Structural Health Monitoring of Offshore Structures Using Wireless Sensor Networking under Operational and Environmental Variability

Srinivasan Chandrasekaran, Thailammai Chithambaram, Shihas A. Khader

Abstract—The early-stage damage detection in offshore structures requires continuous structural health monitoring and for the large area the position of sensors will also plays an important role in the efficient damage detection. Determining the dynamic behavior of offshore structures requires dense deployment of sensors. The wired Structural Health Monitoring (SHM) systems are highly expensive and always needs larger installation space to deploy. Wireless sensor networks can enhance the SHM system by deployment of scalable sensor network, which consumes lesser space. This paper presents the results of wireless sensor network based Structural Health Monitoring method applied to a scaled experimental model of offshore structure that underwent wave loading. This method determines the serviceability of the offshore structure which is subjected to various environment loads. Wired and wireless sensors were installed in the model and the response of the scaled BLSRP model under wave loading was recorded. The wireless system discussed in this study is the Raspberry pi board with Arm V6 processor which is programmed to transmit the data acquired by the sensor to the server using Wi-Fi adapter, the data is then hosted in the webpage. The data acquired from the wireless and wired SHM systems were compared and the design of the wireless system is verified.

Keywords—Condition assessment, damage detection, structural health monitoring, structural response, wireless sensor network.

I. INTRODUCTION

STRUCTURAL HEALTH MONITORING (SHM) is a typical domain of study where the application of wireless sensor networks is useful to quantify the damages as soon as they are identified. SHM is commonly used for damage detection of aerospace, civil, and mechanical systems. This process involves a periodic observation of the system over a period in a spaced measurement. Structural health of the system can be determined through the statistical analyses of variables that are damage-sensitive [1]. Successful applications of Wireless Sensor Network (WSN) in the recent past for structural health monitoring encourage the attempt on an offshore platform, which is novel [2]-[7]. Fiber optic sensors and piezoelectric sensors are successfully used for monitoring vibration responses in damaged structures [8], [9]. One of the important challenges of application of WSN to offshore platforms is the non-stationary response with continuous changes of mass and stiffness characteristics through structural modifications, loading or unloading, wave

Srinivasan Chandrasekaran, Thailammai Chithambaram and Shihas A. Khader are with the Indian Institute of Technology Madras, Chennai, India, 600042 (e-mail: drsekaran@iitm.ac.in, thailammaict@gmail.com, shihaskhader@gmail.com).

loads and other loads that arise during processing and drilling operations [10]. Health monitoring of offshore platforms are advantageous due to several reasons: i) minimizing economic loss of the unit; ii) improving Health, Safety and Environmental (HSE) conditions of the platform; iii) reducing environmental pollution that arise from accidental oil spills etc.; iv) reduction in cost and installation time; v) effective traceability of network failure; and vi) initiating a preventive maintenance culture in place of post-damage repairs [11]-[13]. Due to the high level of complexity of electro-mechanical system and their interference with the structural geometry, monitoring through wired sensors shall result in inefficiency as their failure in connection becomes untraceable [14]. Dense array of smart sensors shall be more effective in monitoring the health of structures [15]. In addition to the above, an average cost of a wired sensor network for hull monitoring is quite expensive. Information of the variable (in the present case, it is structural response of the deck under lateral loads) is gathered by the array of sensors; array layout is optimized in terms of its distance, cost, location and scalability to obtain the maximum possible response of the structure. This study has the forecasted analysis on design and system architecture of SHM over raspberry pi. Actual implementation will have to be experienced.

