

An experimental work on wireless structural health monitoring system applying on a submarine model scale

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Abstract. This paper presents an experimental work to monitor the health of submarine hull structures using strain sensors and wireless communication technology. The monitored - submarine hull was built in a hydro elastic model scale 1: 30 with a steel bar backbone and tested on water tank of Indonesian Hydrodynamic Laboratory (IHL). Specifically, this health monitoring system for the submarine model was developed using wireless modems, data communication software and conventional strain sensors. This system was used to monitor the loads on a steel bar backbone of the running submarine model from the edge of the water tank. Commands were issued from a notebook to instruct the health monitoring system to acquire data from sensors mounted externally to the steel bar. Data from measurements made on the structure are then transmitted wirelessly back to a notebook computer for processing and analysis. The results of the tank test have been validated and showed no loss of communication signal over an area of the tank. This work also presents a potential use of involving complete automation of this system with an in-service structure coupled with an on-line warning/damage detection capability.

1. Introduction

Pressure hulls which is schematically shown on Figure 1 are the main load bearing structures of naval submarines, commercial and research submersibles, and autonomous underwater vehicles (AUVs) whose primary load-bearing responsibility is to withstand hydrostatic pressure associated with diving. The most efficient pressure hull geometries are circular thin-walled cross- sections that transfer the normal pressure load to in-plane compressive forces. The structural integrity of the pressure hull is very important because pressure hulls are subject to several different load types such as those from weapons (underwater explosions), wave slap on superstructure and other sea loads, and the predominant hydrostatic pressure. Non quantified loading on submarines further extends the uncertainty of predicting future performance. With all of these uncertainties, as well as the possibility of manufacturing defects and errors or material flaws, the possibility exists for a submarine to experience damage (cracking, corrosion, etc.) long before any predictive technique would indicate. Methods of detecting submarine damage prior to being found by routine inspections could therefore provide a great benefit by both reducing maintenance costs and extending ship service life. Structural health monitoring is one of the techniques proposed to bridge the gap between extensive testing and frequent inspections and maintenance. Damage detection systems deployed in difficult to access areas could greatly improve the time and cost required for routine maintenance. Hull monitoring systems also offer opportunities to better understand the performance of hulls during extreme sea states.



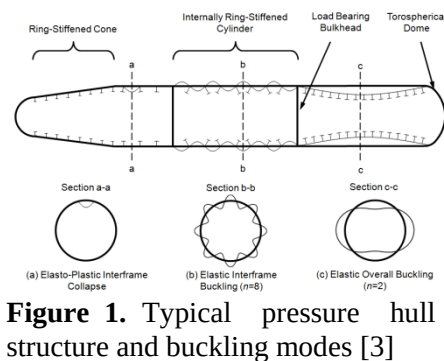


Figure 1. Typical pressure hull structure and buckling modes [3]

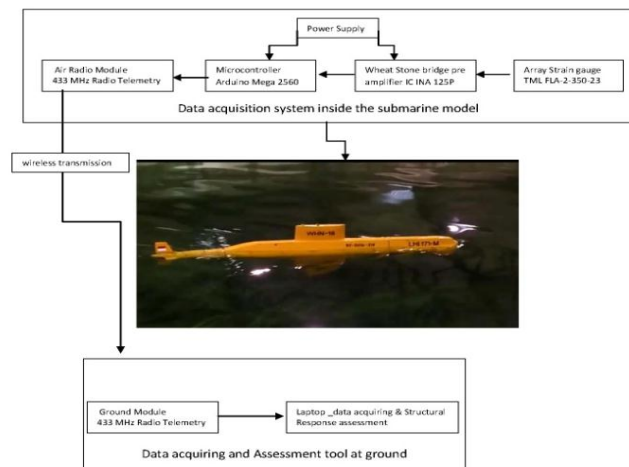


Figure 2. Remote SHM System on submarine model scale

To begin this experimental study there was very little information available about a structural monitoring specifically in submarine hull, since it belongs to military domain. However, the study of structural health monitoring has been motivated for the naval application such as reported on the ISSC report no 468 [9], since the US Navy has recently been incorporating non-traditional construction materials, namely aluminium and composites, into ship structures with greater frequency. This experimental study was supported by the previous works from fields such as wireless technologies, structural health monitoring (SHM) and ship model testing. A conceptual approach using smart sensors and wireless communication technology to monitor the health of large civil structures remotely was introduced by Pinesy [5]. In this paper the concept has successfully applied on a laboratory test specimen with a bolted lap joint from as far away as one mile. A good work presented by Bielen [2] which described the development of a wireless measurement system for multiple strain measurements on rotational structures. Their multi channel systems could measure wirelessly strains in up to 16 points with low cost per channel. Arms [1] has summarized the development of wireless strain sensing systems for a variety of customer driven structural health monitoring (SHM) applications where in the future development these systems could provide a long term, maintenance free, wireless strain monitoring solution. Swartz [8] has shown on his paper a hull monitoring system assembled from wireless sensors that consists of foil strain gauges, accelerometers, gyroscopes installed throughout a vessel to measure hull strain and ship motion. The study presented very encouraging evidence that wireless networks can function within the marine environment for reliable data collection. Drummen [6] also presented a useful material about the setup and results of the full and model scale tests conducted for the US Coast Guard's fatigue life assessment project. In this experimental setup he used a self propelled and self steering model of the NSC USCG BERTHOLF that was built to a scale of 1:25 and tested in MARIN's Seakeeping and Manoeuvring basin.

