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Does the Maturity of Structural Health Monitoring Technology Match User Readiness?

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ABSTRACT

The use of in-situ sensors for real-time health monitoring of aircraft structures can be a viable option to overcome inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage. Reliable, structural health monitoring (SHM) systems can automatically process data, assess structural condition, and signal the need for human intervention. There is a significant need for an overarching plan that will guide near-term and long-term activities and will uniformly and comprehensively support the evolution and adoption of SHM practices. Such a plan must contain input from aircraft manufacturers, regulators, operators, and research organizations so that the full spectrum of issues, ranging from design to deployment, performance and certification is appropriately considered. An important element in developing the FAA SHM R&D Roadmap is a clear understanding of the current status of SHM technology and the pending regulatory issues facing the aviation industry to safely adopt SHM solutions. Towards that end, a comprehensive survey was implemented with the aviation industry to determine the technology maturation level of SHM, identify integration issues, and prioritize research and development needs associated with implementing SHM on aircraft. Specific emphasis was placed on structural and maintenance characteristics that may impact the operational performance of an inspection process or health monitoring system. In addition, an SHM Technology Readiness Database (SHM TReaD) and an SHM Sensor Database were developed to assess the present and future prospects of SHM technology. This paper will present the results from these efforts and describe how the FAA is using this information to support the safe adoption of SHM practices.

INTRODUCTION OF SHM SURVEY – BACKGROUND AND MOTIVATION

The Sandia National Labs' FAA Airworthiness Assurance NDI Validation Center (AANC), under contract to the Federal Aviation Administration's William J. Hughes Technical Center, collected information through the SHM industry survey to identify and prioritize research and development needs associated with implementing Structural Health Monitoring (SHM) on aircraft. An important element in planning the FAA SHM R&D Program is a clear understanding of the current status of SHM technology and the related regulatory issues. This survey was sent to persons involved with the

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operation, maintenance, inspection, design, construction, life extension, and regulation of aircraft. The goal of this survey was to understand the current status of SHM technology, as well as the obstacles impeding the implementation of SHM solutions. The survey covered the gamut of SHM topics including: Background, SHM Deployment, Validation and Approval for SHM Use, SHM Standardization, Sensor Operation, Cost-Benefit Assessment, and Sensor Design. The survey was implemented via a customized, on-line web site. Statistical trends analysis and assembly of the survey results were carried out to meet the objectives listed above.

SHM INDUSTRY SURVEY RESULTS

Some of the survey responses were often broken down by respondent groups such as: owners/operators, OEMs, and regulators. Regulators were classifies as those who issue and enforce regulations and standards related to the manufacturing, operation, certification, and maintenance of aircraft. Owners/Operators were classified as those who own or operate an airline company, military aircraft, private company, or government agency. Original equipment manufacturers (OEM) were classified as agencies that play a principal role in manufacturing aircraft systems or structures. Respondents to the survey came from nineteen different airline companies, twenty-three different equipment manufacturers, twelve different regulatory agencies, seventeen different aircraft maintenance facilities, and 120 different research and development organizations including universities (see Figure 1). This list demonstrates the breadth of agencies and perspectives included in this industry SHM survey. Of the 1,200 people surveyed, there were 455 responses (38%).

Owners/Operators	OEMs	Regulators	Maintainers
All Nippon Airways **American Airlines** **Austrian Air Force** **China Airlines** **Continental Airlines** **Delta Air Lines** **Federal Express** **Finnair** **Hawaiian Airlines** **Japan Airlines** **Jazz Airlines** **Jet Blue Airways** **Kalitta Air LLC** **NASA** **Qantas Airways** **Singapore Airlines** **Swiss Air** **United Airlines** **US Airways** **USAF** **US Army** **USCG** **US Navy**	**Airbus** **Astronics-Adv. Electronic Systems** **Avensys Inc.** **BAE systems** **Bell Helicopter Textron** **Boeing** **Bombardier Aerospace** **Cessna Aircraft Company** **Dassault Aviation** **EADS Military Air Systems** **Embraer** **Goodrich** **Honeywell** **Lockheed Martin Aeronautics** **Messier-Dowty** **Mistras Group, Inc** **Polskie Zaklady Lotnicze Sp.** **PZL Swidnik** **Rolls-Royce Corp** **Systems & Electronics, Inc.** **TecScan**	**Air Transport Association** **CAA - NL** **CAA - Bra** **EASA** **FAA** **NAVAIR** **NAWCAD** **Transport Canada (TCCA)** **USAF** **US Army** **USCG** **US Navy**	**Aerotechnics Inc** **Air New Zealand** **China Airlines** **Christchurch Engine Centre** **Fokker Aircraft Services B.V.** **Fuji Heavy Industries, Ltd.** **Jazz Air LTD** **Lufthansa Technik AG** **NASA** **Olympic Airways Services S.A.** **SAA Technologies** **SR Technics Switzerland LTD** **Texas Aero Engine Services** **Timco / GSO** **United Airlines** **USAF** **US Army** **USCG** **US Navy**

Figure 1: Respondents to SHM Survey of Aviation Industry

Furthermore, 85% of the respondents felt that the near-term application of SHM is for local, hot spot monitoring. In 5-8 years, 57% of the respondents felt that the long term plans for SHM should revolve around global, wide area health monitoring solutions. The anticipated global systems being applied by owners/operators increases by 20% from the near- to long-term, and increases by almost 40% for the OEMs. This indicates that technology is moving in the direction of global monitoring systems and it is more desired by owners/operators. In one of the key questions intended to gage SHM readiness, respondents were asked: “Are SHM solutions viable for aviation?” The majority of the respondents (61%) answered “Yes” while only 17% said “No.”

Figure 2 shows the types of damage/flaws the industry is interested in detecting. It’s not surprising that a large majority of the persons surveyed were interested in detecting the major damage types found on aircraft: cracks, corrosion, delaminations and disbonds. Related damage from stress risers, impact, fluid ingress, and other environments are also sited often. Damage associated with composites, exposure, mechanical malfunction and off-design conditions (e.g. ground support activities) are were also listed. An overwhelming majority of the respondents (95%) would welcome decision sciences or prognostic expert systems to diagnose or predict structural heath using combined information from multiple maintenance and inspection sources.