II. WIRELESS SENSOR SYSTEM WITH PIC MICROCONTROLLER AND ADXL335

A. Hardware Configuration of Wireless SHM System

Fig. 1 shows the wireless sensor module deployed in the present study. Sensing and processing board consists of an accelerometer, micro processing unit and a wireless transmitter. As miniaturization and the lightweight design are necessary for increasing the applicability, accelerometer ADXL335, which is based on MEMS technology have been used. Lead-Acid, rechargeable battery MR645 6V, 4.5Ah battery is connected to a 25V-1000 µF capacitor, which in turn is connected to the transformer; power supply of 5V input is regulated through IC 7805. The chosen accelerometer, ADXL335 is a tri-axial model and compact in shape, size and weight having signal-conditioned voltage outputs. It is a poly-silicon, surface-micro machined sensor and signal conditioning circuitry, which is adaptable to open-loop acceleration measurement architecture. It is capable of measuring dynamic acceleration that results from shock or vibration and measures with a minimum full-scale range of

±3g. Offshore platform model, chosen for the present study has lower natural frequencies; a bandwidth of about 50Hz is seen to be sufficient for measuring the dynamic response. Chip used on board is well protected from harsh environmental conditions by a cover. The micro-processing unit on board gathers pre-processed analog and digital outputs from the detection units; processed data is then fetched to the wireless transmitting unit. The micro controller unit used in this experiment is a Pic16f778A microcontroller, which integrates a large storage memory and interface circuits. Storage memory is 256 bytes of enhanced ROM (EEPROM) with self-programming capability of an 8-bit high performance CPU. Interface consists of 5 channels of analog-digital converter (ADC), two timers to control the start and end of data acquisition and a synchronized serial port. As the data communication between the server and the base station is vital, wireless transceiver of 2.4GHz is connected to the computing core. As the communication distance between the sensor node and the server increases, power consumption would also increase proportionately. Hence, wireless transmission in the present design is based on IEEE 802.15.4 ZigBee application. While it operates on 2.4 GHz frequency, wireless receiver unit is connected to a COM port of a PC through a Serial-USB converter.
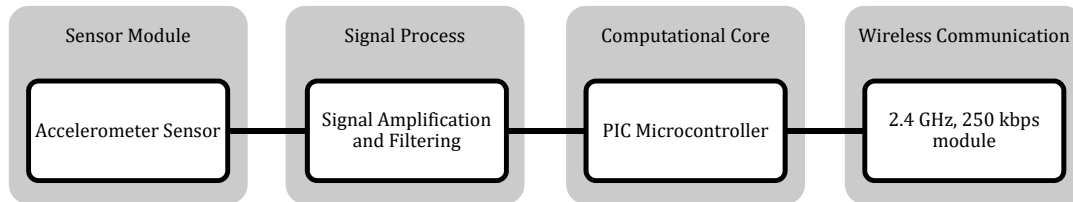

Fig. 1 Wireless Acceleration Sensor Module

B. Experimental Investigations

Structural health monitoring is attempted on a scaled model (1:150) of a Buoyant Leg Storage Regasification platform (BLSRP) under regular waves. BLSRP is relatively new type of offshore production and regasification platform that rests on buoyant legs, which in turn are connected to the sea bed using taut-moored tethers. The chosen platform has a high degree of compliancy in horizontal plane (motion in horizontal plane are not restricted) while it is relatively stiff in the vertical plane motion. The platform consists of a deck that is supported on buoyant legs, which acts as a storage unit. Liquid Natural Gas (LNG) floating storage and regasification unit receives LNG from the offloading LNG carriers. Regasification is carried out onboard and only natural gas is exported to shore through risers and pipelines. While the attempted design of BLSRP is also relatively new [16]-[18], SHM of the platform is a novel attempt made through the present study. Fig. 2 shows the scaled model of BLSRP and the sensor board placed on board. Wired and wireless sensors are placed on the scaled model to compare the acceleration of the deck, acquired from both the modes.
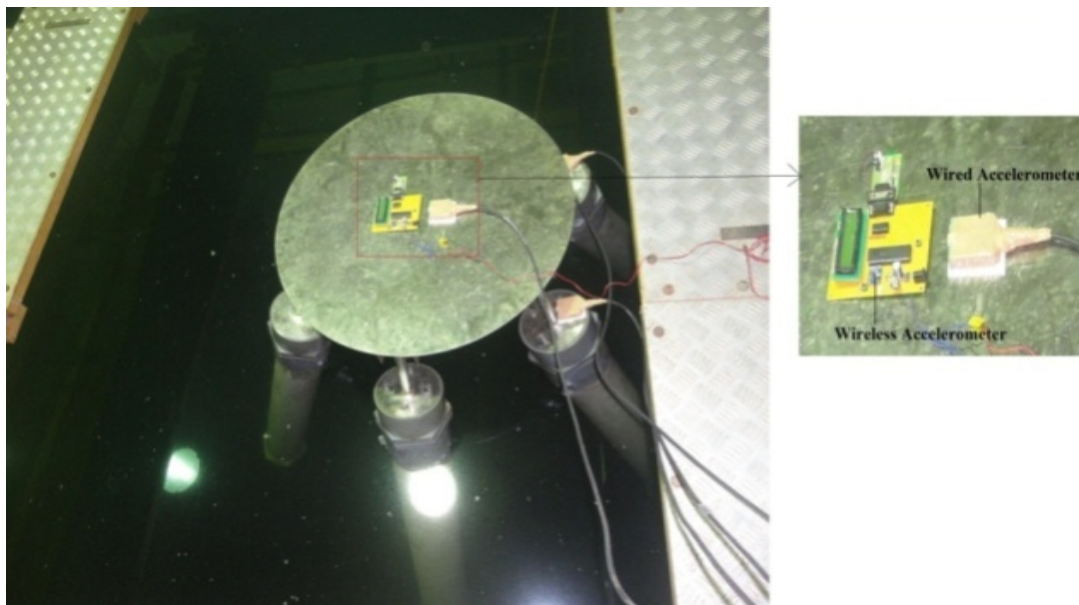

