Verification and Validation of Structural Health Monitoring Algorithms: A Maturation Procedure

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Abstract: Structural Health Monitoring (SHM) system offers new approaches to interrogate the integrity of structures. However, their reliability has still to be demonstrated and quantified to enable confidence transition from R&D to field implementation. In general, SHM algorithms performances are illustrated by topography study but it is not sufficient in a reliability assessment context. In the sense, that there is no quantification of the performance. To address this key issue, a dedicated maturation procedure is proposed in this paper. It is strongly inspired from the six sigma procedure for processes improvement to gradually improve SHM algorithms in order to reach the required maturity level. This paper presents the application of this procedure to a damage SHM localization algorithm as case study. To address this issue, finite element models and experimentation on the monitored structure have been used. It is concluded with a need of a new specific SHM algorithm intrinsic maturity scale. These maturity scales can be defined with respect to the functions of the considered SHM algorithm and the type of the used data.

Keywords: Structural Health Monitoring, Performance assessment, Verification and Validation, Maturation.

1. INTRODUCTION

Structural Health Monitoring (SHM) technology offers a new approach to interrogate the integrity of structures in real-time or on demand without physically disassembling the structures (Hemez, et al., 2003). The objective is to enhance operating safety, increase availability, and reduce direct operating costs. SHM systems use mounted sensors and actuators managed by algorithms to detect, locate, quantify the severity and predict the evolution of damages. SHM in its own has now been around for more than two decades. Unfortunately, the implementation of SHM systems and their commercial deployment is delayed by the lack of maturation. Indeed, no formal methodology has yet been developed to address SHM system maturation despite that it is a critical step to guarantee its reliability and therefore its certification as pointed out in recent publications (Aldrin, et al., 2010), (Stolz, et al., 2013) (Chang, 2014). Hence, as for NDE (non-destructive evaluation) systems a specific Verification and Validation (V&V) procedures for the maturity assessment of SHM systems needs to be realized (Aldrin, et al., 2012).

A SHM system is composed by a hardware part, and a software part. Generally, maturation of the hardware part is well known and well done but maturation of the software part is omitted. For example, in the aeronautic field, the maturation of the hardware part is linked to the Technology Readiness Level (TRL) (Graettinger & al, 2002). Each of the TRL is covering a certain bundle of requirements. Within a maturation process a certain TRL level is reached if the relevant specific requirements have been fulfilled. Experience showed that using TRL does not suit to assess SHM software part (SHM algorithms) performances. Due to the omission of SHM software part maturation, false alarms appear after the SHM system implementation.

Following early works of the authors on the development of SHM (Rébillat, et al., 2014) (Hajrya & Mechbal, 2013) and PHM (Prognosis and Health Management) systems in the field of aeronautics (Hmad, et al., 2013), the present paper, focuses on the maturation of the SHM software part. This induces that before introducing a SHM algorithm in an operational system, it is important to assess very carefully its performances. The fact that a SHM algorithm is perfectly encoded does not guarantee that its performances are satisfactory (Hmad, et al., 2012). The present paper relates to the verification and validation of SHM algorithms for composite structure of an aircraft nacelle thanks to a maturation procedure when the SHM algorithm itself is considered as a process.

After a short description of the monitored structure in section 2, section 3 presents the proposed maturation procedure which is then applied to a case study. A damage SHM localization algorithm for composite structure is considered as a case study. From section 4 to 8, the maturation process is applied through this case study and allows the evaluation of the performance of SHM algorithms. It allows reaching maturity levels regardless of the considered maturity scale. Finally, it is conclude on the presented maturation process and the associated performances in section 9.

2. THE MONITORED STRUCTURE

Aircraft nacelles are a critical part of an aircraft, as they perform multiple functions. They contribute to the braking of the plane on landing and reduce noise emissions in drastically severe conditions as extreme temperatures [-50°C +120°C], pressure and dimension constraints, whilst remaining as light as possible. The structures used for the experimental study were 400 by 300 mm laminate carbon epoxy plate. It represents the laboratory step of the implementation of a health monitoring process for an actual aircraft nacelle (Massot, et al., 2014). A network of actuator and sensor mounted on the surface is used to collect data based on the present condition of the structure. These data are then compared with healthy ones to detect and then localize damage. The data of the host structure are collected thanks to piezoelectric transducer (PZT) and a real-time diagnosis result is obtained. The PZT elements used were numbered 1 through 5 mounted at specific positions on the composite plate's surface. The PZT elements have a diameter of 20mm and a thickness of 0.1mm. Fig. 1 shows the location of the 5 PZT discs and the coordinate values in x and y direction.