This paper presents an experimental work to monitor the health of submarine hull structures using strain sensors and wireless communication technology. The monitored - submarine hull was built in a hydro-elastic model scale 1: 30 with a steel bar backbone and tested on water tank of Indonesian Hydrodynamic Laboratory (IHL). Specifically, this health monitoring system for the submarine model was developed using wireless modems, data communication software and conventional strain sensors. The measuring structural response from array strain sensors was processed based on work of Wibowo [11] to calculate severity of the structure. Some of the results of this study was also based on work on slamming loads of frigate hull by Nugroho [7]. This health monitoring application hopefully will be useful since measurements systems in the naval structure domain are mainly strain gauge to avoid electromagnetic interference usually encountered in military environments.

2. Model Scale of Wireless Submarine Structural Health Monitoring (SHM) System

The advantages of spread spectrum technology used in radio telemetry include system flexibility, interference immunity, error free communication and real-time data throughput. However, the most unique feature about the radio telemetry is to be operated over greater distances with minor modifications in the transmitting antenna. The radio is a 2-way half-duplex wireless communication system with a standard TTL UART interface, based on Hope RF's HM-TRP data link modules, and custom firmware that improves upon the modules' original features and performance. Figure 2 displays a schematic of a simple and inexpensive remote health monitoring system for retrieving data from submarine model scale structures before, during and after an adverse loading condition. The system consisted of train gauge sensor type TML FLA 2-350 – 23, a data acquisition system (preamp INA 125P and Arduino Mega 2560), air and ground module of 433 MHz radio telemetry, a notebook/ personal computer installed communication software for up - linking commands and downloading sensor data. Sensors, mounted externally to the backbone structure, were monitored by a ruggedized data acquisition system in close proximity to submarine model structure of interest. The system was powered by battery. Commands from a notebook computer were uplinked via the radio telemetry to instruct the data acquisition system to record sensor measurements. Upon retrieving these data, additional commands were issued to download the data back to a remote notebook/personal computer for analysis. Damage assessment performed when the data were downloaded to a remote notebook / personal computer. The use of the notebook computer permitted the operator to be mobile or stationary. To test and verify the approach described above which is displayed in Figure 2, a hydro - elastic model scale 1: 30 with a steel bar backbone located in the keel which has flexural stiffness similar to the full scale submarine (see Figure 3 and Table 1). Strain sensor arrays were placed on top and sides of the steel back bone to detect changes in strain due to changes of load. The sensor positions were at a quarter length of LOA from the bow (ST 16), mid-ship (ST 10) and at a quarter of LOA from the stern ship (ST 04) where presumably the slamming and highest normal stress loads may occur. During the experiment a dynamic load was simulated by a falling object to the submarine model which excites the backbone structure in bending. Measurements were then recorded from all 12 strain sensors. Commands to take data were uplinked from a notebook / personal computer through ground module located approximately in range of 50 to 100 m away from the submarine model.

Commands from the remote notebook computer were received through air module connected to the Arduino board (microcontroller) to drive the data acquisition system inside of the submarine model. The 3DR Radio telemetry system had configuration of serial board (for the air) and USB (for the ground) at rates up to 250 kbps in the frequency 433 MHz. Response of the backbone structure due to the dynamic loads was then acquired by microcontroller board and transmitted to notebook or personal computer on the ground. Once the sensor data were acquired to the notebook computer, they could be retrieved wireless for assessment of structural response in the backbone steel. Communication between the two computers and the two radio modules was established using a 3DR Radio open source X bee communication software. This communication software enabled the user to make the remote notebook emulate the data from microcontroller. Thus, commands issued in the Windows environment of the remote notebook computer become the commands issued on the microcontroller board. However, the communication software was more than just an emulation tool; it also enables the operator to view commands being carried out on the microcontroller board. The functional test of the wireless system with configuration for the experiment is presented on Figure 4. Table 2 above summarizes components used to create this experiment demonstration of a remote wireless health monitoring system. The system was validated at ranges up to 100 m for approximately 1 hour without loss of communication link. Using the communication software, a communication link was established via the 3DR Radio telemetry system to make the remote notebook/PC to read the data from the acquisition system. A micro - controller software was applied on the data acquisition board to have the strain sensor response data. Then a download command was then issued from the communication software to transfer data to the remote notebook

computer. Upon receiving the downloaded strain sensor response data, the in – house software was initiated on the remote notebook computer to run assessment of structural response in the backbone steel. Once the communication link is established during the setup mode, sensor data can be retrieved within seconds.



