Discussion about the Axioms of Structural Health Monitoring

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Abstract

In this paper, the axioms of Structural Health Monitoring (SHM) presented by Worden, Farrar, Manson, and Park [2007] are discussed in detail. In many cases, the intent of the axioms is found to be correct, but the terminologies used are confusing. Also, it was found that some axioms could be derived from other axioms that were given in that paper itself. Based on the discussion presented in this paper, it is suggested to replace the seven axioms given in ibid with a set of three new axioms. The main plus point of the axioms given in the paper over those given in ibid is conciseness. Counter-examples are presented to dispute the axioms where necessary. Similar to Worden et al. [2007], the term axiom is used outside its meaning in the field of mathematics and logic. In ibid, the term axiom is stated to refer to the fundamental truth which have not been contradicted in the field of SHM. However, in this paper, the word axiom refers to its second meaning in Merriam Webster dictionary “am established rule or principle or self evident truth.”

Keywords— Structural Health Monitoring, Axioms, Damage, Unified Framework, Definitions

1 INTRODUCTION - STRUCTURAL HEALTH MONITORING

The field of Structural Health Monitoring (SHM) was developed due to the need of non-destructive inspection methods to detect damages in structures that are used to bear large loads, and repeated or cyclic loading. Prior to the perturbation techniques currently being used and research in Structural Health Monitoring, structures were often inspected for damages using (Non-Destructive Evaluation) NDE methods and techniques such as x-ray observations, eddy current techniques, ultrasonic techniques or thermography. These techniques, however, were not the most practical due to certain disadvantages such as being labor intensive. Additionally, in many cases the techniques are only useful to detect damages in critical regions where the potential for damage growth and structural failure is very high. As such, it was necessary to develop new damage detection methods which were less labor intensive and could scan the entire structure. In many structures, such as aerospace vehicles, the structure is dynamically excited and it is believed that the response of a structure to excitation varies with the presence of damages because damage causes changes in stiffness and response is a function of stiffness. Consequentially, the goal of SHM is to use the differences in the structure's responses to detect damages, to identify the locations of damages, and to determine the magnitude and orientations of the damage. The eventual goal of SHM is to predict the remaining life of a damaged structure.

2 LITERATURE SURVEY - STRUCTURAL HEALTH MONITORING

The literature for vibration based SHM can be divided into two aspects, the first wherein models are proposed for the damage to determine the dynamic characteristics, also known as the direct problem, and the second, wherein the dynamic characteristics are used to determine damage characteristics, also known as the inverse problem Friswell and E. [2001] .

In the literature, reviews in particular, for most cases both aspects are tackled together. Doebling et al. [1998], which stems from a report submitted by the same authors to the Los Alamos National Laboratory Doebling et al. [1996], mainly addresses the inverse problem. The work by Dimarogonas [1996] gives a survey of literature that deals with vibrations based SHM. The review paper primarily deals with the direct problem in the modeling of damage, but it also deals with the inverse problem of damage identification to a limited extent. The review is exhaustive, for pre-1996 literature, as far as enumerating methods to model cracks.

Both the above reviews can safely be recommended to any researcher intending to understand the origins of SHM for their respective merits. However, both of them are old and the field of SHM has proceeded since. The next useful review for vibration based SHM is by a team at Los Alamos research laboratory Sohn et al. [2003]. The bulky document has over 300 pages and is an exhaustive literature review of an important phase of the field of SHM, i.e. from 1996 to 2001.

Staszewski et al. [2004] present a collection of papers written by experts in the field. The papers are arranged randomly. The next review of interest is by Carden and Fanning [2004]. There are two other reviews that are focused on specific aspects of the inverse problem of SHM. The first is byMontalvao et al. [2006] and deals with composites, and the second is by Ciang and Lee [2008] and deals with wind turbine systems. A review by Fan and Qiao [2010] specifically focuses on modal parameter based damage diagnosis, while Riggio and Dilmaghani [2020] timber structural health monitoring (SHM) projects.