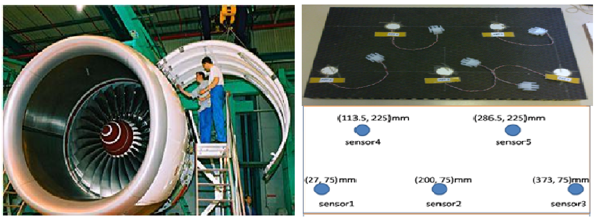

Fig. 1. The aircraft nacelle and a flat view of Laminate Carbon epoxy with PZT elements.

3. SOLUTION CONCEPT

The proposed solution is based on different definitions of algorithm "maturity" when the algorithm itself is considered as a process. In this perspective, all the definitions rely on the concept of continuous improvement. The proposed maturation process is inspired by the "Six-Sigma" approach which is based on the concept of continuous process improvement (Forrest, 2003). We have applied this successfully in the field of PHM (Hmad, et al., 2012) and we propose to extend it to SHM. The aim of this procedure is to gradually improve SHM algorithms by repeating a 5 phase sequence (Fig. 2) named DMAIC: Define, Measure, Analyze, Improve (and Optimize), Control.

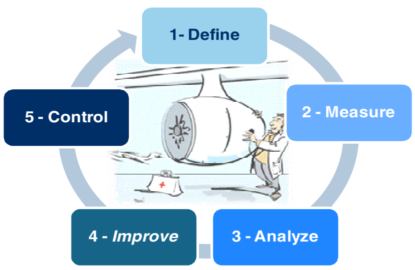

Fig. 2. Proposed maturation procedure scheme.

Each iteration of a complete DMAIC cycle allows reaching a new functional maturity level depending on the maturity level of the used data. Benefits of this procedure are multiple. First of all our interest is focused on the intrinsic performance of the software part of a SHM system. This involves defining Key Performance Indicators Critical To Quality (KPI-CTQ) (Forrest, 2003) and their estimation methods to quantify the performance of the software part. This quantification is based not only on the presence of healthy data but on damaged data too. However it turns out that the availability of damaged data is one of the hard points. To overcome it, we use finite element models and experiments on specimens.

The maturation procedure must be applied to the overall SHM algorithm. This includes data acquisition, damage index extraction, damage detection, damage localization, severity assessment and the evaluation of residual life time of the structure. In this paper, the stages of data acquisition and damage index extraction have been optimized and are therefore not considered. The maturation of the detection function being carried out at several times in the field of PHM (Hmad, et al., 2013) methods and techniques can be adapted to the SHM and are therefore not the subject of this paper. In this paper, we focus on the maturation of the SHM localization algorithm. The maturation procedure has been applied step by step to the SHM localization function on the considered structure and is describe on the following.

4. "DEFINE" PHASE

"Define" phase aims to identify elements to iterate a maturation sequence, hence it is particularly crucial in the first iteration where everything have to be set. This phase must establish the following items:

1. Description of the SHM algorithm version.
2. Specification of requirements to be satisfied.
3. Translation of the customer requirements in terms of Key Performance Indicators Critical To Quality (KPI-CTQ), definition of KPI-CTQs estimators and their estimation methods.
4. Definition of the damage to monitor.

The innovative part of this maturation procedure for the "Define" phase is the chaining of item 2 to items 3 and 4. KPI-CTQs are specifically defined in relation with SHM algorithms. There is a true reflection for the definition of these performance indicators and their estimation methods. These items are applied to the SHM localization algorithm for each DMAIC phase.

4.1 Description of the SHM localization algorithm.

This sub-section of the "Define" phase consists in describing the considered SHM algorithm for the maturation iteration. It allows identifying the potential performance indicators and their estimation methods.