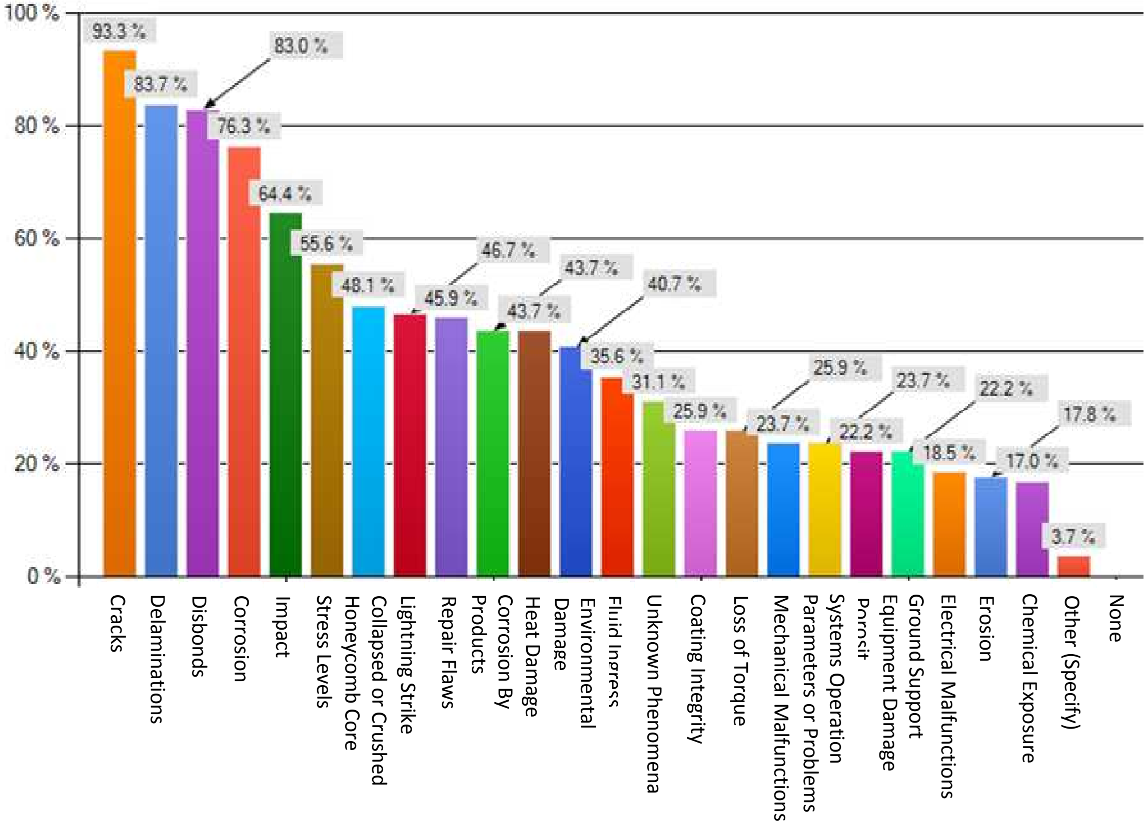


Figure 2: Respondents View on Type of Operational Events or Damage They Would Like to Detect Using SHM

The main trends of potential SHM applications include: general damage detection and crack detection in structural members (bulkheads), corrosion detection and coating monitoring, hard landing, load monitoring, impact detection and indication, hot spot monitoring, bolt tightness monitoring, strain levels, heat damage, monitoring of fuselage door and window areas, bond monitoring, delamination in composite structures, monitoring of existing cracks, monitoring fuselage skin repairs and flaw detection in difficult-to-inspect/access areas. Over 200 applications were listed by survey respondents. Figure 3 shows that over 50% of respondents think that all of the primary structural areas are candidates for SHM applications: fuselage pressure bulkhead, frames, stringers, wing ribs and spars, landing gear, main attachments and skin areas. In fact, there were no aircraft regions that received insignificant responses. Areas where respondents are less interested in implementing SHM were: power train and nonstructural systems.