Another review article by [Sony et al., 2019] presents a literature survey of the applications of smartphones, UAVs, cameras, and robotic sensors used in acquiring and analyzing the vibration data for structural condition monitoring and maintenance. The latest review paper that the author came across is by Gharehbaghi et al. [Gharehbaghi et al., 2022].

3 INTRODUCTION TO THIS PAPER

The last paper that was cited in the previous section that of [Gharehbaghi et al., 2022] has about 10 authors and 240 references. It is difficult to even cite that paper, let alone read it. If we subject a new researcher to read even about 10 reviews papers each having about 250 references, the researcher will lose their mind even before they begin any research of consequence. A natural question that arises is how can we represent the field of SHM in a pithy way so that one is able to get a fair idea without spending unfair amounts of time.

A novel and useful contribution in the field of Structural Health Monitoring (SHM) was done through the paper by Worden et al. [2007]. Commendably, the paper attempts to give a new researcher an alternative starting point rather than wading through the enormous literature that has come up in the area, in the past 45 years.

A point that needs to be emphasized is that the word axioms cannot be used lightly. The true enormity of the word can be understood by reading the book by Professor Brown of Duke University Brown [2007]. In view of the huge ramifications of the word axioms and associated possibilities in defining a particular field in brief and also it ability to serve as a link to related and unrelated fields the unique idea of the proposing axioms for SHM by [Worden et al., 2007] cannot but be applauded for its novelty.

In that paper, however, it was pointed out that lively discussions emanated whenever the axioms were discussed, which indicates there is some confusion regarding the universality of these “fundamental truths.” In this paper, an attempt has been made to carry the discussion forward.

The author is of the opinion that in many cases the meaning of the axioms, as interpreted in the discussion following the axioms, is correct, but, the wordings used lead to dubious interpretations. The examples too corroborate the meaning rather than what may be inferred by the wordings of these axioms. In these cases the wordings are suggested to be changed. In other cases, counter examples are presented to dispute the universality of the axioms. In view of the counter examples, the axiom has to be dropped from the list of axioms.

A common fallacy in ibid is the complicated nature of the axioms. Axioms, as they are in other fields, are usually so simple that even somebody not having any idea of the field can grasp, even if to a limited extent. If the axioms are to gain universal acceptance, they need to be simple in expression. Therefore, efforts are made in this paper to simplify the language of the axioms and make it less technical where possible.

4 DEFINITIONS

In order to properly discuss the axioms proposed by Worden et al as well as the new axioms proposed in this paper, it is important to address certain definitions and terminologies that pertain to Structural Health Monitoring. In some cases, changes are proposed to the definitions.

4.1 Structural Health Monitoring

Structural Health Monitoring is defined in the paper by Worden et al. [2007] as the "process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure."

First, it is suggested that the word 'infrastructure' be changed to 'structure,' otherwise it will become the definition of Infra-structural Health Monitoring. Second, the names of the engineering branches is not a comprehensive list of all the fields that pertain to SHM. Therefore, they should be dropped altogether. Third, the word identification is used to denote both identification and characterization of the damage. It is elaborated in that paper that the word identification of the damage, includes along with identifying the types of damage, determining its characters such as its locations, its type, and its severity too. Therefore, ibid attempts to use the word identification outside of its dictionary meaning. Rather than limiting identification to recognizing that there is a damage, it is hoped that the word will also mean determining the characteristics of the damage. This use of words outside of their dictionary meaning may lead to confusion. The word 'characterization' is the proper word to insinuate the determination of the location, type and severity of damage. Therefore, rather than using identification to indicate identification and characterization of damage, it will be better to use both those words. Fourth, the eventual aim of SHM is that of prognosis Farrar and Lieven [2007]. This important objective is missing in the definition given in Worden et al. [2007].

Based on the above discussion, the following definition is proposed:

The process of implementing a damage identification and characterization strategy with the eventual goal to predict the remaining life of the structure is referred to as Structural Health Monitoring.