Our case study is an algorithm which localizes a damage located on the considered structure (section 2). An active SHM scheme into a pitch-catch Guided Waves (GW) configuration has been used (Chang & Jeong-Beom, 2008). This study uses Lamb waves (Moll, et al., 2010) which is a member of the GW family to localise damage on composite plates. The localization problem consists of using the knowledge of the actuator sensor position to localise the damage knowing the actuator-sensor path and the time duration of the first wave packet from the actuator to the sensor which is known as Time of Flight (ToF)/Time of Arrival (ToA) (Buli, et al., 2009).

The ToF can be computed from the differenced signal (difference between the healthy and the damaged wave signal which is then used to estimate the damage position). The relation between the ToF and the actuator sensor path amounts to the equations used to solve the problem. The steps followed to solve the equation are known as the Forward Algorithm. In this case study, the hyperbola method (Moll, et al., 2010) is used as forward algorithm.

The hyperbola method employs the use of two sensors and one actuator in solving the forward problem. The wave packet thus travels from the actuator to both sensors then to the damage which then scatters the wave back to the sensors. The paths initiated by the waves are from actuator to the two sensors and from the two sensors to the damage which is then reflected back on both sensors. An illustration of this description is given on Fig. 3 (Coverley & Staszewski, 2003).

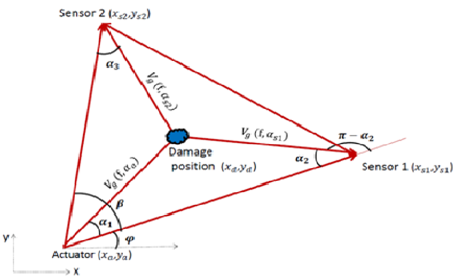

Fig. 3. Forward wave propagation path for hyperbola method.

The length of the path taken by the transmitted waves from actuator to damage being equal gives the ToF, thus the ToF becomes the difference between the duration it takes the first wave packets of the backward scattered waves to reach the two sensors. The damage location corresponds to the intersection point of all hyperbolas for all actuators sensors paths.

A probabilistic version algorithm of the hyperbola method has been developed by the authors and is used to determine the damage location. This is the subject of another publication, demanding its proper space to detail the probabilistic localisation method. The output of this algorithm is a two column vector of several estimated coordinates. These coordinates are then used to compute a Probability Density Function (PDF) that represents the estimated damage location.

4.2 Specification of requirements to be satisfied

This section of the "Define" phase allows the identification of the requirements in terms of SHM algorithm expected performance. These requirements may be captured through interviews of customer representatives and business representatives. The interviews are then transcribed to identify common requirements of both sources.

"Airlines operations" requires information about the presence of damage to enable them to organize maintenance tasks. The line maintenance needs an explicit confirmation (from the SHM algorithm) of the damage location.

These requirements have been translated into performance indicator in subsection 4.3.

4.3 Translation of the customer requirements in terms of KPI-CTQ and definition of their estimation methods.

Performance indicators namely KPI-CTQ are based on Customer Requirements (Forrest, 2003). In the present case, it is wanted that the estimated coordinates are as close as possible to the actual damage. This notion can be expressed as a distance between the estimated coordinates and the actual damage location. In that perspective, a good metric to express this notion and is easy to interpret by maintenance is the Manhattan distance (or city block metric) between the estimated coordinates and the actual damage location. The Manhattan distance (Krause, 1987) in (1), is a metric that compute the distance between two points by computing the sum of the absolute differences of their Cartesian coordinates.

$$d_{uv} = \sum_{j=1}^{n} |u_j - v_j| \quad (1)$$

where u and v are vectors $\in \mathbb{R}^k$with $k = 2$ (in practice, the minimum value of k is 1 and the maximum value is 3), $u = (u_1, \dots, u_n)$ and $v = (v_1, \dots v_n)$.

In our application, we consider that the structure is in a healthy state. It is therefore necessary to generate damage before starting the localization procedure. The damage generation is discussed in item 4. Once this damage is generated, the localization algorithm is launched and estimate n damage coordinate. Distances between each estimated coordinate and actual ones are computed using Manhattan distance. Subsequently, the mean of the calculated distance is used as a *KPI-CTQ* (2) and will serve to compare the different characteristics of the generated damage.

$$\textit{KPI-CTQ} = \sum_{i=1}^{n} \frac{d_{uv}(i)}{n} \quad (2)$$

A good performance is obtained when the KPI-CTQ is as low as possible which means that we are close to the actual damage location.