Figure 3. Strain Sensor placement on Submarine Model



Figure 4. Functional test of wireless monitoring system

Table 1. Properties of Submarine hydro- elastic model

Physical property	Units
EA/L (stiffness of backbone steel)	108.9 MN/m
LOA (length over all)	2.04 m
Breadth	0.206 m
Draught	0.190 m
Displacement	55.45 kg

Table 2. Components of wireless SHM of submarine model

Item	Manufacturer
Strain Sensor	TML FLA – 2- 350 – 23
Data Acquisition System	Preamp INA 125P and Arduino Mega R3 2560
DAAS Software	Arduino
Radio Telemetry (air and Ground module)	433Mhz Single TTL 3D Robotics 3DR
Radio Telemetry Software	Radio Telemetry Kit, Type cp2102Silicon Lab
Notebook/ Personal Computer	Open source 3 DR
Damage Detection Software	Sony/Any
	IN HOUSE

3. Results obtained on experimental test specimen

The submarine model in the water tank is shown on the Figure 5. Using this remote structural health monitoring system, the back bone of the submarine model was excited by a falling object to obtain bending moment response data to strain sensor. These data were retrieved across the wireless link for various dynamic loads. These loads was in form of hydro-dynamics impact load where in this study obtained by measuring the stresses that occurs on the backbone of model submarine when it hits the surface of the water tank . Results for the measurement from the sensors were plotted to the screen of the remote notebook computer and later stored as image files. Figure 6 presents the results in operation during a typical data run from the twelve strain sensors. Notice that in Figure 6 the screen of the remote notebook computer displays the data across the wireless link that were being taken from backbone steel of submarine model.



Figure 5. Submarine Model scale in the water tank



Figure 6. A notebook for recording data from sensor measurements

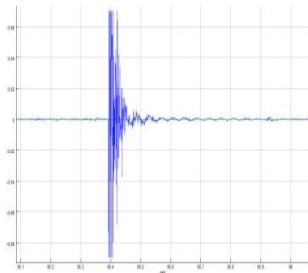


Figure 7. Stress data due to falling object at ST04 of the submarine model

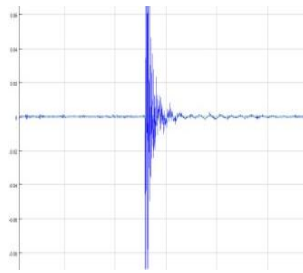


Figure 8. Stress data due to falling object at ST10 of the submarine model

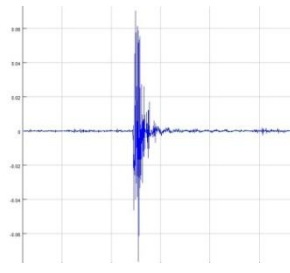


Figure 9. Stress data due to falling object at ST16 of the submarine model

The excitation by the falling object was based on the results of the numerical calculations. The numerical calculation used stripe theory to calculate relative vertical motion and velocity of the submarine during operation on the sea. The relative motion represented the height of the falling object. To determine the height from relative velocity the free - fall physics formula was applied. There were five variations of the height of the falling object were used on this experiment. Examples of data reading of the stresses from strain sensors of the ST 04, ST 10 and ST 16 are presented on Figure 7 to 9 respectively.

The data stresses were collected with sampling rate of 1000Hz, to have the transient response of the load. To validate the results the stress measurements of this experiment were compared with stresses that predicted by make use of slamming pressure values from Stavovy and Chuang in report of ISSC-385 [4]. Their methods provide a procedure to compute slamming impact pressure of high performance vehicles (HPV). Their empirical methods based on two- and three-dimensional data. The method determines the impact pressure in an infinitesimal area of the hull bottom. In that area the dead rise, buttock trim and heel angles are determined from ship lines, body plan, ship motions and wave profile. The empirical formula for impact pressure can be shown as follows [4]:

$$p_i = k_1 V_n^2 \quad (1)$$

Where,

V_n = relative normal velocity of impact body to wave surface on plane normal to wave surface. And values for k_1 are shown in Figure 10 as a dashed line.