Fig. 2 Experimental Model and the sensor board with PIC-Microcontroller and ADXL335

As seen in Fig. 2, wired and wireless accelerometers are placed with a minimum separation of few millimeters at the centre of the deck. The model is excited by 10 cm regular wave of different wave periods ranging from {1.2, 1.4, 1.6, 1.8, 2. s}. Data acquisition of the wireless and the (referenced) wired sensors is carried out simultaneously.

C.Discussion of Results

Accelerometer readings acquired through both the wired and wireless sensors are plotted in Figs. 3 (a) and (b), respectively. Detailed analyses carried out on the acquired data showed that the maximum value of the wired sensor is 0.62716 m/s^2. With due consideration to the time delay, corresponding maximum value of the wireless sensor is found to be 0.654 m/s^2 while the overall maximum value is 0.817 m/s^2. Maximum value acquired from wireless sensor does not match with that of the wired ones due to the noise ratio in the device and differences in the sensitivity of both the devices. Considering the maximum value of wired and wireless accelerometer, error value calculated is 4.2% while the peak signal to noise ratio is about 9%.

Power Spectral density of the data acquired by both the type of sensors is plotted as shown in Figs. 4 (a) and (b), respectively. By comparing the figures, it is seen that there exists a few mismatch between the wired and wireless accelerometer data. This difference is attributed to many factors namely:

i)   delay caused in the transition time;
ii)   due to noise in the wireless sensor data;
iii) difference in sampling rate; and
iv)   sensitivity and difference in the measuring methods.