KPI-CTQ estimation method has to be established as soon as possible because it may have strong practical implications such as the need for damage generation. This point is discussed on the next item.

4.4 Definition of damage to monitor.

Composite materials are built to emulate certain mechanical properties, due to environmental variations and wearing initiated by the extended age of the structure, there may be changes present. The change in the mechanical properties of the structure is known as damage. There are different types of damages that can occur in a composite material. The common damages are: impact (caused by moving objects in forceful contact with another), Bolt-hole damage, Disbond, Fiber breaking…

In the considered plate, no damage has been generated. It is so necessary to generate it. Several ways can be used to address this issue. The way the most expensive is to generate a calibrated damage after choosing the damage type and location. This way is the most expensive because it mobilizes many means and condemns a plate. Another way is to simulate the structure using a finite element model and then generate an impact by changing the characteristics of the model to the desired damage type and location. In our case, we only focus on impact damage. A solution, to midway between the two previous, to generate this damage is the use of magnet. The latter allows not affecting the integrity of the structure to test different size of impacts.

The damage used in this study is the adding mass. We used Neodym magnets (Superaimants) of different sizes to simulate the added mass effect. The magnets are circularly shaped with smooth metal coated surfaces (Table 1). They are used on both face of the structure to introduce additional mass and applied local stress.

Table 1. Magnets used for the experimental study.

(a)	(b)	(c)
$14mm$	$20mm$	$28mm$
$3.2\ Kg$	$5.75\ Kg$	$13\ Kg$
		

Finally, the "Define" phase also establishes the version of algorithm, software, documentation, sub-functions, calibrations… to be considered in the "Measure" phase.

5. "MEASURE" PHASE

The "Measure" phase consists in estimating the performances of the current version of the considered SHM algorithm thanks to the estimation methods established during the "Define" phase. This phase is structured according to the two following items:

1. KPI-CTQ estimation for the current version of the SHM algorithm
2. Proposition and prioritization of potential algorithm improvements to be considered in the "Analyze" phase

At the end of the "Measure" phase the KPI-CTQ of the SHM algorithm are known. Then, some potential improvement axes are proposed. The influences of these potential improvement axes on the KPI-CTQ are then studied during the "Analyze" phase.

5.1. KPI-CTQ estimation of the considered SHM algorithm.

The KPI-CTQ estimation has been obtained by introducing experimental data (ToF) into simulations. The experimental data have been obtained in normal environment condition for a temperature of $20°C$. After several iterations to select the best parameters of the localization algorithm (variance…) simulations have been done using a Markov Chain Monte Carlo (MCMC) method (Beck & AU, 2002). The chain length is $100{,}000$ samples but we use the $50{,}000$ last to warrant its convergence. Fig. 4 shows an example of Probability Density Function (PDF) contour of the estimated locations for the impact of size 20mm and the actual location represented by a white cross. It appears that the location precision is not good since the PDF of the estimated locations is far from the actual location. This analyze is not sufficient without a quantification step to know how far are the estimation from the actual damage location.

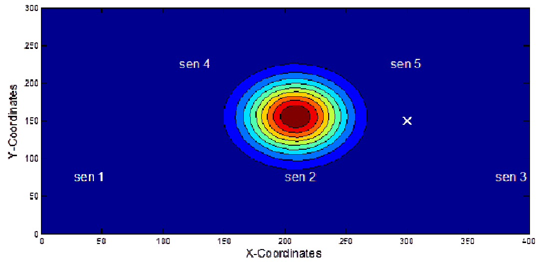

Fig. 4. Hyperbola method, PDF contour of the estimated locations for the impact of size 20mm and the actual damage location (white cross).

The performance quantification is done thanks to the considered KPI-CTQ. Fig. 5 shows the estimation of the considered KPI-CTQ against the impact size for the hyperbola method.

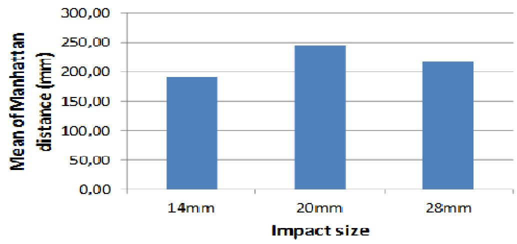

Fig. 5. Hyperbola method, KPI-CTQ for three impact sizes.