4.2 Damage

Damage, as defined by Worden et al., are the "changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the performance of these systems." The paper, however, mentions that this definition "must be extended to include the concept that damage is present when one cannot account for the imperfections in system design and performance prediction using bulk material properties." In order to clear the taxonomy, Worden et al. [2007] presents new definitions for fault, damage, and defect, which are defined as follows:

“A fault is when the structure can no longer operate satisfactorily. If one defines the quality of a structure or system as its fitness for purpose or its ability to meet customer or user requirements, it suffices to define a fault as a change in the system that produces an unacceptable reduction in quality.

Damage is when the structure is no longer operating in its ideal condition, but it can still function satisfactorily, but in a suboptimal manner.

A defect is inherent in the material and statistically all materials will contain a known amount of defects. This means that the structure will operate at its optimum if the constituent materials contain defects.”

Such trifurcation of a definition is not recommended because it can be confusing. Any confusion should be avoided in a paper that deals with axioms and basic definitions. A defect even though accounted for in the bulk properties of the material can still be ‘damage’ or even a ‘fault’ for some applications. Also, a ‘fault’ for one application may or may not be a damage for another application. For example, a minor crack in a beam of a bridge may not even be a ‘damage’, but this same crack in a beam of a nuclear power plant may be a ‘fault.’ As mentioned earlier, a paper dealing with axioms of SHM, among other uses, is an alternate starting point for a new researcher who wishes to understand the field saving them from being overwhelmed by enormous literature in this field. Therefore, a paper about axioms should be as simple as possible. However, the concept of defect and fault are good. Therefore, to incorporate the concepts without cluttering the mind-space of the reader, ’expected system’s performance’ may be included in the definition. A simple encompassing definition of the damage is as follows:

Damage is the part of the state of a structural system that adversely affects the system’s performance. The ‘state of a structural system’ is defined by its material properties, geometric definition (its layout in the global 3D coordinates) and its boundary conditions, frozen at an instant of time.

4.3 Sensor, Post-Processor

Two other important terms in the field of SHM are Sensor and Post-processor. As such, they are defined below to complete the set of relevant definitions.

Sensor: A sensor is a device that measures a physical quantity and converts it into a signal that can be read by an observer or by an instrument

Post-processor: An algorithm that processes the data obtained by sensors to categorize the system as damaged or not.

The process of Structural Health Monitoring involves the recording of data obtained by a sensor. Thereafter, a post-processor (algorithm) interprets the readings to classify the structure as damaged or not. Although there are algorithms in sensors too, the word algorithm usually refers to the post processing algorithm in the field of SHM. In some cases the sensor and post-processing algorithm are tightly coupled, in other cases, they are uncoupled and exist as individual entities.

5 AXIOM I

Axiom I as given in the paper of Worden et al. is as follows:

Axiom I: All materials have inherent flaws or defects.

Among all the axioms given by Worden et al., Axiom I is put in the best way. It is short, to the point and conveys its idea in common understandable manner. There is nothing to dispute or argue about the axiom except perhaps that the axiom seems to be a fact, but not a useful fact. The most famous axioms are perhaps the Newton's laws. Newton's laws are not just facts, but facts that can be used as a starting point of derivations. For example, Newton's second law is the starting point of the derivation of equilibrium equations in mechanics. However, axiom I given by Worden et al. does not give rise to a thought process that will yield in development of SHM. As such the author proposes a corollary of the given axiom to replace it.

Axiom AD-1: Perfect material is theoretical construct and all materials need much less energy to be damaged than the corresponding perfect material.

6 AXIOM II

In the paper by Worden et al. [2007] the following Axiom II is given.

Axiom II: The assessment of damage requires a comparison between two system states.