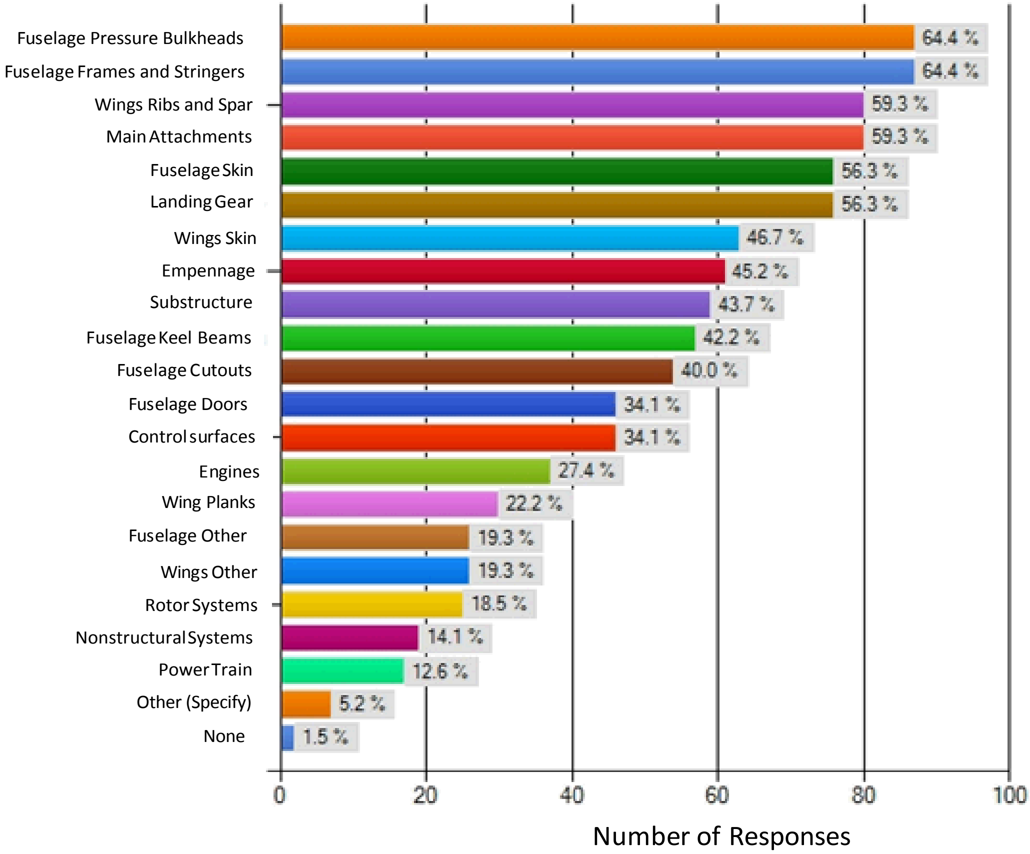


Figure 3: Aircraft Areas Where Respondents Feel SHM Solutions are Viable

Figure 4 shows that the main reasons respondents are interested in SHM are associated with cost considerations (e.g. avoiding disassembly, reduction in labor hours) and safety/reliability considerations (e.g. early flaw detection, improved sensitivity). Another item of note is that almost all of the possible reasons for using SHM were listed in over 1/3 of the survey responses. Reasons that were deemed as less important pertained to obtaining design credits or weight savings, and monitoring electrical and aircraft systems. These are mostly long-term prospects for SHM so it is not surprising that these are currently of less interest to end-users.

The only response that the majority of the OEMs and operators strongly perceived to be a major impediment to the deployment of SHM on aircraft was achieving a positive cost-benefit. The question that SHM must satisfy with the airlines is: How long will it take for an SHM system to pay for itself in inspection time, maintenance credits, safety benefits etc.? The top five cost-benefit considerations for an SHM solution were listed as: 1) elimination of structural teardown to access regions to be monitored, 2) recurring cost of SHM sensors, 3) initial cost of SHM equipment, 4) time required for validation/qualification, 5) compliance requirements. Other highly-rated hurdles to SHM utilization include: insufficient probability of detection or excessive false alarm rates, overall performance assessment and validation of technology, field trials on operating aircraft is necessary but time consuming, concerns over durability, insufficient coverage area, lack of maturity of turnkey SHM systems, and lack of regulatory guidelines and advisory materials for deploying SHM (certification). Fifty-five percent of <u>aircraft operators, maintainers, and military personnel</u> say that 5 years is a reasonable payback period for recouping the cost associated with using an SHM system while 31% say that 2 years is a reasonable time.

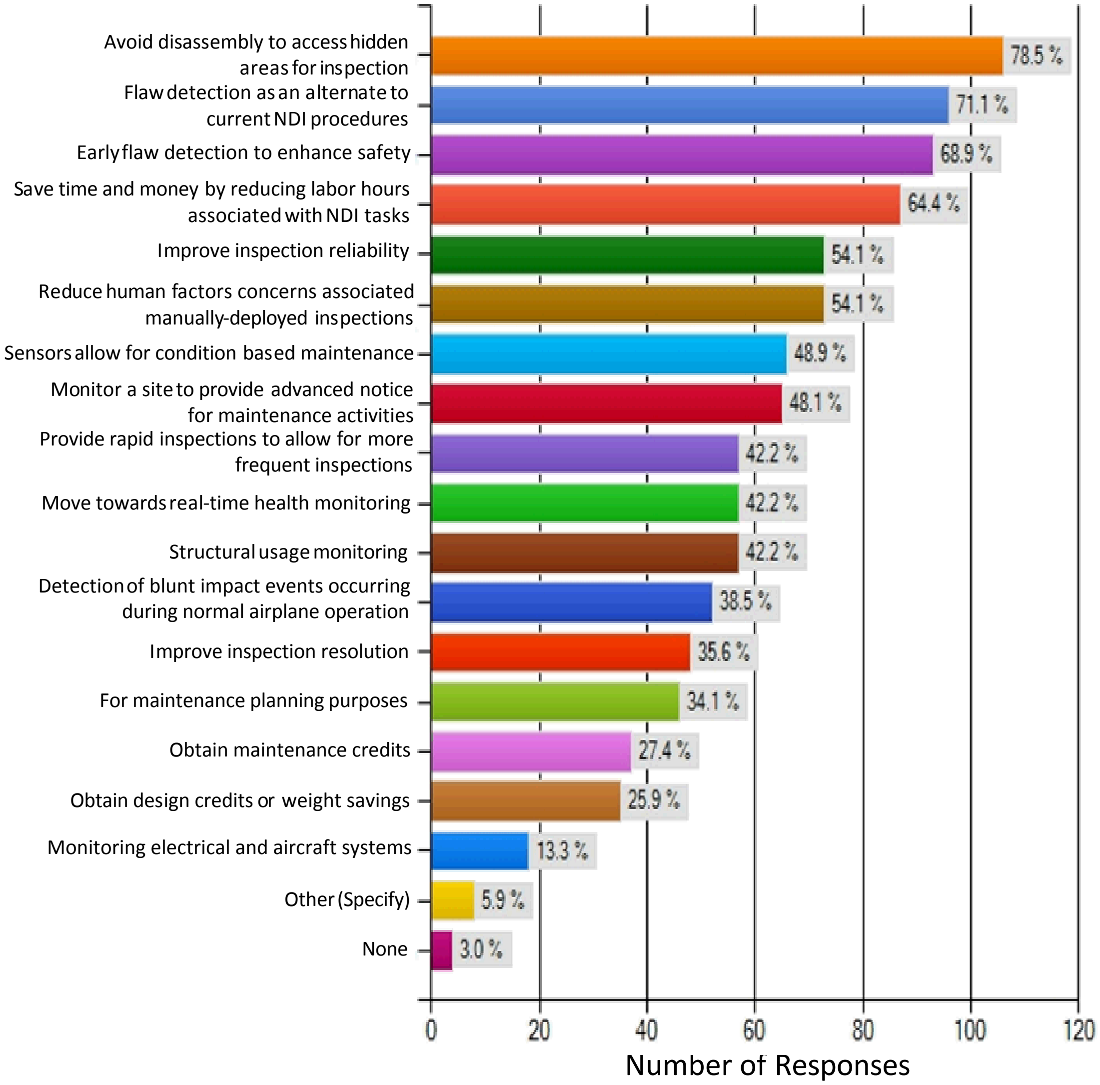


Figure 4: Respondents Reasons for Interest in SHM

With respect to validation and certification, survey respondents were asked: “Would you accept performance data from operators/vendors /industry groups/military or require the regulatory agency and/or OEM to be involved in a formal test program?” Most of the responses (55%) fell into the affirmative/possible categories of “Yes” and “would be considered.” However, almost 30% of the respondents indicated that some sort of approval or oversight from the OEM or regulator was necessary to include such validation data for SHM system certification. The “Yes” responders also indicated that the performance data must have some sort of well-documented pedigree. Since the validation data is so critical to SHM certification, the message taken from this question is that a formal team - comprised of personnel from the operator, OEM, regulator and others - should be established up front. All SHM validation testing should be carried out with the agreement, and suitable oversight, of all team members.