This step allowed quantifying the performance of the SHM localization algorithm for the three size impact. It appears that there is no monotonicity with the impact size. The presence of monotonicity allows correlating the impact size to the precision of the estimated location. It is expected to have a better estimate of the impact location if its size is important than if it is small. This induces the fact that wherever the impact location, beyond a certain size the coordinates of the impact are correctly estimated.

This quantification step shows that the performances are not acceptable since the KPI-CTQ are around $200mm$ far from the actual damage location. It is not easy to conclude with this kind of results. Despite this, we can propose some improvements to show how performances are enhanced. This last point is discussed on the next item.

5.2. Proposition and prioritization of potential algorithm improvements to be considered in the "Analyze" phase.

In this item, we consider that the data acquisition and the feature extraction steps are optimized, so they don't need any improvements. In this case, two opportunities are available to improve the localization performance: the first one is to change the localization strategy by using a different approach than the hyperbola method. In the literature, the ellipses method seems to give good results (Moll, et al., 2010). The second one is to restrict the area of the impact research in reasoning by cluster.

Table 2 shows the rating result of the potential improvement axes. It gives the order for the investigation of their impact on the KPI-CTQ during the “Analyze” phase.

Table 2. Table of potential improvements**.**

Improvement n°.	Improvement axes to assess on KPI-CTQ	Prioritization
$A1$	Ellipses method	1
$A2$	Localization by cluster	2

6. “ANALYZE” PHASE

The “Analyze” phase consists in quantifying the impact of the proposed improvements on the KPI-CTQ. It requires estimating the KPI-CTQ of the SHM algorithm after changes according to Table 2.

The first improvement ($A1$) consists in replacing the hyperbola method by the ellipses method. This method has been applied to the same data used in the “Measure” phase and the KPI-CTQ has been estimated by the same procedure. Fig. 6 shows the PDF contour of the estimated locations for the impact of size $20mm$ and the actual location represented by a white cross after improvement $A1$.

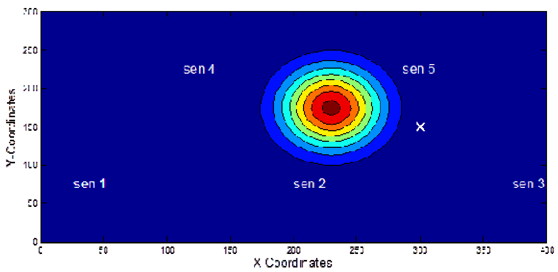

Fig. 6. Ellipses method, PDF contour of the estimated locations for the impact of size $20mm$ and the actual location (white cross).

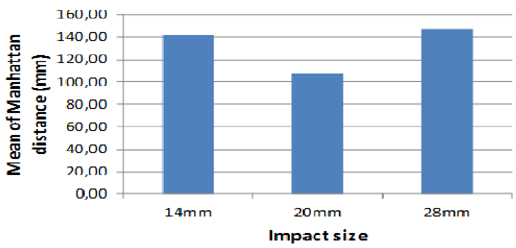

Fig. 7. Ellipses method, KPI-CTQ for three impact sizes.

It appears that the location precision is better than before improvement $A1$ since the KPI-CTQ value has been divided by 2 after improvement $A1$ and is now about $100mm$ (Fig. 7). It still not enough good since the actual location doesn’t belongs in the PDF contour of the estimated locations.

Fig. 7 shows the results of the quantification step. It appears with this second approach, there still no monotonicity with the impact size and the considered KPI-CTQ. We have to note that performances are a little improved. Improvement $A1$ has a good influence on the localization performance.

In order to improve the localization, we employed the use of a clusters-based approach (Shenfang, et al., 2014) (improvement $A2$). The idea is to subdivide the structure in zones to be independently monitored (Fig. 8).

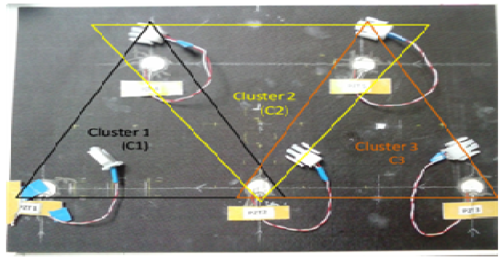

Fig. 8. Clustering to improve the localization performance.