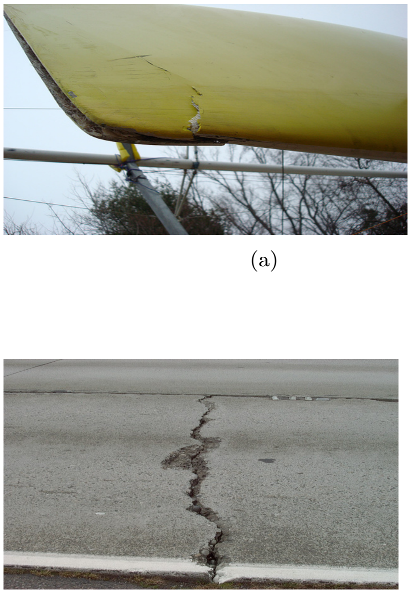
This axiom is the most controversial axiom of all. The tremendous effort that Worden et al. put to convince the reader of the validity of their axiom is a testimony to the shaky grounds on which this axiom stands. The are several examples in the technical literature that violate the paradigm of the axiom. Though it is not clear from the wording of the axiom, implicitly, as is evident from the discussion following the axiom in that paper, two structural states referred in the axiom are the undamaged (baseline) and damaged states, respectively. Though the authors of that paper insist that an undamaged structural state is needed to decipher damage, their arguments are contrary to general practice. A set of examples are presented to show that it is possible to identify damage to a structure without having an undamaged structural state or for that matter any other structural state. In the examples presented, just the damaged structure is sufficient to ascertain damage. Initially, simple and non-technical examples are given to understand the concept. Thereafter, technical examples are given to strengthen the argument.

Consider an example of shopping for articles (say tomatoes). Different people will reject different sets of tomatoes, or in other words, different people will find different sets of tomatoes to be unsuitable for their purpose. The determination or damage or suitability does not need a baseline such as an undamaged tomato in their hand or even in their mind.

How does a shopper make a determination that a particular tomato is damaged or unsuitable for their purpose? The shopper has a set of characteristics in their mind. If a tomato does not fulfill their desired characteristics, it is rejected as damaged. These characteristics form a body of knowledge based on the shopper's experience and the purpose for which the purchase is being made. This body of knowledge is different from a baseline state, because the body of knowledge is never enough to define a state completely.

A bad (damaged) tomato that is rejected might never have existed in the undamaged and state that would have made it acceptable to the buyer. Therefore, only a set of characteristics in the mind of the shopper will determine if the tomato is characterized as damaged or undamaged. At least for this simple case no baseline state is needed to make an 'assessment of damage.'

Obviously, SHM is more than just buying tomatoes. Therefore, as an example closer home, consider the visual examination two pictures given in figure 1. No undamaged state is given, yet both the road and the boat would be characterized as damaged by most people if not all. Visual or sensory examination is a popular mode of ascertaining damage in the field of SHM. Again, unlike what the axiom asserts, just one state was sufficient to determine if the structure is damaged or not.



(a)

(b)

Figure 1: (a) Damaged Structure 1 (b) Damaged Structure 2

Another simple example where baseline state is not needed to detect damage is that of railroad tappers who judge the damage based on the sound. The railroads are repeatedly tapped. The tapper makes a determination if the railroad is damaged or not just based on the sound they hear of the tapped railroad. Again, no undamaged state of the damaged railroad is available to the tapper.

The skeptics in the field of SHM vouching that a baseline state may still be unconvinced because the above examples after all are not specifically from the field of SHM. Such localization of the field is not recommended. An axiom cannot be just true for complicated sensing and post-processing apparatus and not applicable to monitoring the health of vegetables in the kitchen or for that matter cannot counter intuitive to general cognition practice. Just to satisfy the skeptics, though, some of the several examples, within the field of SHM, where only one state is sufficient and a baseline state is not needed to ascertain damage.

In the paper by Stubbs et al. [1995], a definition for damage recognition using only the curvature of the test beam bending is given. There is no need for knowing the curvature state of an undamaged beam per the methodology suggested in ibid. This claim is disputed in their paper by Worden et al., who argue that the Euler Bernoulli beam is the implicit baseline. The axiom does not talk about implicit baseline; it just talks about two system states. Even if we consider Euler-Bernoulli beam as an implicit baseline, there is not comparison between that baseline and the damaged structure. Curve fitting using admissible functions, as is done in ibid, is not comparison with those functions. By plotting the measured modal quantity and using admissible functions to curve fit, the damage location was identified. No other structural state (undamaged) was used.