Figure 5 shows respondents views on needed research and development to evolve SHM to the point of implementation on aircraft. Most of these pertain to SHM sensor development to improve sensitivity and spatial resolution while reducing the cost and weight of the sensors and the peripheral SHM equipment. Other important items are related to SHM deployment and include data acquisition and analysis, system validation, and integration into maintenance programs. There was significant (> 33%) but slightly less interest in the related items of education, training, and regulatory guidance.

SHM TECHNOLOGY READINESS

The SHM Technology Readiness Database created a systematic method and structure to compile, organize, and summarize SHM related data to identify the level of maturity and rate of evolution. It provides a quick and ongoing evaluation of the current state of SHM among research institutions and industry. Hundreds of technical publication and conference proceedings were read and analyzed to compile the database. Microsoft Excel was used to create a useable interface that could be filtered to compare any of the entered data fields. Over 3,000 papers, covering SHM topics from 1975 to 2010, were selected from all major, pertinent conferences and analyzed to gain an accurate perspective of current SHM technologies. Papers addressed the full gamut of SHM activities including: theory, technology description, development, hardware, applications, lab work, evaluation, education, field work, certification, and implementation.

During the information extraction process, the data processing agent was tasked with identifying the specific technology type that best fit each individual entry. The “Technology Type” descriptors accurately reflect the full spectrum of topics covered in the large SHM TReaD. Figure 6 shows the technology type distribution across the complete database. Figure 6 shows that pizeoelectric and crack detection transducers are the most cited technologies within the database, followed by acoustic emmission, fiber optics, corrosion and strain based sensors. Note that system operation and SHM response modeling also received significant mention. The lowest cited technologies within the database are shape memory alloy, nickle strip magnetorestrictive and thermography based sensors.

In the next stage of this assessment, Technology Readiness Levels (TRL) were used to rank SHM technology/systems through the development stages. The TRL’s mimic those used by NASA and the military where this classification system clearly defines benchmarks, direction and maturity of emerging technologies as:

TRL 1 - Physical principles are postulated with reasoning

TRL 2 - Application for physical principles identified but no results

TRL 3 - Initial lab tests on general hardware configuration to support physical principles

TRL 4 - Integration level showing systems function in lab tests

TRL 5 - System testing to evaluate function in realistic environment

TRL 6 - Evaluation of prototype system

TRL 7 - Demonstration of complete system prototype in operating environment

TRL 8 - Certification testing on final system in lab and/or field

TRL 9 - Final adjustment of system through mission operations

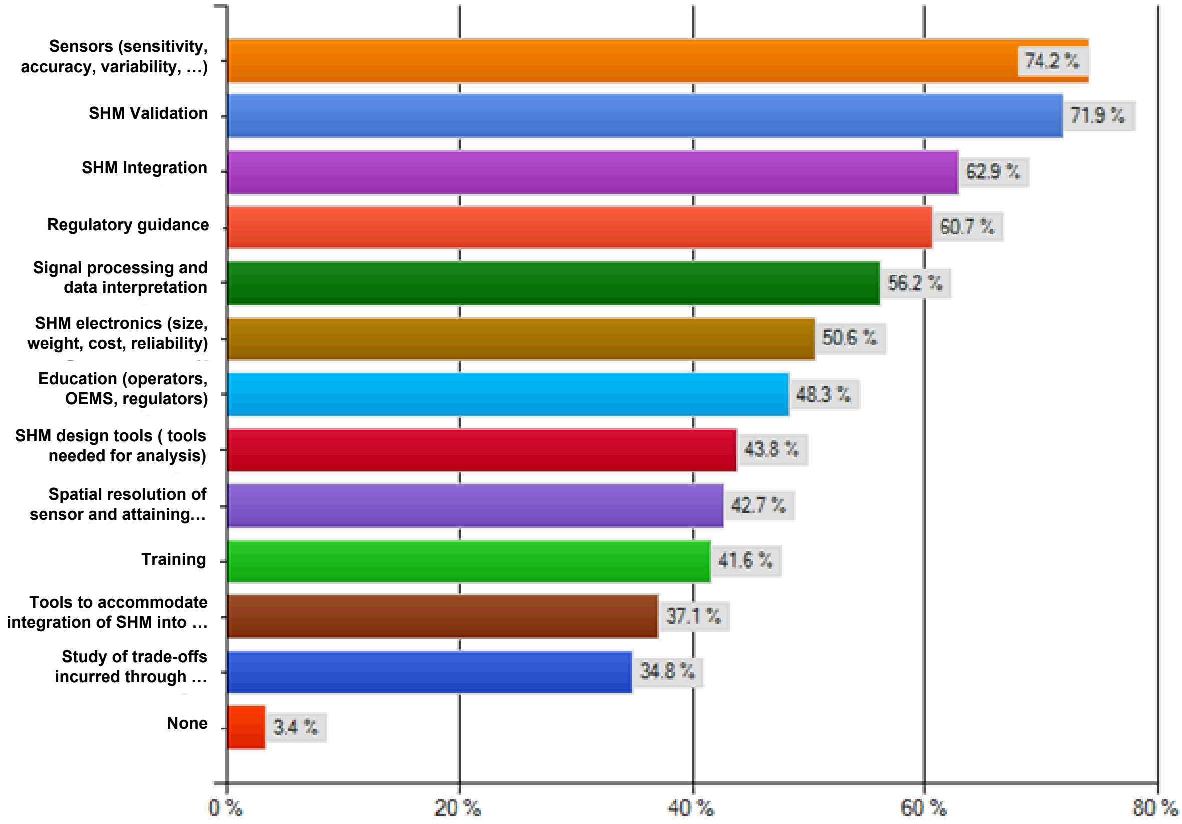


Figure 5: Type of Research and Development That OEMs and Owners/Operators Believe is Needed to Evolve SHM Systems for Aircraft Use

The TRL metric, which defines a technology's stage of development, allows for objective evaluation of its progression based upon benchmark goals and timetables. The Technology Readiness Level (TRL) metric allows for direct comparisons and projections for the technology's implementation schedule**.** The technology readiness levels of the entries in the database are very useful pieces of information that can be easily compared and understood. The initial analysis done using the TRL levels in the

SHM database was to compare the entire population of entries in the database. Figure 7 shows the distribution of SHM TRL levels from all individual entries in the database.