In practice, a clustering approach needs more experimental data and specific measurement logic, but could offer more improvement. The position of the PZT elements on the composite plate forms three triangles. The cluster focuses on using one triangle for the localisation process by using a particular PZT element as an actuator at a specific time and the others as sensor. After this another PZT element in the same triangle is used as an actuator and the others as sensors this is done in the same manner as the first process. When all the three PZT elements in one specific triangle have taken their turn as an actuator localisation is finished. In this application, we only focus on cluster n° 3 since the damage is located in it as shown in Fig. 8.

As for the previous approaches, Fig. 9 shows an example of PDF contour of the estimated locations for the impact of size $20mm$ and the actual location represented by a white cross after improvements $A1$ and $A2$.

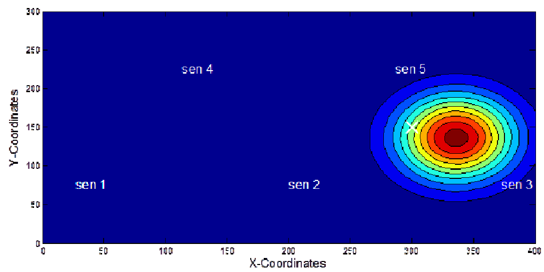

Fig. 9. Cluster approach + ellipses method, PDF contour of the estimated locations for the impact of size 20mm and the actual location (white cross).

It appears that the location precision is better than the two previous cases since the actual location belongs in the PDF. The quantification step gives us information about how much improvements $A1$ and $A2$ enhance the localization performance.

Fig. 10 shows the KPI-CTQ after applying this approach and considering the ellipses method. It appears that there is monotonicity with the impact size and the KPI-CTQ. Bigger the impact is better the localization. Using the cluster approach combined with the ellipses method allowed reducing drastically the KPI-CTQ which is less than $50mm$.

Improvement axes on Table 2 have been tested. The expected effect on KPI-CTQ has been assessed. Thus these improvements increase the maturity levels of the SHM algorithm for the considered type of data (data maturity).

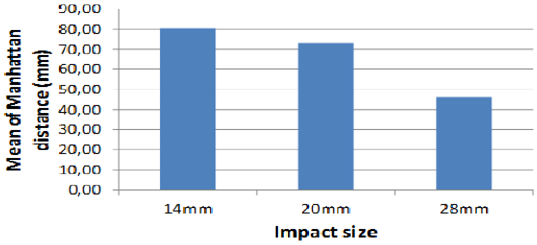

Fig. 10. Cluster approach + ellipses method, KPI-CTQ for three impact sizes.

7. "IMPROVE" AND "OPTIMIZE" PHASE

At the end of the "Analyze" phase, suggestions for optimization of the SHM algorithm are prepared and submitted in an inter-modules review. The "Optimize" phase lists the improvements to incorporate into the SHM algorithm. In the presented example, the different improvement axes have been specified to be added to the current algorithm. After encoding them, the "Control" phase is unrolling.

8. "CONTROL" PHASE

At the end of an iteration of maturation, the axes of improvement should be implemented into the considered SHM algorithm. Subsequently, the new version of the algorithm is matured in the same way to control the implemented improvements and rise other technical blocking.

Firstly, the "Control" phase compares KPI-CTQ of the specified SHM algorithm after the "Optimize" phase to those obtained during the "Analyze" phase. Then the "Control" phase specifies items to consider in future iterations on the next versions of the SHM algorithm with more mature data.

9. CONCLUSION

Constantly, V&V of SHM systems focus only on the hardware part. Indeed, current V&V method focusing on the software part are not relevant. This paper highlights the fact that these two parts need two different maturation way and focuses on the software part by proposing a maturation procedure. This first maturation study was focused on the damage SHM localization function. Voice Of the Customer and Voice Of the Business study lead to the definition of a KPI-CTQ which is defined here as the mean of the Manhattan distance obtained for each experimentation. This maturation procedure allowed first to quantify the performance of SHM algorithms and then leads to improve it up to more acceptable performances than the "Measured" one. The maturation of SHM systems is as important as the development of the system itself. It allows achieving results in terms of mastery of the maintenance costs and reduction of interventions on healthy material. The objective now is to apply this procedure in a systematic manner on each function constituting SHM algorithms for more mature data and damage models. It is this way that V&V allows the introduction of SHM systems in operation.

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