STRUCTURAL HEALTH MONITORING TECHNIQUES

Mr.CH.SANDEEP REDDY[1] , Mr.S.MAHESH[2], Mr.P. BIKKU[3], Mr.P M B RAJ KIRAN NANDURI[4]
Department of Civil Engineering, Samskruti College of Engineering and Technology

ABSTRACT

Structures are normal or special; these are precious part and are promptly associated with living as well as non living things. Sometimes minute fault inside the structure might affect whole body and it would lead to collapse the structure which might create a significant loss of property and human beings too. So, increased awareness of structural Health Monitoring Techniques (SHM) gives an idea and remedies for the concerned defect due to aging, deterioration and fault during construction. Previous day's people used just a visual inspection for defect detection but extreme and worst damage in infrastructure leads to invent new technologies for the recognition of new methods on Structural Health Monitoring as a damage detection tools. Different kind of sensors is linked with computer system along with special hardware and software which gives the signature and helps to point out the risk zone. This paper emphasis on wired and wireless techniques under which several sub techniques like Impedance-Based, Nondestructive Evaluation using vibration signature, Limit strain measurement, Data fusion method, Inverse method etc studied and their comparative study on the performance based approach for the infrastructure like Building, Bridges, Towers are noted which most likely concerned with civil infrastructure. This paper mainly emphasis on the presence of different SHM Techniques briefly on one paper which might give access for knowing it in a glance.

KEYWORDS: Structural Health Monitoring (SHM), Wired Technique, Wireless Technique, Computer System, Software, Risk Zone

INTRODUCTION

Civil infrastructures, which include bridges, buildings, pipeline, furnace and transition lines, begin to deteriorate once they are built and operated. Maintaining safe and non viable civil infrastructures for daily use is important to the well being of all of us. Knowing the integrity of the structure in terms of its age and operation, and its level of safety to withstand infrequent but high forces such as overweight trucks, earthquakes, tsunami, and hurricanes is important and necessary. The process of determining and tracking structural integrity and identifying the nature of damage in a structure is often referred to as health monitoring [1].

Quantitative and non-continuous methods was long been used to detect structures for checking their stability and risk zone. Nearly about the 19th century railroad wheel-tappers have used the sound of a hammer striking the train wheel to evaluate if damage was present [2]. In damage detection sector, different kind of research and innovation has been developed. In ancient time people used to find the defect on the structure or in any body by visual inspection and also by hitting the body with hammer and by the sound difference they used to predict the risky zone or defect inside the body or structure. In rotating machinery, vibration monitoring has been used for decades as a performance evaluation technique. Structural health monitoring techniques are widely used for detection of risky zone or faults or defects on the body whether it may be Building, bridges, steel structure like truss and towers, and also in the machines and in equipments like plane, trains etc. Wired techniques are mostly useful for the bodies which are small and in which the structure is physically in

ISSN: 2278-4632
Vol-12 Issue-09 No.02 September 2022

touch with the sensors whereas in wireless technique, the sensors are not in physically in touch with the structure. Revolution and movement of the several techniques gives new and precious methods for the damage detection. Basically Non-Destructive principle is the pin point and importance of it.

Wired technique is most widely used. In this intelligent parameter varying (IPV) technique uses PZT (Lead-Zeocronate-Titanate) patches are apply for determining the defect or risky zone on concrete structure and analytical study can be done with ANSYS 11.0 [3] Limit Strain Method is widely used in steel structure. All the private and governmental organization wants to detect damage on their products and the manufacturing structures for quality control, Best result, and for safety measures in earliest finish time. For example one steel company manufactures rolled steel sections for steel bridge, their earliest finish time of project was 24 months, Due to fault inside the rolled section, caused damage during the construction hence lengthen time of project, increment in cost occurs. Public safety is most concern in social infrastructures like Bridges, towers, Buildings. Clearly, such damage identification has significant life-safety implications. Also, there are currently no quantifiable methods to determine if buildings are safe for reoccupation after a significant earthquake. SHM may one day provide the technology that can be used to significantly minimize the uncertainty associated with such post-earthquake damage assessments. The prompt reoccupation of buildings, particularly those associated with manufacturing, can significantly mitigate economic losses associated with major seismic events. Finally, many portions of our technical infrastructure are approaching or exceeding their initial design life. As a result of economic issues, these civil, mechanical and aerospace structures are being used in spite of aging and the associated damage accumulation. Therefore, the ability to monitor the health of these structures is becoming increasingly important [4].

SHM is emerging engineering field that is lead by two main objectives 1) Safety and increasing performance 2) Commercial motivation and basis for condition-based maintenance, which are basically associated for fault detection, Fault identification, fault assessment, Fault monitoring and finally remaining lifetime evaluation or failure prediction.

