sater.

LIST OF FIGURES

List of Abbreviations

CANSMART	Canadian Smart Materials and Structures Group	NRC	National Research Council of Canada
CF	Canadian Forces	SMA	shape memory alloy
dB	decibel	SMART	Smart Material Actuated Rotor Technology
HUMS	Health Usage and Monitoring System	UAV	unmanned aerial vehicle

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