It is interesting to note that the above differences essentially arise due to the characteristics of the sensor device and not due to the system architecture adopted for the acquisition. The difference in the PSD magnitude is mainly caused by the different sampling frequencies used in the two systems. The qualitative value of the acquired data does not change significantly, this strengthens the adopted architecture of WSN for health monitoring of offshore platform, used in the current study.
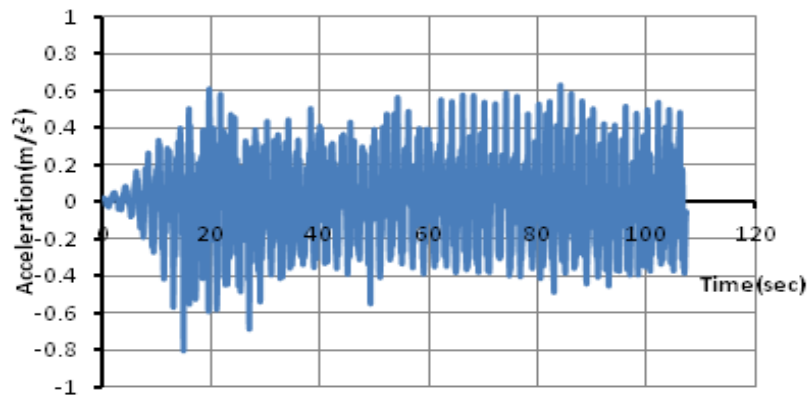
(a)
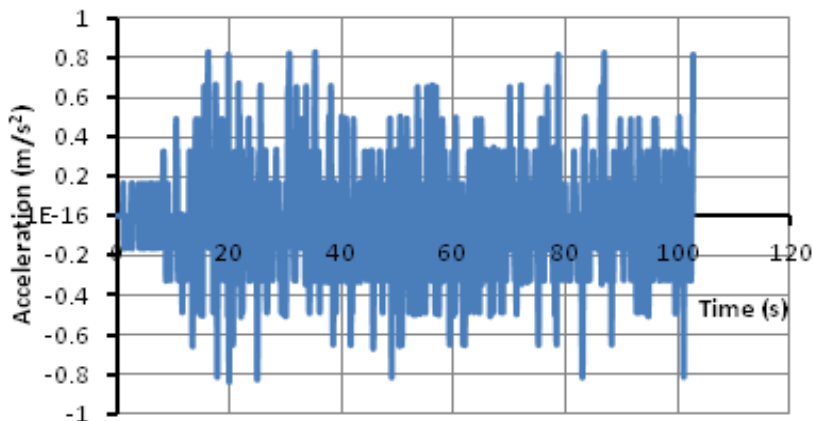
(b)

Fig. 3 a) Acceleration data of wired sensor, (b) Acceleration data of wireless sensor
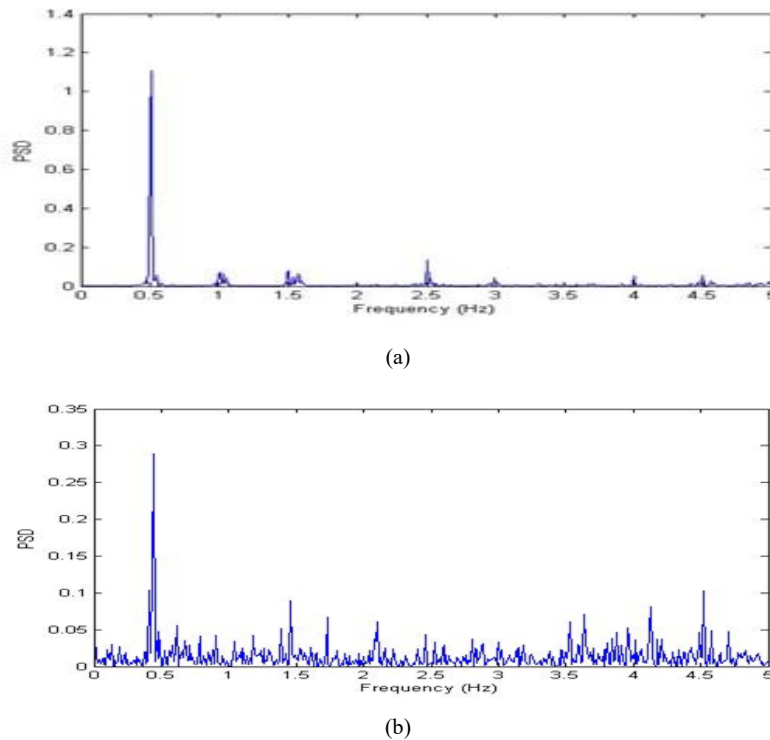
(a)

(b)

Fig. 4 (a) Power spectral density of wired sensor data, (b) Power spectral density of wireless sensor data