TECHNIQUES OF STRUCTURAL HEALTH MONITORING

WIRED TECHNIQUE

When sensors are physically in contact with the structure/body on which we are going to investigate for damage detection, then such kind of technique is referred as wired techniques. Wired techniques are widely used from past and comes into present situation uses of smart sensors, fiber optics sensors, etc. Sensors and sensors characteristics depends on the location, Material, and methods applying to detect the flaws or faults. Generally Vibration based method, Impedance based method, Data fusion method, and inverse methods are used in wired techniques. Techniques are discussed below:

Impedance-Based Structural Health Monitoring Techniques

Electrical impedance is the measure of the opposition that a circuit presents to the passage of a current when a voltage is applied. With the help of resistance on current flow measured by the computer system installed with related software gives electric signature through which we can find out risk zone. By seeing, the non-destructive evaluation (NDE) technologies of concrete structures are relatively undeveloped. Furthermore, due to their extensive and complex nature, conventional NDE methods might be very tedious, expensive, or unreliable. Therefore, more reliable and automated NDE techniques are being investigated for real-time health monitoring of concrete structures. The structural health monitoring (SHM) research community is shifting their focus towards incorporating SHM technology into real world structures, and consequently compact hardware with low power dissipation become demanding feature for a SHM System [3]. At the first time the performance based practical study was done in self contained prototype which consist of digital signal processor(DSP) evaluate model and Analog to digital convertor and vice versa [5]. After analyzing the result, it successfully replaced other traditional methods and makes easy to detect risky zone on the structure.

Impedance based structural Health Monitoring system can be done by various ways like by Analogue and digital formats using PZT patches, Frequency variation approaches. This method of Structural Health Monitoring was done by 1. S. Park & S. Ahmad & C.-B. Yun & Y. Roh [6] 2. Kim, Benjamin L. Grisso, Dong S. Ha, and Daniel J. Inman [7] and others are uses for more precise detection tools. In this method it follows the main three operations: excitation signal generation, sensor actuation and sensing and finally damage detection.

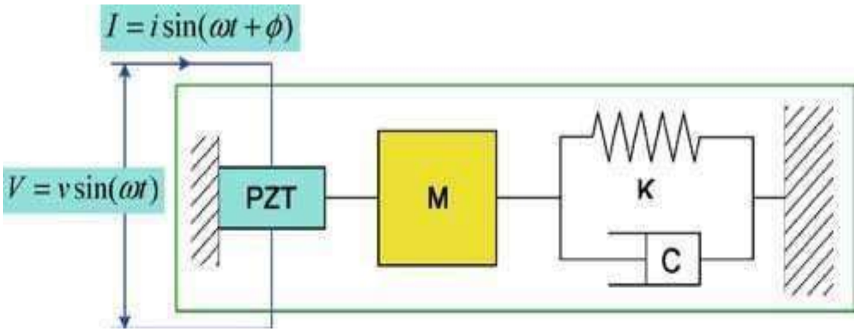

Figure 1: Electro- Mechanical Impedance System [8]

In Electro-Mechanical impedance, we can analyze both the results analytically as well as practically. In this study, a root mean square deviation (RMSD) in the impedance signatures of the PZT patches is used for damage indicator [8]. PZT is operated by giving the power which is assembled with electro-mechanical system. Then, the apparent electro-mechanical impedance of the PZT patch as coupled to the host structure is obtained as

$$Ztotal(\omega) = \left\{ j\omega \frac{wl}{s} \left[\frac{d_{3x}^2 Y_{xx}^E Z_{A(\omega)}}{Z_{A(\omega)} + Z_{s(\omega)}} \frac{\tan(kl)}{kl} + \varepsilon_{33}^T - d_{3x}^2 Y_{xx}^E \right] \right\}^{-1} \tag{1}$$

In equation (1), Mechanical impedance Z_A is the ratio of harmonic input voltage V(ω) to a current response *I*(ω). Zs represents the mechanical impedance, Fo(ω) is harmonic excitation force at an angular frequency ω to the velocity response $\dot{x}(\omega)$. By getting the apparent electromechanical impedance, by calculating RMSD then we can detect the risky zone. RSMD is impedance signature obtained and is used as an indicator. Which is calculated by knowing post damage signature Z(ωt) and with corresponding pre-damaged value Zo(ωt) [8]. Which is calculated is percentage and given by

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{i=N} \left(Z(\omega_i) - Z_0(\omega_i) \right)^2}{\sum_{i=1}^{i=N} \left(Z_0(\omega_i) \right)^2}} \times 100 \tag{2}$$

Another approach used in Impedance based SHM is System-On-Board approach. Almost Principle for getting a risk zone is same by calculating the RSMD but the only difference is in it miscellaneous components, such as resistors and an LED, are also included [3].