The way Stubbs et al. [1995], deduce damage is very similar to the process of discarding tomatoes by the shopper as described earlier. Damage is found out using certain characteristics such as admissible functions, which are mode shapes of the undamaged beam in this case. It should be noted and it is very important that it is, is the fact that the admissible function could very well have been any other complete set of functions. Even otherwise, if the mode shape of undamaged beam are used to curvefit, those mode shapes together is not the undamaged beam. Expectation comes from insight and foresight which comes from knowledge and experience. This knowledge and experience is different from a comparison, which comes from observation. According to the axiom, the process of damage identification "requires comparison between two system states." However as shown above just based on knowledge a particular system behavior is expected and any deviation from that means damage. Knowledge is different from a baseline state.

Another argument given by Worden et al. to buttress the validity of Axiom II for the damage identification procedure in ibid was that "feature computed - the curvature - cannot be used without a thresh hold significance, which is computed on the understanding that most of the estimated curvature data comes from the rest of the structure that is undamaged". In simple terms, Worden et al. are saying is that the damaged structure has a damaged part and an undamaged part. Since the damaged part is computed using the undamaged part, therefore, Axiom II holds. What Worden et al. fail to note is that in essence only one structural state is used, which is the damaged state. Axiom II explicitly requires 'two system states'. If the damaged part can be determined by the information about the undamaged part of the damaged structure alone, as is done in ibid, Axiom II stands violated because only one state is used.

Though in ibid, mode shapes of the corresponding undamaged structure are used, Ratcliff and Bagaria Ratcliffe and Bagaria [2012] went a step further. In their paper, quoting from their abstract, "[t]he procedure [of damage identification] can operate solely on data obtained from the damaged structure. Models or data from the undamaged structure are specifically not required or used during the analysis."

As a next example, to show that the baseline state is not required for damage identification consider a recent publication by Dixit and Hanagud Dixit and Hanagud [2012]. In this method, a new physical quantity, which does not require a baseline state and is named partial mode contribution is proposed. As per the method outlined in the paper, the free vibration modes (operating deflected shape when the structure is excited at its natural frequency) of the damaged structure, are expanded using the undamaged modes of the structure as the basis functions:

$$\mu_d^i = \chi \mu_{ud}^i + \sum_{j=1, j \neq i}^{\infty} \xi_{ij} \mu_{ud}^j = R_1(x) + R_2(x) \quad \chi < 1, \quad \chi >> \eta_{ij} \tag{1}$$

where μ is the mode shape, the subscript 'd' denotes damaged and 'ud' denotes undamaged. χ and ξ are numerical factors. The second part of the response, (R_2), has a form that gives the "damage signature." Damage signature has a definitive spike at the damage location because it exists solely due to the damage. Damage signature arises due to partial mode contribution of the damaged structure and hence the method is called 'Partial Mode Contribution Method,' Partial mode contribution method does not need any baseline structure to identify the damage.

Some examples from the paper by Fryba and Priner Fryba and Pirner [2001] are presented to show that even for automatic detection the requirement of a baseline is not valid. In ibid, examples of different types of definitions to detect damages are given. For static tests three conditions are given:

$$\begin{aligned} &\beta < \frac{S_e}{S_{cal}} \leq \alpha \\ &\frac{S_r}{S_{tot}} \leq \alpha_1 \end{aligned} \tag{2}$$

S_r is the permanent part of the measured value and S_e the elastic part of the measured value S_{tot}. S_{cal} is the calculated total value. The width of cracks is limited for concrete bridges to a value δ which depends on environmental conditions. As can be seen, the second and third conditions are based on damaged state of the structure only, no other structural state is considered, whereas the first condition depends on the theoretical model and the damage measure value only.