III. WIRELESS SENSOR SYSTEM WITH RASPBERRY PI ARMV7 PROCESSOR AND MPU6050

A. Design of SHM with Low Computing Devices

In this method 802.11.x IEEE standard, a low-cost sensory that can collect data based on Raspberry pi single board computer has been used. Low power consumption in sensor ensures possibility to operate from mobile power stations like battery for an extended operation period. The Raspberry pi system is introduced with a linux based operating system. In this study, Raspbian Wheezy OS has been chosen. To elevate the data storage capacity the extended scalable storage device of 16 GB memory slot have been added. The MPU6050 a combination of accelerometer and gyroscope will act as an independent sensor node capable of sending the acquired data directly to the server through wifi transmitter. Fig. 5 shows the MPU6050 connected to the Raspberry Pi. This design accelerates self-organization of sensors such that for an increased number of sensors, the intermediate node will participate in forwarding the data packets between the source and destination. The transmitted data is stored in MySQL database system installed in the server. This data will be used for reporting in a front-end GUI web application, which will be accessed by an end user. Fig. 6 shows the screenshot of the webpage. If the value exceeds the threshold the alert e-mail to the corresponding authority will be triggered by the raspberry pi system and the same will be notified in webpage. For an easiness of a user to access the SHM reports, a web page shall be designed and hosted with on an open source web servers and shall be listed in a public domain with configurable threshold values for the user customized report generation and alert monitoring.
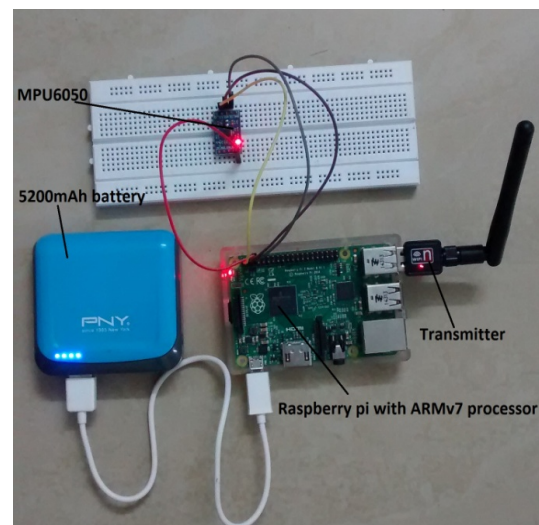

Fig. 5 Wireless System with Raspberrypi and MPU6050

This has been experienced with wired system, wireless system with PIC microcontrollers and wireless system with Raspberry Pi and MPU6050. This detailed study proved that the wireless system with Raspberry Pi and MPU6050 is very successful in terms of data accuracy and transmission speed. Table I explains all the three designs in detail.

(a)

Detailed Report for all Horizontal

ID	Date - Time	Time	X	Y	Z	Roll	Pitch
1	2015-12-14 00:03:17.246483	1.0051	0.0015	-0.0001	0.9757	-0.0896	-0.0072
2	2015-12-14 00:03:17.269609	1.0284	-0.0034	0.0052	0.9972	0.1930	0.3017
3	2015-12-14 00:03:17.290559	1.0493	0.0005	0.0096	1.0001	-0.0315	0.5527
4	2015-12-14 00:03:17.313817	1.0726	0.0001	0.0026	0.9916	-0.0035	0.1482
5	2015-12-14 00:03:17.344208	1.1030	-0.0056	0.0013	0.9975	0.3192	0.0772
6	2015-12-14 00:03:17.371328	1.1301	-0.0004	-0.0023	0.9911	0.0247	-0.1342
7	2015-12-14 00:03:17.395346	1.1541	-0.0026	-0.0013	1.0018	0.1502	-0.0768
8	2015-12-14 00:03:17.417841	1.1766	0.0005	-0.0006	0.9913	-0.0318	-0.0353
9	2015-12-14 00:03:17.433877	1.1926	0.0003	-0.0013	0.9987	-0.0175	-0.0771
10	2015-12-14 00:03:17.453130	1.2118	0.0040	0.0050	1.0006	-0.2273	0.2867
11	2015-12-14 00:03:17.469770	1.2286	-0.0007	0.0094	0.9931	0.0388	0.5426
12	2015-12-14 00:03:17.487225	1.2459	-0.0034	0.0009	0.9943	0.1935	0.0493
13	2015-12-14 00:03:17.505884	1.2646	-0.0012	0.0018	1.0143	0.0655	0.1035
14	2015-12-14 00:03:17.523662	1.2824	0.0018	-0.0026	0.9996	-0.1015	-0.1470
15	2015-12-14 00:03:17.543182	1.3019	-0.0021	0.0055	1.0016	0.1223	0.3144
16	2015-12-14 00:03:17.565451	1.3242	0.0052	-0.0028	1.0009	-0.2971	-0.1608
17	2015-12-14 00:03:17.581569	1.3403	0.0003	0.0023	0.9982	-0.0175	0.1332
18	2015-12-14 00:03:17.603416	1.3622	-0.0034	0.0038	0.9989	0.1926	0.2172
19	2015-12-14 00:03:17.619767	1.3785	-0.0051	0.0004	1.0048	0.2890	0.0209
20	2015-12-14 00:03:17.638830	1.3975	-0.0085	0.0016	0.9962	0.4882	0.0913