Data Fusion Technique

Data fusion techniques can combine data from multiple information sources and related information from associated databases to achieve improved accuracies and more specific inferences than by the use of a single source alone [9]. Some structure got damaged due to natural disaster like tsunami, earthquake and also due to explosives, at that moment structural component got damaged due to the vibration and other effects. Hence to detect exact and accurate zone of damaged zone data fusion technique is used. By reviewing all the techniques, principle for point out defect or risky zone is almost same. Researchers like 1) Guo and Zhang [10] regarded the changes of frequencies and mode shapes as two different information sources and used the data fusion method to detect the damage of two-dimensional truss structures [9]

ISSN: 2278-4632
Vol-12 Issue-09 No.02 September 2022

and 2) Bao and Li [11] 3) Basir and Yuan[12] described the about decrease the uncertainty and increase accuracy and multi sensor implementation.

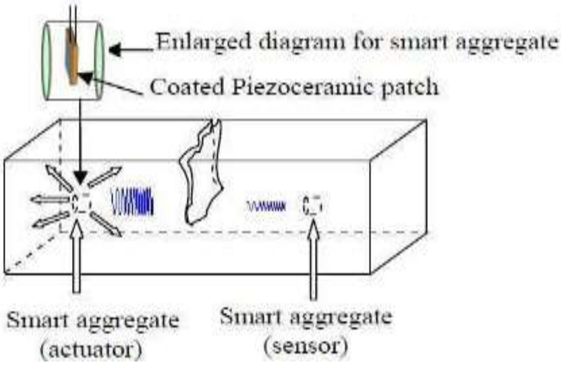

Figure 2: Smart Aggregate Based Active Sensing System [9]

Here damaged index can be computed by calculating the RSMD between the energy vector of healthy and damaged state. Where energy vector of healthy and damaged data are distinguish by, Energy vector of healthy structure [$E_h= E_{h,1},E_{h,2}\ldots..E_{h,2^n}$] and Energy vector of damaged structure is [$E_i= E_{i,1},E_{i,2}\ldots..E_{i,2^n}$] and hence the damaged index at time 'i' is defined as[9]

$$I_t = \sqrt{\sum_{j=1}^{2^n}(E_{i,j}-E_{h,j})^2 \Big/ \sum_{j=1}^{2^n}(E_{h,j})^2} \qquad \ldots\ldots\ldots\ldots(3)$$

This technique is mainly based on Dempster-Shafter D-S evidence theory. And fusion damaged indices were determined by the displacement of graph plotted by the help of PZT patches and hence cracks were detected.

Vibration Control Technique

Stochastic Subspace-Based Fault Detection Method (SSFD) used in France, Inverse Technique, Time domain method, Frequency domain method these techniques were used in vibration control technique. According to Rytter, there are 4 levels on the damage assessment scale, where the information about the damage is increased from step to step: Level I: Damage detection; Level II: Damage localization; Level III: Damage quantification and Level IV: Prognosis of remaining service life [13]. Guangzhou new TV tower of 601 m height uses an integrated vibration control technique [14] for detecting the risky zone on the GNTV Tower; modular design concept had been applied. Which were previously practices in long span bridge of Hong Kong (2009). This concept comprises six modules those included data sensing, Acquisition, processing, management and finally monitoring.

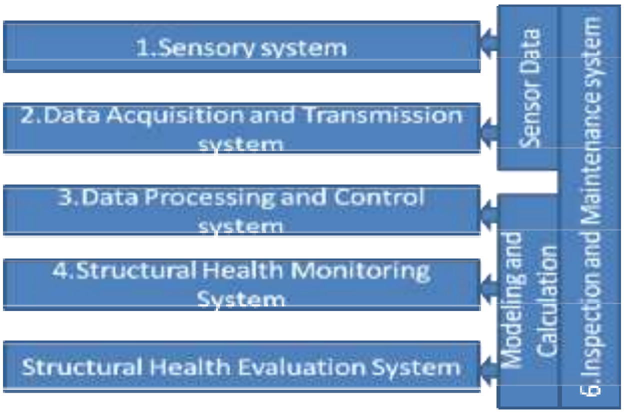

Figure 3: Module of SHM System for GNTV Tower [14]

Sensory System (SS) are deployed for monitoring of three categories of parameter, 1) Loading 2) Environmental effect and 3) Structural response. Which was possible because practice was implemented by placing 800 sensors in different location to collect signal of the proposed structure and digitize the analogue signals which transfer into digital data hence monitoring can be easy. Vibration is critical on structure, for the control of vibration along major and minor axis we have to apply Active mass damper (AMD) along with Tuned mass damper (TMD). But is case of major axis, vibration is control by TMD because AMD will be activated only if wind speed crosses the predefined threshold. By observing this method, Monitobahs golden boy statue also monitored using SHM vibration technique and also by Finite element approach too [15]. The Dynamics of a general non-linear, time varying, damaged structure are described by 1) spatially discrete and coupled system of non-linear equation of motion. 2) The non-linear evolution of damage [13] which is governed by

$$M(\theta_d, \theta_e, x, t)\,\&x\& + g(x, x\&, \theta_d, \theta_e, t) = f(t, \theta_d, \theta_e) \quad (4)$$