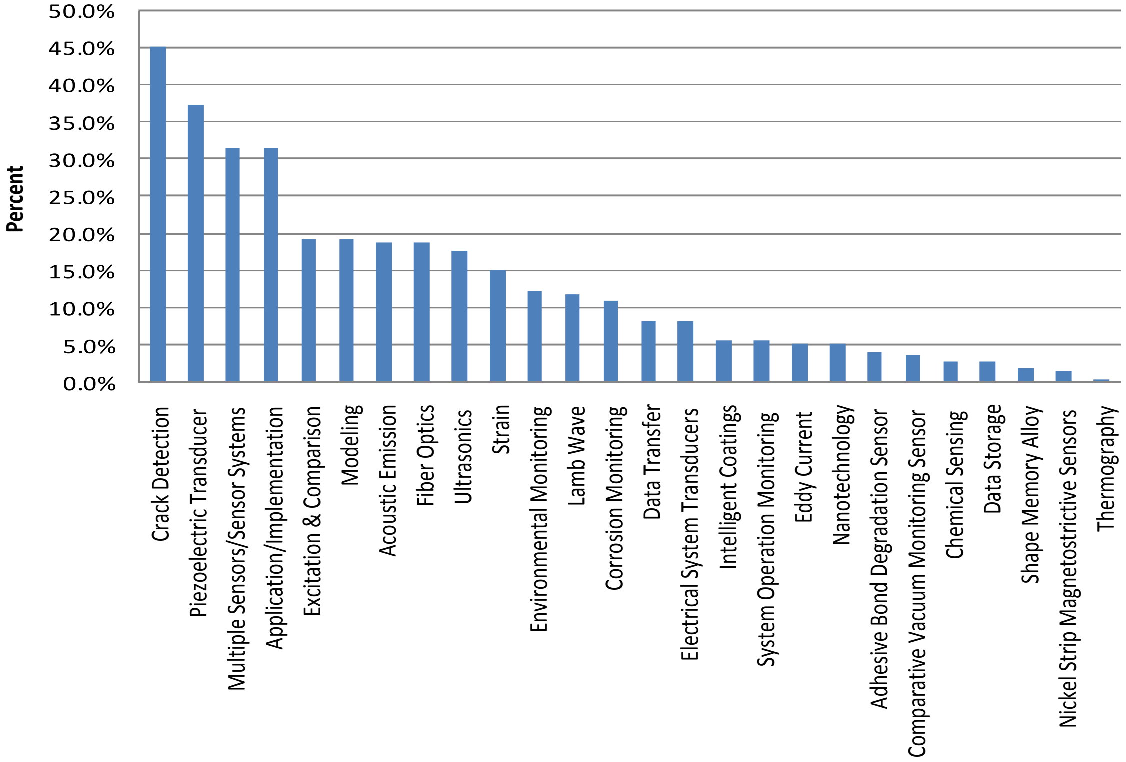


Figure 6: Technology Types in SHM Readiness Database

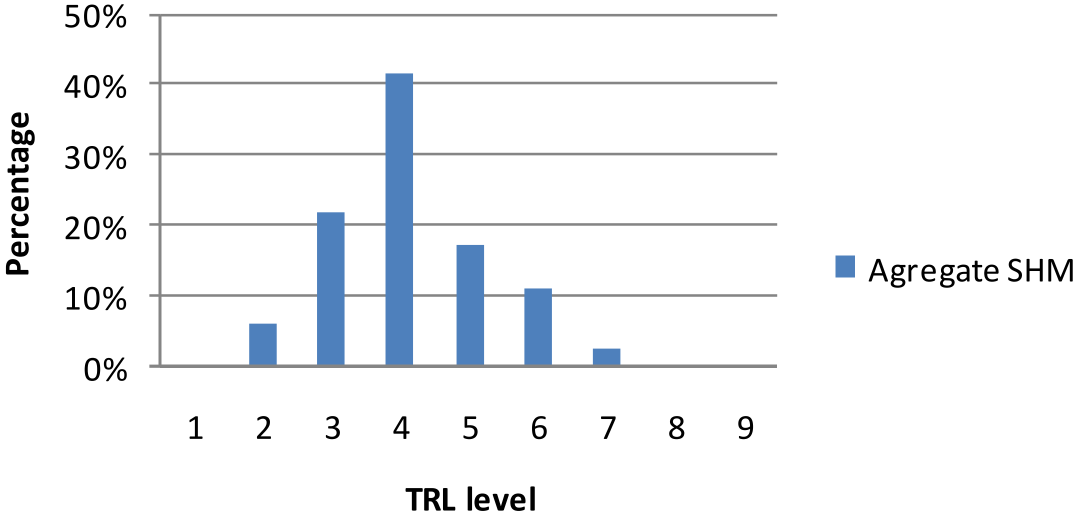


Figure 7: Distribution of Overall SHM TRL Levels From All Papers Within SHM TReaD Database

There are some key insights provided by Figure 7. The most obvious point is that the overall TRL values are centered around level 4. This indicates that the SHM field is well on its way but is not fully developed when it is analyzed using the TRL value system. The peak in the distribution indicates that the bulk of technologies are at the same level of maturity when viewed through the TRL values. The end result is that a large number of these SHM technologies could move into the market in a tight time frame when many of these technologies are projected to mature in the same period. The skewness of the technologies (lower levels at 1 and 2 vs. higher levels at 6 and 7) indicates that the number of technologies entering the system is trending downward. This indicates a need for further R&D funding to energize startups. The final piece of information that can be taken from the distribution is that there are no entries in the database that have achieved TRL levels of 8 or 9. The gradual waning towards the upper bound suggests that there is no restriction causing bottleneck or stoppage, although the guidance or path may not be sufficient to allow these technologies to smartly push through these final barriers. The current TRL center at levels 3-6 demonstrates that some technologies have reached full prototype systems designed for aircraft and are entering the field (on-aircraft) evaluation stages.