(b)

Fig. 6 (a) Screenshot of the graph in the webpage (b) Screenshot of the webpage (random demo value before installing in the model)

TABLE I
COMPARISON OF VARIOUS SHM SYSTEMS

Wired	Wireless SHM System with PIC microcontroller and ADXL335 - 802.15.4 Protocol	Wireless SHM system with Raspberry pi and MPU6050 - 802.11.x Protocol
Sensors are physically connected	sensors are not physically connected	sensors are not physically connected , they are independent module
More number of Sensors are required	Minimum number of sensors are required	Minimum number of sensors are required
Costly	Affordable price	Affordable price
Occupies more storage space and makes confusion in appearance	Occupies less space with no confusion in appearance	Occupies less space with no confusion in appearance
Setup and Installation is complex and time consuming	Easy and quicker to setup	Easy and quicker to setup
Wired transmission	Wireless transmission (through 2.4GHz txn module)	Wireless transmission (through WiFi adapter)
Data Acquisition Unit will collect data from sensor unit	Central Server will collect the data from sensor nodes through 802.15.4 Protocol and then makes it visible in public domain	Local database will collect the data at sensor nodes itself and then transmits it through 802.11.x Protocol to make it visible in public domain
Central server should be connected through wires to the sensor nodes	No wires. Central server should be placed near the acquisition node	Central server can be placed anywhere, as the database will be uploaded directly to the web server
No intermediate node is required	intermediate sensor will role play as master node to forward the data to the server	Two approaches followed: 1. No intermediate node is required. Sensor node will act independently 2. Instead of uploading the data to the server , it can also send the data to the adjacent node from where the data can be forwarded to the server
All the nodes are visible to the other nodes in a wired network	The nodes are not visible to the other nodes	The nodes are not visible to the other nodes
Data loss is less as long as the distance is less	Probability of data loss is high comparing the wired	Probability of data is very less as the data get stored to a local database on the system itself
There is no noise interference	Signal noise ratio is observed	The noise interference is comparatively less
Having 2 or more wired networks will not have a signal interference	Presence of two or more wireless networks will affect each other	Having 2 or more networks will not have a signal interference
Highly reliable	Reasonably reliable (If a major section like the forwarding/master node is failed, it will affect the entire network)	Reasonably reliable (If a router has lossed connectivity, it will affect the entire network)
High speed and bandwidth achievable at lesser distance	Low speed and bandwidth(depends on the protocol and interference)	High speed and bandwidth

IV. CONCLUSIONS

Design architecture to monitor the structural health of offshore platforms using wireless sensor networking is presented. Implementation of the wireless sensor networking assures low system cost, rapid system installation, local data processing capabilities, low power consumption, reliable wireless communication and reduced space occupancy. Data acquired using wired and wireless sensors with PIC microcontroller are compared and the system architecture used for WSN is validated. Vital factors namely: sampling frequencies, operational specifications of smart sensors, interference in the real time monitoring and data integration are highlighted through the experimental investigations. It is also recommended that the process simplifier of PIC microcontroller, used in the present study be replaced with an ARM11 processor of Raspberry pi as mentioned in the design of SHM with low computing devices to enable the data transmission directly to a web server. The experimental work is yet to be carried out.

REFERENCES

[1] Charles.R.F. and Keith,W. 2007. An Introduction to Structural Health Monitoring. Phil. Trans. R. Soc. A, 365: 303-315 , doi: 10.1098/rsta.2006.1928

[2] Wang, Y., Kenneth J.L., Jerome P.L., Michael, F., Kincho, L. and Ahmed, E. 2006. Vibration Monitoring of the Voigt Bridge using Wired and Wireless Monitoring Systems. The Proceeding of 4th China-Japan-US Symposium on Structural Control and Monitoring Oct.16-17, 2006.