$$\theta\&d = \Gamma(\theta_d, \theta_e, x, x\&, t) \quad (5)$$

$$y(t) = h(\theta_d, \theta_e, x, x\&, t) \quad (6)$$

Where M represents the mass matrix, g is the force vector of elastic forces depending on displacement, velocity and time (x, $\dot{x}$ and t). These equations describe the non-linear function (Γ) of evolution of damage parameter (θ_d) and environmental effect (θ_e). θ_e are assumed to be constant during vibration data acquisition[13]. Generally Vibration based SHM approach to damage identification are 1) Model approach 2) Eigenfrequencies 3) Eigenfrequencies and mode shapes 4) Model force residual 5) Minimum-Rank Pertubation Technique (MRPT) 6) Model curvatures and model energy expression 7) output residual method 8) input residual method 9) Frequency response function 10) Projected input residual method 11) Antiresponses 12) Tranmissibilities 13) impedance method 14) Time domain method 15) Stochastic Subspace-Based Fault Detection Method (SSFD) [13].

WIRELESS TECHNIQUE

Spatially distributed autonomous sensors to monitor physical information without physically in contact with particular object, but by the help of data received from it, can analyze several important features. Structural health monitoring using wireless technique invents presently and it requires a High resolution images or data. Wireless sensors can be used to detect the defect within the buildings, bridges, embankments, and tunnel. Basically on SHM it is applicable to simulate load carrying capacity, fatigue resistance, Vibration control for the structure and finally for crack detection. Wireless SHM is important mainly for large structure where wired techniques spend more time as well as fund, but it performs a whole detection at once hence time saving as well as fund too. Generally it is most useful on bridge structure. Active and passive sensors are used to capture data and are evaluated with the help of special computer system along with software like Arc GIS. In the conventional SHM system, the expensive cost for purchase and installation of the SHM system components, such as sensors, data loggers, computers, and connecting cables, is a big obstruction. To guarantee that measurement data are reliably collected, SHM systems generally employ coaxial wires for communication between sensors and the repository. However, the installation of coaxial wires in structures is generally very expensive and labor-intensive [16].

Wireless techniques are mainly associated with to find out the ground information like land use and land cover, possible urban area, solid waste disposal site selection, possible best way for roads etc. Comes into the structural health monitoring, it’s not that much in use in past decade, after finding out the sensors which captures a high resolution images, then it comes into use.

Smart Wireless Technology

Smart wireless sensor is an emerging sensor with the following essential features: on-board micro-processor, sensing capability, wireless communication, battery powered, and low cost (Nagayama, 2007). When many sensors are implemented on a SHM system for a sizable civil structure, wireless communication between sensors and data repository seems to be attractive in the aspects of the cost [16].

For the improvement in SHM techniques, new sensors are developed. Different sensors system like Micro-electromechanical system (MEMS), Nuclear magnetic resonance (NMR) for accelerometers and to detect chloride ions are used for the detection of defects [17, 18]. These sensors are typically targeted to monitor specific defect like concrete cracking, bridge breaking, and steel reinforcement corrosion [17], this is one major defect of wireless technique.

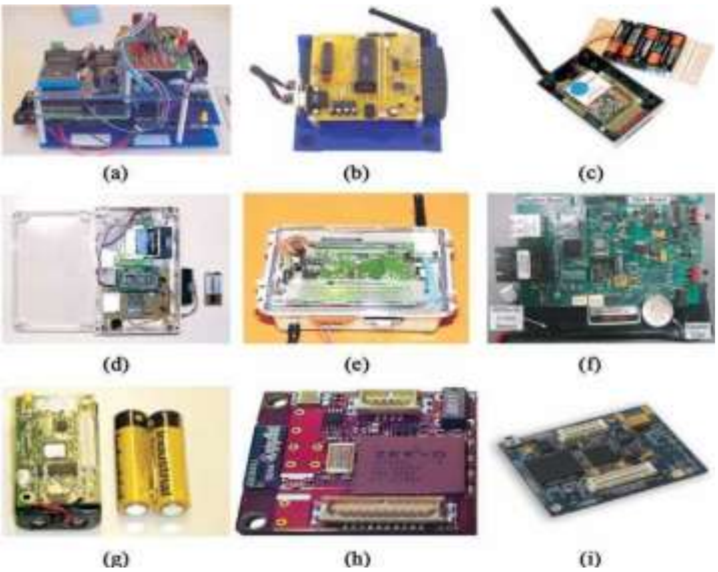

Figure 4: Various Wireless Sensors Prototypes (a) WiMMS b) WiMMS c) WiMMS d) RIMS e) Husky f) Dura-Node g) MICAZ Node h) Imote (Intel) i) Imote2 (intel))[23]

Wireless smart sensor are cost and time effective [23]. For e.g. It has been found that on Bill Emesion Memorial Bridge in the U.S. is instrumented with 84 wired accelerometers with an average cost of $ 15,000 per channel and the cost of the SHM system with 350 sensing channels on Tsing Ma Suspension Bridge in China has exceeded $8 million[19] and along with maintenance charge.