Figure 8 shows the TRL calculation broken down by year from 2006-2009. It shows a progress from 2006 TRLs that are centered around 2-4 to the 2009 TRLs that are centered around 4-6 with growth into TRL 7. This moving "wave" of Technology Readiness Level, clearly shifting from left to right in Figure 8, indicates the rapid technology maturation that is ocurring in the SHM industry. At this current rate, a number of SHM technologies should arrive at the TRL 7-9 levels in the next 3-5 years.

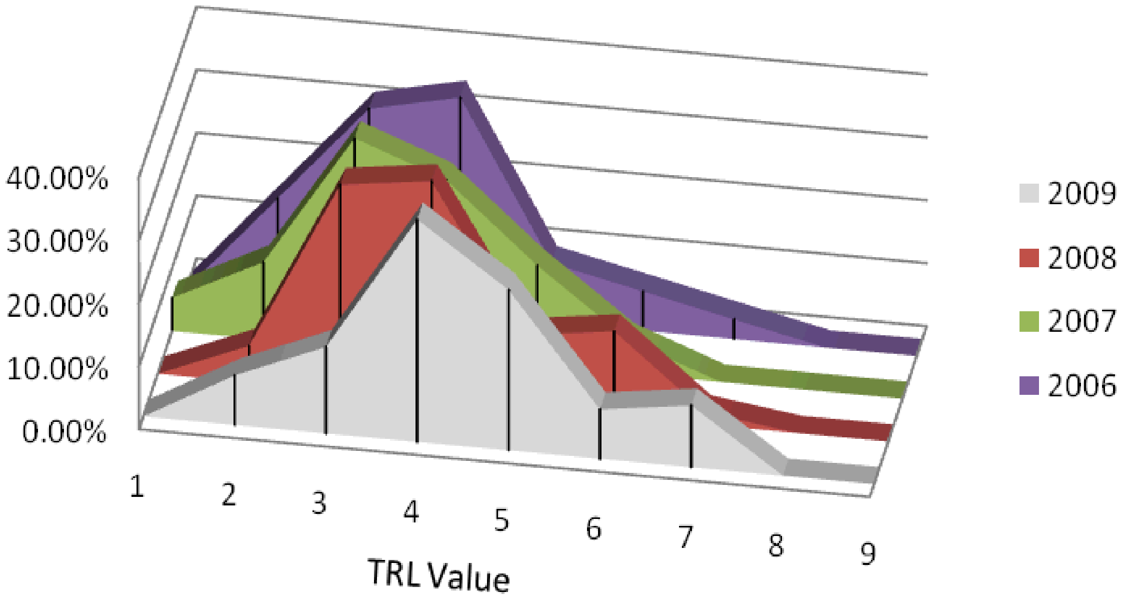


Figure 8: TRL Distribution by Year Showing Evolution and Maturity Rate for SHM

The literature review revealed that SHM evaluation and development are high while certification and field work are lagging. Responses from related questions in the SHM survey indicated the following maturity levels as determined by the SHM development company:

- 43% of SHM systems have been through initial laboratory tests
- 37% had completed formal laboratory performance evaluations
- 9% have had field evaluations
- 7% have undergone complete validation of the SHM system
- 7% have been proven and are ready for aircraft.

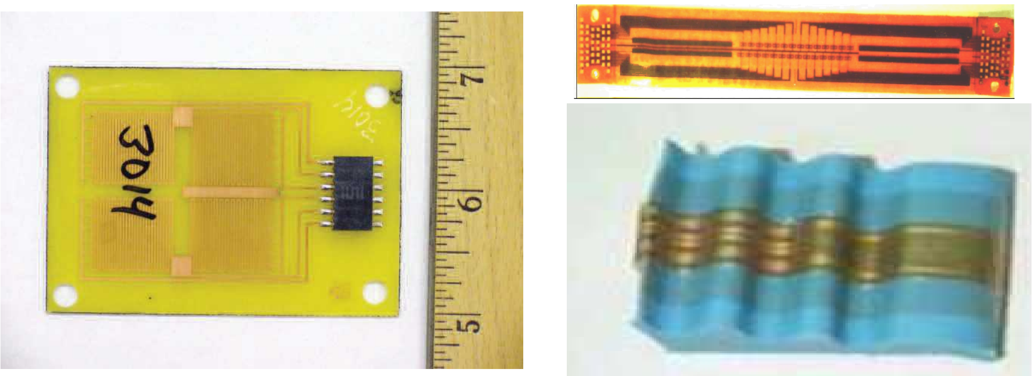
These self-evaluation results indicate TRL levels that are slightly ahead of those determined from the SHM TReaD. However, whether the central TRL is currently a 4 or 5 with upper extensions into 7 or 8, both the industry and the literature reviews suggest very similar trends in SHM evolution.

SHM SENSOR DATABASE

Sensors are the backbone and most critical part of a structural health monitoring system. No matter how developed the accompanying software and data analysis algorithms, and the data acquisition hardware of a system are, if the sensor function is not adequate, the system will not operate properly. The sensor must be appropriate for the application if the system is to be reliable and effective. Because of an increasing demand for lighter, cost-effective, highly sensitive and robust sensors, research laboratories, universities and private industry have been vigorously pursuing sensor development and production. A comprehensive SHM sensor database was created to display a variety of SHM sensors that are in different stages of development, testing, and manufacturing. Analysis across the technology readiness database was performed in order to determine what types of sensor technologies are being implemented throughout SHM. Information in the SHM sensor database includes: 1) image of the sensor, 2) name of the device, 3) parameter it senses, 4) how the sensor measures that parameter, and 5) the company identified as either testing or producing the sensor.