For dynamic tests two criteria are used,

$$\begin{gathered}\Delta_{(j)} = \frac{f_{(j)teor} - f_{(j)obs}}{f_{(j)teor}}.100 \\ (\delta_{obs} - 1)k_{dyn} \leq \delta - 1\end{gathered} \tag{3}$$

where $f_{(j)}$ denotes the j^{th} natural frequency. *teor* denotes calculated and *obs* the measured values, δ_{obs} or observed dynamic factor is equal to $\frac{S_{max}}{S_m}$. S_{max} is the maximum dynamic response and S_m the maximum static response due to the load. δ is the standard dynamic impact factor. The first criterion depends on the damaged state and an assumed theoretical model behavior of the system, while the second criterion depends solely on the damaged state of the system and the knowledge of dynamic impact factor.

The monitoring is done using stress ranges $\Delta\sigma = \sigma_{max} - \sigma_{min}$ where σ_{max} is the maximum stress and σ_{min} the minimum stress. The monitoring is solely based on the single state of the beam. Finally under "modal analysis and identification" two parameters, Modal Assurance Criterion (MAC) and Coordinate Modal Assurance Criterion (COMAC), are given. The two criteria that determine the damage are based on two states of the structure.

The controversy arises in defining and understanding baseline. The baselines or structural states are different than the knowledge that the post processor acquires over a period of time. Similarly, a criteria or an assumption is also different than a baseline. The knowledge that the post processor acquires over a period of time, a criterion or an assumption, can all be used to define a damage, similar to how a baseline can be used to define a damage. In all fairness the authors of the paper, Worden et al. [2007], also possibly meant the same thing. The problem is with the terminology used. Defining damage detection as a difference of two structural states would confuse researchers, especially new ones and constrain their ability to determine damage. This confusion is evident in the paper too.

7 THE IMPORTANCE OF AXIOM II

As was noted in the introduction section 3, the importance of the paper by Worden et al. [Worden et al., 2007], cannot be emphasized enough. Similar to their entire paper, Axiom II conveys an important concept. The concept is in the first clause of their axiom, i.e. "The assessment of damage requires [..]." It is indubitable that for damage identification and consequently for the field of SHM, the principle behind damage identification needs to be outlined. Worden et al. might not have defined that principle correctly, but were successful in outlining the importance of the principle. For any complete set of axioms, that principle needs to be defined.

If it can be agreed that the principle behind damage assessment needs to be a part of the set of axioms, it can also be concluded that the definition of the damage is similarly important. Based on the foregoing discussion and also the other research papers in the field of SHM as given above, it can be opined that the definition of damage is a function of the intended use of the structure. Different intended uses gives rise of different damage measures. The intended use will define the types and severity of damages that need to be identified. For example, in the SHM of bridge structures, the damage that need to be identified are different than that for aircraft structures. The intended use and the resulting definition of the damage is also necessary to predict the remaining life of the structure.

Based on the foregoing, it is proposed that the axiom by Worden et al. be changed to Axiom AD2 as follows.

Axiom AD2 - A: The assessment of damage is dependent the definition of system performance parameters. The clarity of assessment is dependent on the clarity of the definition of the parameters.

8 AXIOM III

The Axiom three as given in the referenced paper is

Axiom III: Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode.

It is suggested by Worden et al, that it is only possible to identify the type of damage and its severity in a supervised learning mode. An axiom, by definition, should hold true for all cases. Even Worden et al. call them fundamental truths. Therefore, having the word generally in the axiom itself is unacceptable. It is true that the statement of the axiom generally holds for the state of art as it is today, however, as SHM progresses, the ability of damage identification methods available in an unsupervised learning mode will improve and damage characterization too will improve in an unsupervised learning mode. An example of this ability of the damage characterization in the area of SHM in unsupervised learning mode is given in the paper by Glass, Cannon, Branson, Hanagud, and Paulsen [2008]. The paper describes the process of a drill project on Mars that not only characterizes the damages but also takes corrective measures in case the drill gets stuck under various conditions, in an unsupervised learning mode. Since Axiom III is not a fundamental truth, it should be removed.