Revolution on wired technique invents wireless smart sensors hence find new solution for economical aspect. Radar technology, robust techniques largely depends on the incident rays, absorbed, transmitted and reflected rays. Robust technique uses X-rays and gamma-rays to get visual images of interiors of structures such as steel cables, slabs etc. Increase in research due to challenging environment, different techniques comes into practice in civil, mechanical, aerospace field.

Straser and Kiremidjian, first proposed a design of a low-cost wireless modular monitoring system (WiMMS) for civil structures by integrating a microcontroller with a wireless radio. Lynch et al. have improved the WiMMS with emphasizing the power of the computational core [18] The WiMMS platform has been improved further by Wang et al [20] with implementing software which allows multiple threads [17] This system was based upon the decentralized system, which was used by Gao and Spencer [21] based upon vibration –based detection algorithm. And in present damage detection reported to the base station in sleeping mode [17] which was shown in figure.

ISSN: 2278-4632
Vol-12 Issue-09 No.02 September 2022

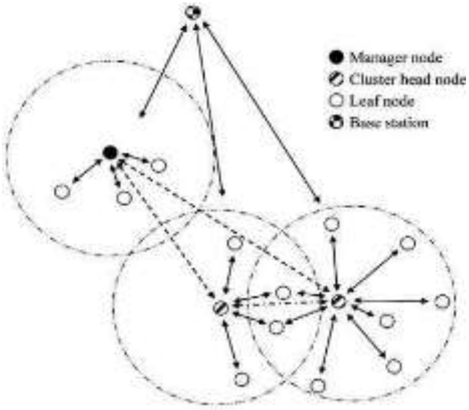

Figure 5: System Architecture [17]

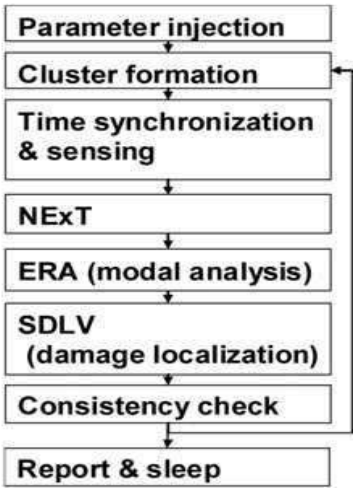

Figure 6: Implementation Flow Chart [17]

COMPONENT OF STRUCTURAL HEALTH MONITORING SYSTEM (SHM)

Different Types of SHM Systems have same components but we may find the variation in integrated algorithm on the software, hardware used on the system and finally the sensor type. But overall component and the process of performing work in same series like Sensing data from specified structure/body, analog data digitize and transform into the system finally system software analyze the data in digital format as a graphical or in attribute form. Hence through variation of the data finally gives clue to detect risky zone or detect zone.

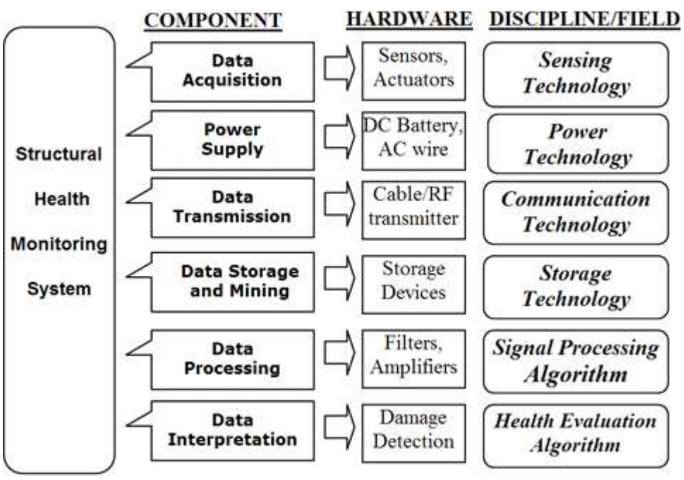

Figure 7: Component of Structural Health Monitoring (SHM) Techniques

The component on wired as well as in Wireless Techniques are almost same but only difference is position of sensor, but overall theme is to monitor the health of structure.

EFFECTIVENESS AND REQUIREMENT OF SHM

Although in civil engineering structure Bridge was the first on which SHM used for damage detection, vibration control and to locate risky zone [15]**.** SHM is not limited within civil engineering. Its application field increases its demand.

Due to age factor and environment factor, Structure gets deteriorated and steel structures got corroded. Due to that reason, structures strength decreases regarding serviceability and load bearing approach. For detecting it several techniques investigated and researchers still doing for up gradation. Although SHM techniques can be used in several structure like beam [22] shell [23] and in pipeline also. Using those techniques on such a structure enhances to up gradation for the effective efficiency as well as secure public service.