By multiplying the impact pressure with the water plane area of the submarine in a particular draught the excitation force F can be found. This force is a useful quantity to calculate a bending moment at a particular station of the submarine. Hence, the normal stress on pressure hull of the submarine (full scale) by following formula [10];

$$\sigma_{ni} = \frac{M_i Y_i}{I_i} \quad (2)$$

where;

M_i = bending moment at station i of submarine hull; Y_i = distance of the neutral axis to surface of the backbone structure at station i ; I = sectional moment inertia of the backbone structure at station i

Figure 11 shows the comparison of maximum normal stress between measurement and prediction. From the picture above it shows that the patterns produced by these two methods are in a good agreement. However, the stress values from the experiment seem to have a higher value than the predicted one. The difference value of stress is approximately 30%. This is probably because the value of k_1 in Stavovy and Chuang are more suitable for surface ship hull forms and numerical approximations. This actually supported by the Figure 10 where the value k_1 of the wedge test tend to be larger than other numerical approximation.

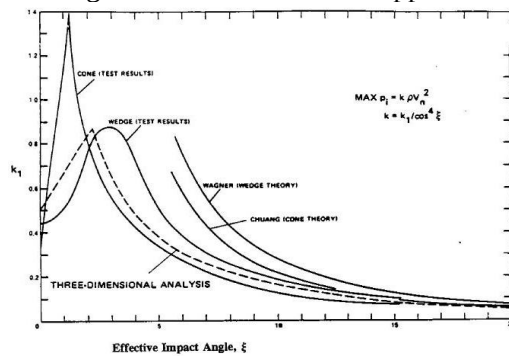


Figure 10. Values for k_1 of Stavovy and Chuang method [4]

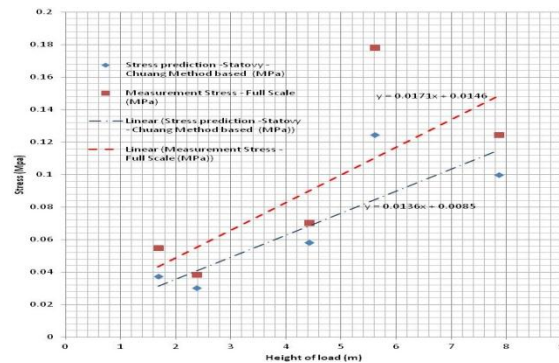


Figure 11. A comparison between stress measurement and prediction

4. Conclusions

This paper has presented a simple model and inexpensive approach for remote health monitoring for submarine structures involving spread spectrum wireless modems, a note book based data acquisition system, off-the-shelf communication software, conventional sensors and custom structural response software. The wireless system can work with a submarine hydro-elastic model over ranges of up to approximately 100 m with no loss of communication signal. The results of test measurements from the tank test have a good agreement with a modified well known impact pressure method. Data rates achieved on transferring data files are of the order of 250 kbps which are suitable enough for this particular monitoring application. Future work will involve complete automation of this system with an in-service structure coupled with an on-line warning/damage detection capability

Acknowledgments

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References

- [1] Arms SW and Townsend CP 2003 *Wireless Strain Measurement Systems – Applications & Solutions*, NSF-ESF Joint Conference on Structural Health Monitoring Strasbourg, France
- [2] Bielen P, Lossi, and Vandepitte M 2002 *Proceedings Of Isma II*, p 663 – 670
- [3] Fricke W, Bronsart R (Eds.) 2012 *18th International Ship And Offshore Structures Congress, Rostock Germany, Vol 2*
- [4] Daidola JC and Victor M 1995 *Hydrodynamic impact on displacement ship hulls, an assessment of the state of the art*, Ship Structure Committee (SSC – 385)
- [5] Pinesy DJ and Lovellz PA 1998 *Journal of Smart Material and Structure* **7**, 627–636.
- [6] Drummen I, SchiereM, Dallinga R and Stambaugh K 2014 *Ship Structure Symposium, Linticum Heights, MD*

- [7] Wibowo NH and Mujahid AS 2015 *World Maritime Technology Conference, Providence, USA* 03 – 07
- [8] Swartz, Zimmerman RA, Lynch AT, Brady JP, Thomas F, Salvino JR, Law LW and Kincho H, 2009 *Wireless Hull Monitoring Systems for Modal Analysis of Operational Naval Vessels*, Proceedings of the IMAC-XXVII, Orlando, Florida USA, Society for Experimental Mechanics Inc. 9-12
- [9] Ship Structure Committee 2013 *Development Of A Structural Health Monitoring Prototype For Ship Structures*, Report no 468
- [10] Vidosic JP 1987 *Mechanics of Material*, Sec 5.2 of Marks Standard Handbook for Mechanical Engineers, 9th Ed Mc Graw – Hill Book Company
- [11] Wibowo HN and Chiu WK 1998 *COMADEM Proceedings, Launceston, Tasmania, Australia* p 905-917