9 AXIOM IV

In the referenced paper, Axiom IV is divided into two sub-axioms. Those axioms are discussed one after the other below.

Axiom IV a: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information.

In the first part of axiom IV a, it is stated that "sensors cannot measure damage." Although this is true, it should not be considered to be part of axiom because it the definition of a sensor. Sensors sense the response, they cannot measure damage. This is mentioned in the paper too "Sensors measure the response of a system to its operational and environmental input. Therefore, there is nothing surprising about the fact that sensors cannot directly measure damage." The second part of the definition is just a reiteration of the first part. Furthermore, not all methods of SHM follow feature extraction through signal processing and statistical classification to convert sensor data into damage information as discussed elaborately in the section 6. Therefore, second part of the axiom is a subset of Axiom AD2. It is suggested to drop this axiom from the list of axioms.

Axiom IV b: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions.

The axiom is confusing because intelligence or lack of it for feature extraction has nothing to do with sensing or assessing damage. In other words, there cannot be any relation between the feature extraction referred to in the first clause of the axiom and sensitivity of measurement referred to in the remaining two clauses. The feature extraction is a post processing step and it is different from sensing.

Though it is possible to conduct post processing through feature extraction using the same mechanism that does the sensing, they are two separate steps. An example of this can be seen through railroad tappers who inspect railroads for damages by tapping the railroads with a hammer. The railroad tapper first inspects the rail by tapping it with a hammer and listening to the noise of tapping (sensing) and then based on his experience, determines if the rail is damaged (post-processing). Even though both processes are conducted simultaneously by the same person, the sensitivity of the observations to changing environmental conditions remains independent of post processing.

Since sensitivity of measurement is not related to analysis of the measured data to find the damage, the first clause of the given axiom should be omitted. A proposed variation of this axiom is given in Axiom AD3.

Axiom AD3: "The more sensitive a measurement is to damage, the more sensitive it is to changing operation and environmental conditions affecting the sensitivity parameter."

10 AXIOM V

Axiom V: The length- and time- scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system.

Most of the literature in the area of SHM does state their preference to detect damage, which has evolved over a particular length- and time-scales. A counter example would be that there several damage measures that do not differentiate in damage detection whether a beam is damaged due to corrosion over a long period of time or if it is damaged due to impact. This fact is illustrated in the paper by Fryba and Pirner [2001]. In the beginning, the process is described to observe the structure. The observation procedure does not mention use of different sensors to take observations to detect damages that have evolved over a particular length- and time-scales.

A more direct example is given in the paper by Felber [1997]. Two vibration testing methods, Forced Vibration Testing(FVT) and Ambient Vibration Testing(AVT), are described here for conducting vibration tests on long span bridges. Both these methods are said to give similar results. These methods are not dependent on particular length- and time-scales that the damages have evolved over.

It may be helpful for the design of the sensing system if it is geared to a particular type of damage and it can be a desired characteristic for the ease of design of the sensing system. However, a desired characteristic cannot be an axiom, which is a fundamental truth about a field. Also, since it is stated in the paper that the sensing system should be as de-coupled from 'operating environmental and operational variability', it should be made as independent as possible from the source of type of damage to give the sensing system a truly generic nature.

Based on the counter examples given, it is recommended to remove the axiom V from the list of axioms.

11 AXIOM VI

Axiom VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability.

There is a contradiction in the above axiom. Through this axiom, Worden et al. suggests that the cost of raising an algorithm's sensitivity to damage is its noise rejection capability. However, if an algorithm is more sensitive to damage that means its noise rejection capability is actually high. The example given in that paper also does not corroborate the premise of the axiom. Actually, the example corroborates the opposite. The example that is given in that paper tries to demonstrate the axiom by artificially corrupting the data. It shows that 'higher noise leads to higher level of damage.' In figure 14 of that paper, it is shown that as noise level increases, only coarser damages are detected. For a noise to signal ratio of 0.1, only damages that have stiffness reduction of 30% are detected and for a noise level to signal ratio of 0.02, even damages which have stiffness drop of only 5% are detected, i.e. the sensitivity of an algorithm is decreasing with increasing noise level, but the relation between damage sensitivity and noise rejection capability of the algorithm has not been demonstrated.