Due to increasing cost for inspection and the demand of periodic investigation of defect on the structure, previous maintenance concept of periodic inspection is no longer in use. Thus present SHM techniques is seeking the use of intelligent powerful data acquisition unit and a fast and direct monitoring and maintenance planning concept is required [24].

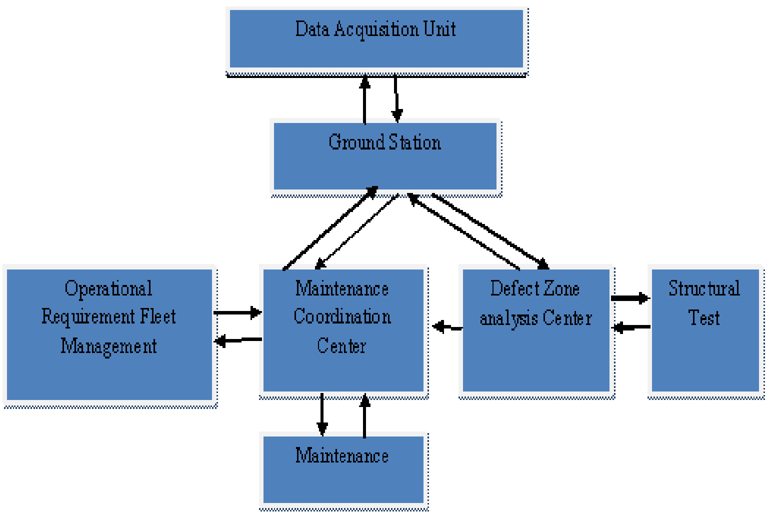

Figure 8: Requirement Proposal for Modern SHM [24]

COMPARISION AND DISCUSSIONS

There are number of system existing on the market which allows detecting strain, temperature effect, moisture and overall risk zone, flaw/faults on the structure. Different types of structural health monitoring techniques have their own advantage and limitations. As a technician, we have to look for cost effective, precise and accurate methods. The state of structural system subjected to those physical and climatic processes is changing continuously. The condition of the structure may not predict without considering both aleatory and epistemic uncertainties. So, it is possible if we monitor structure in periodic sequence, through it we have to consider the techniques which give standard and believable result in terms of structural integrity and economic approach [25] Uses of vibration control techniques, impedance based approach leads higher cost and for periodic monitoring installation charge may add up but through these techniques we can get accurate result. Comes to the smart wireless a technique, it’s considered as cost effective but the result obtained through it is not that much accurate in comparisons of wired techniques. The comparisons are mentioned below:

 ISSN: 2278-4632
Vol-12 Issue-09 No.02 September 2022

Table 1: Comparison between Wired and Wireless Techniques

Wired Technique	Wireless Technique
Sensors are physically contact with structure hence expectation for determination of exact position of fault/flaws.	Sensors are not in physically contact with structure hence fault/flaw/risk zone detection is expected to be not that much precise
More number of sensors is needed because sensors are particularly sensed up to the specific region designed by the manufacturer.	Number of sensors is minimized in case of these techniques.
Sensors can be used for various materials. For e.g. if sensors are used for detecting flaw in concrete structure it can used in Steel structure also.	In case, here one sensor is limited to one material only. For e.g. if one smart sensor are invent to detect flaws/fault on concrete structure it can't sense of steel structure.
It is old techniques, which gives bases for further innovation of sensors, and detecting technology. Through this, Sensors are directly connected with system and the signals whether it is vibration or acoustics, regular signature will obtained and with specific paradigm fault/detection can detected.	This is emerging new technique in which, Sensed data is recorded and is analyzed in system in which embedded algorithm for specific material would be made, through which acoustic emission, X-ray signature is obtained and hence can detect fault/flaws.
Little bit Costly techniques because if we need to detect, we have to install is periodically.	Initial cost is higher but in life time analysis, cost becomes less and regular monitoring can achieved.

Table 2: Different Structural Health Monitoring Techniques General Discussion

SHM Techniques	General Discussion
Impedance based SHM techniques	Working principle is supplying electricity power, sensing through PZT patches, hence through the help of signature obtained, we can able to detect, monitor and giving the best solution option.
Data Fusion techniques	Used principle in this technique is same as in Impedance based approach but in this process of integrating data and knowledge representing the same real world object in consistent, accurate, and useful representation. Situation awareness, user refinement, and mission management, Finally finding RMSD is the way of detection defect/fault [26].
Vibration Control Technique	Mostly used technique from ancient time, is depends on Vibration applied from the sensors, Damping, and signature getting from system. Difference shown in signature through system can help to predict the defect/risk zone on the structure. Care should be taken in it, due to vibration structure may further damage.
Acoustic emission (AE) Technique	Used to diagnostic of overall structural integrity, detection, location, identification and assessment of flaws/faults. It is continuous or periodic monitoring used in wireless and wired technology. In this echo of sound is measured.
Smart sensors wireless technology	Recent development and applications of smart sensors and sensing systems have a wide area of structural health monitoring including Optical Fiber Sensors (OFS), piezoelectric sensors, smart wireless sensors, and vision-based displacement measurement systems. They have been developed to complement the limitations of the conventional sensors such as electric resistance strain gauges, wired accelerometers, and extensometers, and to measure new types of structural characteristics such as electromechanical impedances and guided waves [25] Many Research are doing corresponding to Wireless smart sensing system for full scale structure.