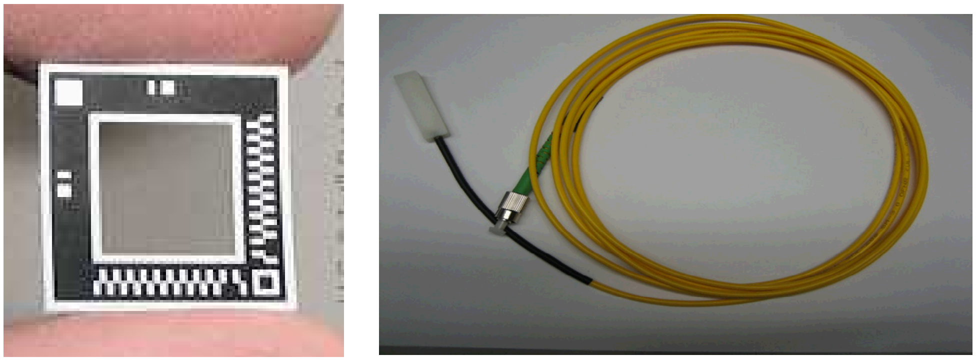
The sensor database was produced to display a variety of SHM sensors that are in different stages of development, testing, manufacture and sales for use in turn-key SHM systems. An assessment of SHM sensor evolution provides insights into overall SHM maturity and the potential for utilization on aircraft. There are many different sensors on the market today. Figure 9 shows some of the almost 100 sensors that were documented in this study. This sensor database was compiled to gain an appreciation for the variety of applications and the maturity of technologies used. This database is also able to provide insights into the many different physical parameters can be sensed, such as strain, temperature, pressure, load, corrosion, displacement, and bond integrity. The SHM sensor database is meant to be as all-inclusive as possible but is not intended to intercompare sensors from different companies. The sensors were identified from technical publications, conference proceedings, industry brochures, the SHM Industry Survey, and internet searches.

Another issue highlighted in the survey is that operators and maintainers are concerned with the recurring costs associated with SHM sensors. This coincides with the expected life of an SHM system which ranges from 10 to 20 years. Reliability tests must be performed on sensors to ensure that the lifespan of the sensor meets an operator's lifetime requirements. Environmental testing and reliability standards are needed in order to instill confidence in SHM sensors among operators and maintainers.



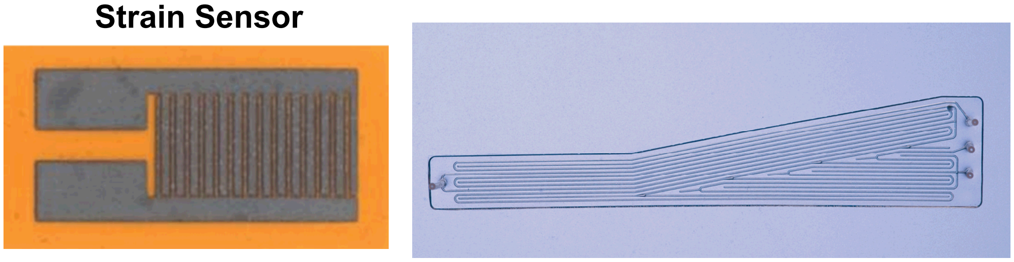
Cumulative Environmental Corrosion Sensor

Flexible Eddy Current Array Probe



Direct Measurements Strain Sensor

Vibro Fibre SHM Sensor



Linear Polarization Resistance Sensor

Comparative Vacuum Monitoring Sensor

Figure 9: Sampling of SHM Sensors

A key element of the foreseen impediments in the deployment of SHM is the cost benefit of the system. The survey revealed that half of the sensors developers are working with a price range of $10-100 and a quarter of the sensors cost above $100. A single, $100 dollar sensor is inexpensive in the grand scheme of an aircraft, but the survey indicated that global systems are expected to double in the next five to eight years and will make their way onto aircraft. Global systems utilize more sensors to increase the area being monitored, hence sensor costs become critical. The survey shows that sensor developers understand that industry is leaning towards global systems and have long term plans to develop sensors for these systems. The SHM TReaD indicates that about 13% of the papers read discuss local health monitoring and about 9% discuss global health monitoring. This is consistent with how researchers responded to the survey in that more local systems are currently being developed than global. Overall SHM system costs provided by survey respondents were: 1) 8% less than $1,000, 2) 28% between $1,000 and $8,000, 3) 21% between $8,000 and $16,000, and 4) 31% greater than $16,000.

Related questions in the SHM survey indicate that the largest group of sensors (29%) are deterministic and provide a direct readout of flaw indication. Figure 10 shows that three other modes of data analysis are well-represented. Almost 25% of the sensors use comparisons with previously-acquired data to arrive at a conclusion while another 25% use standardized algorithms to reduce data for interpretation of damage. This indicates that over 50% of the SHM systems contain a built-in self-diagnostic capability to automatically interpret the data. Very few of the sensors require data fusion from other sensors to detect flaws.

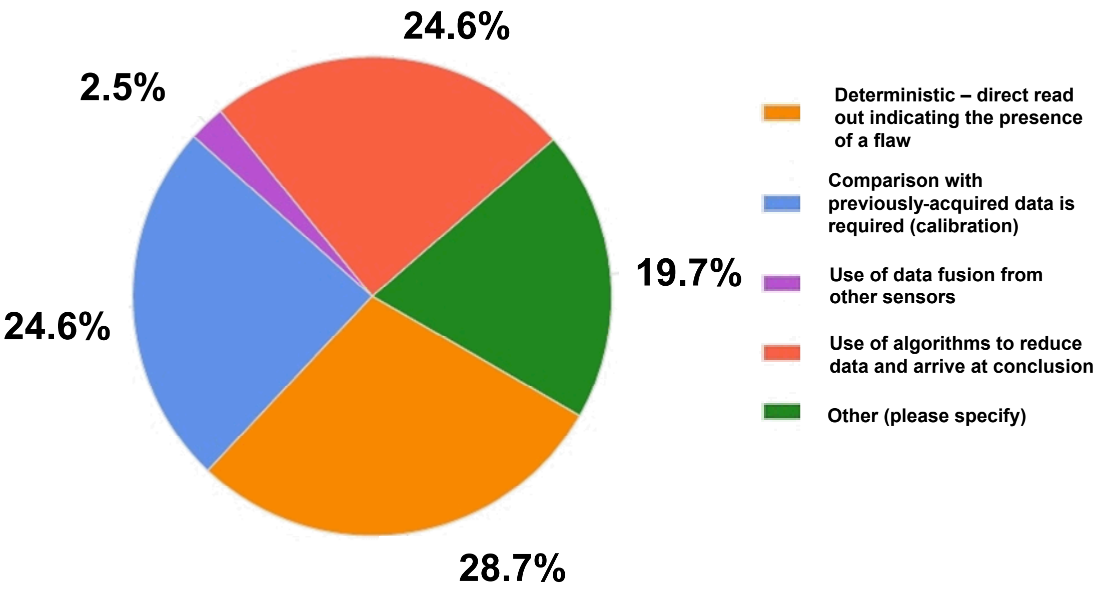


Figure 10: Response from SHM Developers Regarding the Amount of Data Interpretation Required to Classify the Sensor Output