To prove the above axiom it would be required to show that post processing algorithms that are more sensitive to damage detection are able to reject lesser amounts of noise and are therefore less sensitive to damage detection. It is not possible to show that the same algorithm is more sensitive and less sensitive, therefore, there is a contradiction in the above axiom. Due to the lack of evidence corroborating the axiom and the inherent logical fallacy, this axiom should be be removed from the set of axioms.

12 AXIOM VII

Axiom VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

As elaborately discussed in Axiom II, the baseline state is not required to detect damages. Therefore, ‘changes in system dynamics’ should be removed. The definition now reduces to:

The size of damage that can be detected using the system dynamics is inversely proportional to the frequency range of excitation.

The example that is given to prove this axiom does not relate to the axiom. The example shows, “how sensitivity to damage increases with increasing frequency.’ However, the axiom talks about the frequency range rather than frequency. Even if we consider that the word range was a mistake, the example shows that higher frequency gives higher sensitivity rather than higher frequency has lower sensitivity as asserted in the axiom. Finally, the effect of size of damage has not at all been addressed.

The author does feel that there is axiomatic relationship between frequency (and wavelength) and sensitivity of damage detection. However, any conclusion on the relationship should be valid both for vibration based and wave propagation based damage detection methods. As such, the axiom lacks generality that is required for an axiom. Based on the above reasons, it is proposed that axiom VII be dropped from the list of axioms.

13 CONCLUSION

In this paper, a novel and useful work by Worden et. al. in Worden, Farrar, Manson, and Park [2007] is critiqued. In general, new definitions were proposed for certain terms used in Structural Health Monitoring. The proposed definitions were of Structural Health Monitoring, damage, sensor, and post processor. A discussion was also presented to the axioms presented by Worden et. al. in Worden, Farrar, Manson, and Park [2007]. Some axioms are proposed to be modified and others are proposed to be dropped from the list of axioms. In essence, three axioms are obtained as the result of the discussion. The definitions and axioms presented in this paper are given below.

1. Structural Health Monitoring: The process of implementing a damage identification and characterization strategy with the eventual goal to predict the remaining life of a structure is referred to as Structural Health Monitoring.
2. Damage: Damage is the part of the state of a structural system that adversely affects the system's performance. The 'state of a structural system' is defined by its material properties, geometric definition (its layout in the global 3D coordinates) and its boundary conditions, frozen at an instant of time.
3. Sensor: A sensor is a device that measures a physical quantity and converts it into a signal that can be read by an observer or by an instrument.
4. Post processor: Post-processor: An algorithm, which processes the data obtained by sensors to categorize the system. In the case of structural health monitoring the system is the structural system and the categorization is if that system is damaged or undamaged.
5. Axiom AD1: Perfect material is theoretical construct and all materials need less energy to be damaged than the corresponding perfect material.
6. Axiom AD2 - A: The assessment of damage is dependent the definition of system performance parameters. The clarity of assessment is dependent on the clarity of the definition of the parameters.
7. Axiom AD3: The more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions affecting the sensitivity parameter.

The importance of the original paper is reiterated, since it was the first to come up with the idea of having axioms for the structural health monitoring. This paper attempts to serve as the next step in the evolution of comprehensive set of axioms for the field of SHM. The attempt here is to take the discussion regarding the axioms to the next level. More discussion regarding the ideas presented would help in obtaining a complete set of comprehensive axioms which may become the foundation for the development of theorems and laws for the field of SHM.

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which is very relevant to understanding of the meaning of axioms as it relates to this paper.

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