By Reviewing number of paper related to SHM techniques, moreover root-mean-square deviation (RSMD) is commonly used [6, 8, 9]. By this damage index we can able to compare the difference of healthy and damaged structure.

RESULTS

The established SHM have proven the well defined effort on the sustainability and safety of the structure and have forecasted the greater possibility in monitoring and control of structural damage and reduce the incidental loss of lives making the SHM necessary in the life structures like Bridge and Towers.

By reviewing journals of SHM, the fact found is four step processes 1) Operational evaluation 2) Data acquisition, normalization and cleansing 3) Feature selection and information consideration and 4) Statistical model development for the feature determination is common for all the techniques [13]. By following these steps, apart from simple structure such as axial rods [27], beams [22], thin plates [28], shell [23] and framed structure [29], experimental implementation of the SHM techniques can be applied on several complex structures. In present Days Structural health monitoring techniques for Pipeline are in the research phase for getting higher efficiency to damage detection.

ISSN: 2278-4632
Vol-12 Issue-09 No.02 September 2022

Talking about the efficiency that sensors can give the data for probable damage detection is much concern about the number, area covered by sensor and the type of material that structure is built. For choosing the SHM techniques first its need to collect the features like material used, efficiency required and area that need to be sensed of structure has to be noted and the cast outflow for the corresponding work should be determined. Wired techniques seems to be used in large scale than wireless techniques because of its popularity and its efficiency, among wired technique Vibration based approach and acoustic emission approach more commonly used than wireless techniques.

CONCLUSIONS

SHM as a whole in present has lots of benefits regarding the safety and sustainability, but there is a need of improvement and further research to establish the effective and advance technique in SHM. Whatever the methods and systems that are discussed above speaks the requirement of regular inspection and use of expensive instruments in the detection and identification of the damage in the structures. So there is need of cost effective and more efficient techniques in SHM for its revolutionary implementation and make the world better. Remarkable improvement on the sensors like one sensor can be used for different materials is needed. For periodic monitoring, wired techniques have a difficult for installation and hence such kind of system is needed though which we can monitor structure in regular time interval. From the review of different techniques, newly emerging wireless techniques have a more scope in terms of economic aspects, time constraint and easiness although several research are carried out in both the methods and remarkable diminutive amendments on the system, software algorithm was found. Still if we do research for a SHM like as remote sensing, for it higher resolution image is needed and it will add up new resolution in from all aspects of life time assessment. Indeed SHM systems are more important day by day especially on public structures like Bridge, Towers, Transportation means for the human safety and environmental sustainability approach too.

REFERENCES

1. Peter C. Chang, Alison Flatau and S. C. Liu (2003),“ Review Paper: Health Monitoring of Civil Infrastructure”, *SAGE Publication, Vol 2(3): 0257–267*
2. Dawson, Brian (1976). "Vibration condition monitoring techniques for rotating machinery". *The Shock and Vibration Digest* (London: SpingerLink) **8** (12): 3
3. Jina Kim, Benjamin L. Grisso, Dong S. Ha, and Daniel J. Inman (2007), “A System-On-Board Approach for Impedance-Based Structural Health monitoring”, *Proc. of SPIE,* Vol. 6529
4. Charles R Farrar and Keith Worden (2007), “An introduction to structural health monitoring”, *Philosophical Transaction of Royal A Society,* 365, 303–315 doi:10.1098/rsta.2006.1928
5. B.L. Grisso and D.J. Inman,(September 2005) “Developing an Autonomous On-Orbit Impedance-Based SHM for Thermal Protection Systems,” *International Workshop on Structural Health Monitoring,* pp. 435-442
6. S. Park & S. Ahmad & C.-B. Yun & Y. Roh (2006), “Structural health monitoring using electro-mechanical impedance sensors”, *Fatigue & Fracture of Engineering Materials & Structures,* doi: 10.1111/j.1460-2695.2008.01248.x
7. Benjamin L. Grisso, Jina Kim, Justin R. Farmer, Dong S. Ha, and Daniel J. Inman (2007)”, A system -on-board impedance based approach for structural health monitoring”, *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems,* SPIE 6529 doi:10.1117/12.715791

8. S. Park & S. Ahmad & C.-B. Yun & Y. Roh,(2006), "Multiple Crack Detection of Concrete Structures Using Impedance-based Structural Health Monitoring Techniques", *Experimental Mechanics* , 46: 609–618

9. Xiukuan Zhao, Haichang Gu, Gangbing Song, Y L Mo, Jinwu Xu, (2010), "Structural health monitoring with data fusion method", *Earth and Space 2010, ASCE*

10. Guo, H., and Zhang, L. (2006). A weighted balance evidence theory for structural multiple damage localization. *Computer Methods in Applied Mechanics and Engineering,* 195, 6225-6238.