Almost 70% of respondents are developing sensor technologies for detecting cracks in metal structures. Figure 11 also shows significant development (> 30% response levels) in sensor technologies for composite delaminations, disbonds, and impact, and metal corrosion. These trends in sensor development correlate well with the type of damage owners, operators and manufactures are interested in detecting as determined in the SHM survey. Another important consideration is the desire to create sensors with a fail-safe feature. Fail-safe operation avoids the acquisition of data from faulty sensors in order to avoid false positive or false negative indications. In the SHM survey, 52% of the SHM developers indicated that their sensor and system had a fail-safe feature.

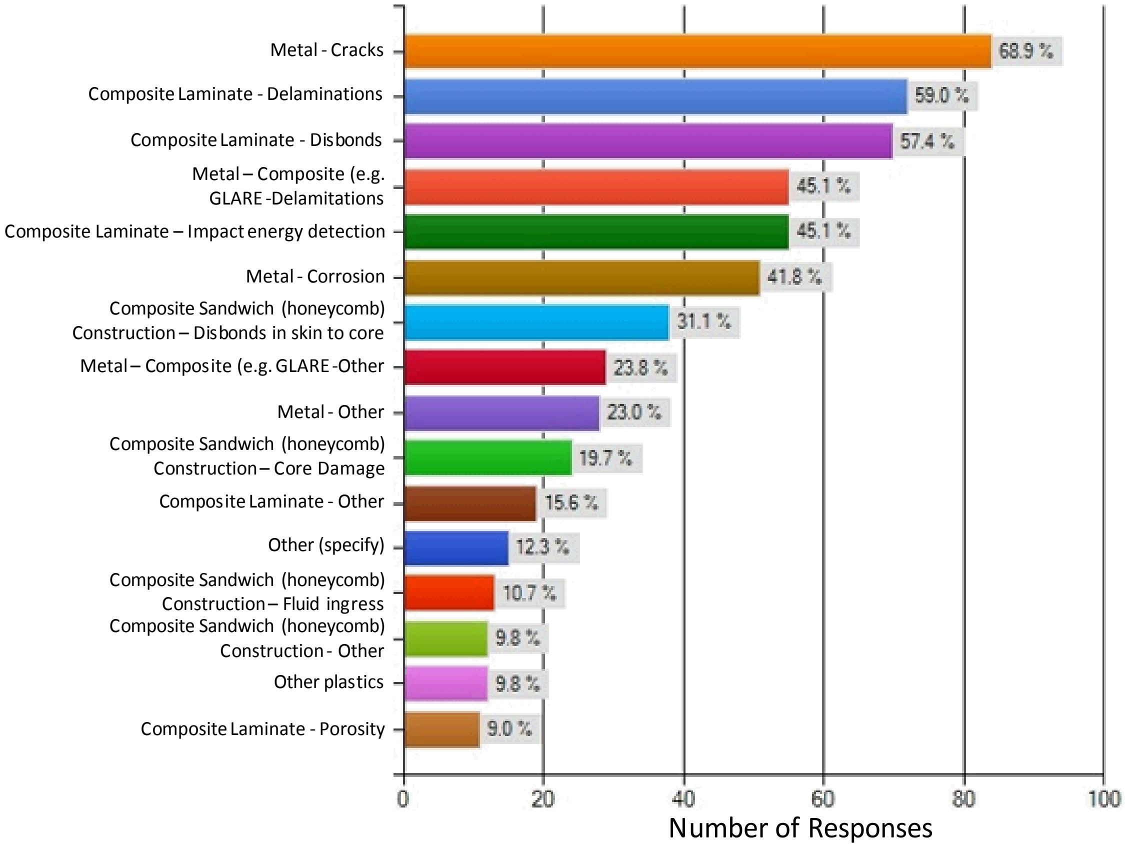


Figure 11: Type of Materials, Flaws and Damage That Can Be Monitored with Available Sensors

CONCLUSIONS

There is a strong commercial and military interest in pursuing SHM solutions for aircraft. Multiple applications have been identified covering all aircraft structural, engine, and systems areas. Research and development efforts should be focused on: global systems, sensor technology, system validation and integration, and regulatory guidance while standardization and guidelines are needed in the areas of: certification, laboratory and field validation, and sensor design with aviation in mind. In order to certify SHM systems, most people believe that SHM should run in parallel with current NDI inspections for a period of time. There are a wide variety of SHM sensors currently developed that have shown potential in aircraft applications. SHM maturity has grown exponentially so desired usage and need for certification is expected to rise rapidly. Industry’s main concern with implementing SHM on aircraft is achieving a positive cost-benefit and the time needed to obtain approval for SHM usage. Thus, validation and certification guidelines are needed. The SHM Technology Readiness Database identified specific and overall SHM Technology Readiness Levels and evolution trends. Currently, the majority of TRLs fall between 4 and 5 while no TRLs were identified at the most mature, 8 or 9 levels. The sensor database shows that SHM sensing is mature and expansive, in addition to being highly tested and proven in various test settings. There are multiple, mature sensors that are being produced, used, tested and evaluated. The sensor database is a tool that can be used to describe what SHM sensors look like, how they work and what they can detect. When coupled with the results from the SHM survey and the SHM TReaD, these databases can help determine the technology gap that needs to be filled in order to implement SHM on commercial aircraft. Overall, interest in SHM is high. SHM technology has been steadily advancing in TRL over the past four years and, with the exception of a few SHM systems, a substantial number of SHM systems should reach appropriate readiness levels for on-aircraft use in the next 3 to 5 years. Of course, aircraft maintenance programs and maintenance personnel will also need to adapt to SHM processes in order for any usage to succeed.

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