[3] Daniele, I. and Roberto, W. 2011. Integrated Structural Health Monitoring System for High-Rise Buildings. First Middle East Conference on Smart Monitoring, Assessment and Rehabilitation of civil structures. February 8 - 10, Dubai, UAE.

[4] Mollineaux, M., Konstantinos, B., Kim Branner., Per Nielsen., Angelo,T. and Ram, R. 2014. Damage Detection Methods on Wind Turbine Blade Testing with Wired and Wireless Accelerometer Sensors. 7th European Workshop on Structural Health Monitoring, July 8 - 11, 2014, La Cite, Nantes, France. hal-01022037.

[5] Peng, J., Hongbo, X., Zhiye, H. and Wang, Z. 2009. Design of a Water Environment Monitoring System Based on Wireless Sensor Networks. Sensors, 2009: 6411-6434. doi:10.3390/s90806411.

[6] Albaladejo, P.C., Jiménez, M., Soto, F., Torres, R., López, J.A., Iborra, A. 2011. A System for Monitoring Marine Environments based on Wireless Sensor Networks. IEEE, doi: 978-1-61284-4577-0088-0/11

[7] Wang, P., Yan, Y., Gui, Y., Omar, B., and Zhiguo, D. 2012. Investigation of Wireless Sensor Networks for Structural Health Monitoring. Journal of Sensors, 2012(2012), Article ID 156329. doi:10.1155/2012/156329.

[8] Nader, C. and Farid, T. 2007. A Damage Index for Structural Health Monitoring based on the Emprical Mode Decomposition. Journal of Mechanics and Material Structures, 2(1): 43-61.

[9] Michael, D.T., Jonathan, M.N., Stephen, T.T., Mark, S., Christy, J.N. and Lawrence, N.V. 2007. Bragg grating-based fibre optic sensors in structural health monitoring. Philosophical Transactions of The Royal Society A, 365: 317-343, doi: 10.1098/rsta.2006.1937.

[10] Brownjohn, J.M.W. 2007. Structural Health Monitoring of civil infrastructure. Philosophical transactions A, 365: 561-587, doi: 10.1098/rsta.2006.1925.

[11] Yan, Y. and Jinping, O. 2008. Wireless sensing experiments for structural vibration monitoring of offshore platform. Front. Electr. Electron. Eng., 3(3): 333–337 , doi: 10.1007/s11460-008-0051-1.

[12] Tifenn, R., Abdelmadjid, B. and Yacine, C. 2014. Energy efficiency in wireless sensor networks: A top-down survey. Computer Networks. 67: 104–122

[13] Tomonori, N. and Billie F.S. 2007. Structural Health Monitoring using Smart Structures. NSEL Report Series Report No. NSEL-001.

[14] Swartz, A., Zimmerman, A., Jerome, P.L., Thomas, F.B., Jesus, R., Liming W.S. and Kincho H.L. 2009. Wireless Hull Monitoring Systems for Modal analysis of operation Naval Vessels. Proceedings of the International Modal Analysis Conference (IMAC-XXVII) , Orlando, Florida, February 9 - 12, 2009.

[15] Yingtao, L and Subhadarshi, N. 2012. Structural Health Monitoring: State of the Art and Perspectives. JOM: the Journal of the Minerals, Metals & Material Society, 64(7), doi: 10.1007/s11837-012-0370-9.

[16] Srinivasan Chandrasekaran, Jain, A.K. and Seeram madhuri. 2013. Aerodynamic response of offshore triceratops, Ship and Offshore structures, 8(2):123-140. doi:10.1080/17445302.691271.

[17] Srinivasan Chandrasekaran. 2015. *Advanced Marine Structures,* CRC Press, Florida, USA, ISBN: 978-1498739689.

[18] Srinivasan Chandrasekaran, 2015. *Dynamic analysis and design of offshore structures*, Springer India, ISBN: 978-81-322-2276-7.