11. Bao, Y., and Li, H. (2007). Application of information fusion and Shannon entropy in structural damage detection. *In: Health Monitoring of Structural and Biological System*s 2007, San Diego, California, USA. SPIE, 65320U-9.

12. Basir, O., and Yuan, X. (2005). Engine fault diagnosis based on multi-sensor information fusion using Dempster-Shafer evidence theory. *Information Fusion,* 8, 379-386.

13. Claus-Peter Fritzen, (2005 Sep 15), "Vibration-based Structural Health Monitoring – Concepts and Applications" , *Trans Tech Publications, Switzerland,* Vols. 293-294, pp 3-20

14. Y. Q. Ni and H. F. Zhou,(2010), "Guangzhou New TV Tower: Integrated Structural Health Monitoring and Vibration Control", *Structures Congress © 2010 ASCE*

15. Aftab A. Mufti (19 August 2003), "Restoration and structural health monitoring of Manitoba's Golden Boy" *Can. J. Civ. Eng.* Vol. 30

16. Soojin Cho, Chung-Bang Yun, Jerome P. Lynch, Andrew T. Zimmerman, Billie F. Spencer Jr., and Tomonori Nagayama (2008), "Smart Wireless Sensor Technology for Structural Health Monitoring of Civil Structures", *Smart Wireless Sensor Technology for Structural Health Monitoring of Civil Structures*, Steel Structures 8 (2008) 267-275

17. Adrian Oth and Matteo Picozzi, "Structural HealthMonitoring UsingWireless Technologies: An Ambient Vibration Test on the Adolphe Bridge, Luxembourg City", *Hindawi Publishing Corporation Advances in Civil Engineering*, Volume 2012, Article ID 876174, 17 pages

18. Lynch, J. P., Law, K. H., Kiremidjian, A. S., Kenny, T. W., Carryer, E. and Patridge, A. (2001). "The design of a wireless sensing unit for structural health monitoring," *Proc. 3rd Int'l Ws. Structural Health Monitoring*, Stanford, CA, September 12-14.

19. Farrar, C. R. (2001). "Historical overview of structural health monitoring. Lecture notes on structural health monitoring using statistical pattern recognition." *Los Alamos Dynamics*, Los Alamos, USA.

20. Wang, Y., Lynch, J. P. and Law, K. H. (2005). "Validation of an integrated network system for real-time wireless monitoring of civil structures," *Proc. 5th Int'l Ws. Structural Health Monitoring*, Stanford, CA, September 12-14.

21. Gao, Y. and Spencer Jr., B. F. (2008). "Structural health monitoring strategies for smart sensor networks," *Newmark Structural Engineering Laboratory report Series* 011

22. V. Giurgiutiu and A. N. Zagrai (2002), "Embedded self-sensing piezoelectric active sensors for on-line structural identification," *Journal of Vibration and Acoustics*, vol. 124, no. 1, pp. 116–125

23. Y. Yang and Y. Hu (2008), "Electromechanical impedance modeling of PZT transducers for health monitoring of cylindrical shell structures," *Smart Materials and Structures*, vol. 17, no. 1, Article ID 015005

24. M. Neumair (1988), "Requirement on Future Structural Health Monitoring Systems", *Paper presented at the RTO AVT Specialists' Meeting on Exploration of structural Loads/Health data for Reduced Life Cycle cost*, Held in Brussels Belgium

25. Chung-Bang Yun and Jiyoung Min (2011), "Smart Sensing, Monitoring, and Damage Detection for Civil Infrastructures", *KSCE Journal of Civil Engineering* (2011) 15(1):1-14 DOI 10.1007/s12205-011-0001-y

26. Erik Blasch, Ivan Kadar, John salerno, Miecyslaw kokar, Subrata Dase, Gerald powell, Daniel Corkill and E Euspinni (2006), " Issues and challenges in situation assessment*",Journal of advance in information fusion.*

27. G. Park, H. H. Cudney, and D. J. Inman (2000), "An integrated health monitoring technique using structural impedance sensors,"*Journal of Intelligent Material Systems and Structures*, vol. 11, no. 6, pp. 448–455

28. G. Park, C. R. Farrar, F. L. Di Scalea, and S. Coccia (2006), "Performance assessment and validation of piezoelectric activesensors in structural health monitoring," Smart Materials and Structures, vol. 15, no. 6, pp. 1673–1683

29. D. L. Mascarenas, M. D. Todd, G. Park, and C. R. Farrar (2007), "Development of an impedance-based wireless sensor node for structural health monitoring," *Smart Materials and Structures*, vol. 16, no. 6, pp. 2137–2145