Title:

Monitoring of a High Speed Naval Vessel using a Wireless Hull Monitoring System

Authors:

Jerome P. Lynch[1*]
R. Andrew Swartz[1]
Andrew T. Zimmerman[1]
Thomas F. Brady[2]
Jesus Rosario[2]
Liming W. Salvino[2]
Kincho H. Law[3]

ABSTRACT

As the U.S. Navy acquires high-performance littoral combat ships, there is a growing need for cost-effective hull monitoring systems. High-performance ships are typically constructed from light-weight construction materials such as aluminum. In addition, they are designed with multi-hull forms resulting is complex hull behavior during high-speed operation. Hull monitoring systems installed in these ships can illuminate the behavior of the hull during extreme operational conditions (*e.g.*, high-speed operation) in addition to serving as a long-term hull health monitoring system. To keep the costs of hull monitoring systems low while accommodating a large number of sensors in their design, wireless communication between sensors in the hull monitoring system is proposed. In this study, a dense network of *Narada* wireless sensor nodes are installed on the FSF-1 SeaFighter to create a wireless hull monitoring system. The strain and acceleration response of this high-speed aluminum ship is monitored during seakeeping trials. Response data collected by the wireless hull monitoring system is compared to data collected by the ship's permanent hull monitoring system which is wired.

INTRODUCTION

High-performance littoral combat ships have been proposed for future U.S. Navy missions. To achieve high-speeds and nimble maneuverability, littoral combat ships

[1]Department of Civil and Environmental Engineering, University of Michigan, 2350 Hayward St, Ann Arbor, MI, 48105; [*]Email: jerlynch@umich.edu
[2]Naval Surface Warfare Center, Carderock Division, 9500 MacArthur Blvd., West Bethesda, MD 20817-5700
[3]Department of Civil and Environmental Engineering, Stanford University, 473 Via Ortega, Stanford, CA 94305

are designed using light-weight materials (*e.g.*, aluminum) and non-conventional hull forms. These ship design concepts pose a number of technical and management challenges for the Navy [1]. With limited experience with aluminum, aluminum ships are anticipated to be prone to fatigue cracking and stress-corrosion cracking. High-speed operation in rough sea conditions during combat will place a high-level of demand on the hull. In addition, multi-hull forms will exhibit complex hull dynamics during high-speeds. To better understand the behavior of high-speed aluminum ships, hull monitoring systems are necessary. As damage detection and prognosis algorithms continue to improve, they can be included within the design of the hull monitoring system so as to offer automated structural health monitoring of the ship.

Hull monitoring systems provide real-time structural response measurements of the hull during seaway loading. Data from hull monitoring systems allow crews to ensure safe operation of the ship within allowable operational envelopes. Hull monitoring systems consisting of strain gauges and accelerometers are routinely installed in commercial and military vessels. These systems employ coaxial wiring to communicate data to a centralized server where data is stored and processed for presentation to the crew. For steel mono-hull ships, traditional hull monitoring systems require relatively low sensor densities to capture the global behavior of the ship. However, complicated naval vessels (*e.g.*, multi-hull vessels) designed for more extreme operational envelopes (*e.g.*, high-speeds) require a higher density of sensors in the hull monitoring system. As the hull monitoring system grows in scope, the cost and efforts necessary to install the system increase in tandem.

To increase the number of sensors installed in a hull monitoring system without incurring a high cost penalty, wireless sensors can be adopted in lieu of tethered sensors. Wireless sensors have rapidly matured into reliable sensor platforms capable of collecting data with accuracies equivalent to tethered counterparts. Many successful field deployments of wireless monitoring systems have been accomplished for monitoring large and complex structures such as buildings [2] and bridges [3]. In this study, a low-cost wireless sensor platform developed at the University of Michigan is proposed for use in a wireless hull monitoring system. The advantages in using the *Narada* wireless sensor is that its design has been optimized for structural monitoring applications [4]. The node can collect data with 16-bit digital resolution on 4 independent sensing channels, locally store and process data using an 8-bit embedded microcontroller (Atmel ATmega128), and communicate data using an IEEE802.15.4-compliant transceiver (Texas Instruments CC2420) that is capable of line-of-sight communication ranges in excess of 30 m.

In this paper, a wireless hull monitoring system is installed on an experimental high-speed aluminum ship currently being evaluated by the U.S. Navy. A dense network of wireless sensors are installed on the FSF-1 SeaFighter to measure its strain and acceleration response during seakeeping trials in the Atlantic and Pacific Oceans. Results from the proposed wireless hull monitoring system are presented followed by a modal analysis of the ship.

HIGH-SPEED ALUMINUM LITTORAL COMBAT SHIP

The FSF-1 SeaFighter (Figure 1a) is a 83 m long multi-hull catamaran-style ship designed for high-speed littoral combat missions. To provide the ship with speed, the

Figure 1. The high-speed aluminum littoral combat ship FSF-1 SeaFighter: (a) SeaFighter at sea; (b) the internal mission bay featuring open spaces on the ship main deck.

ship is constructed from aluminum, thereby keeping the total weight of the ship down. The ship is capable of operating at speeds in excess of 40 knots. The ship's main deck consists of a large enclosed space known as the mission bay (Figure 1b); the mission bay accommodates the transportation of shipping containers housing military equipment for different littoral combat missions.

As an experimental vessel, the ship is closely monitored using an extensive hull monitoring system custom designed for the U. S. Navy. The Scientific Payload Data Acquisition System (SPDAS) is a wired hull monitoring system featuring more than 10 tri-axial accelerometers to measure rigid-body motions, over 100 metal foil strain gauges to measure hull strains, and a wave height measurement system installed on the ship bow [5]. These sensors are installed throughout the ship and are interfaced to local data collection units known as data acquisition bricks. The bricks locally filter and digitize the sensor data before it is communicated on the ship's high-speed fiber-optic network. Measurement data communicated by the system bricks are aggregated at a server connected to the network in a lower deck of the ship. A visualization client running on the ship bridge queries the server for data to be presented to the crew.

WIRELESS HULL MONITORING SYSTEM

A wireless hull monitoring system (Figure 2) is designed for installation in the FSF-1 SeaFighter. In total, 20 *Narada* wireless sensors with accelerometers and strain gauges interfaced are installed throughout the ship. To capture the rigid-body motion and vibrations of the ship, 16 accelerometers are installed in a grid-fashion within the mission bay area. Of these accelerometers, 14 are single-axis accelerometers (Crossbow CXL02LF1Z) oriented to measure acceleration orthogonal to the plane of the deck. The CXL02LF1Z has a $\pm$ 2g range with a sensitivity of 1 V/g. In addition, 2 tri-axial accelerometers (CXL02TG3) are installed along the longitudinal axis of the ship with one of them (sensor number 5) located on the ship's center of gravity. The CXL02TG3 is a tactical-grade (0.6 mg rms noise floor) accelerometer with a $\pm$ 2g range with a sensitivity of 0.83 V/g. Each accelerometer is epoxy bonded to the surface of the mission bay deck (Figure 3a) and covered with a small cone for added protection from the crew. The output of each accelerometer is interfaced to one Narada wireless sensor node encased in a weather-proof plastic enclosure (Figure 3b).
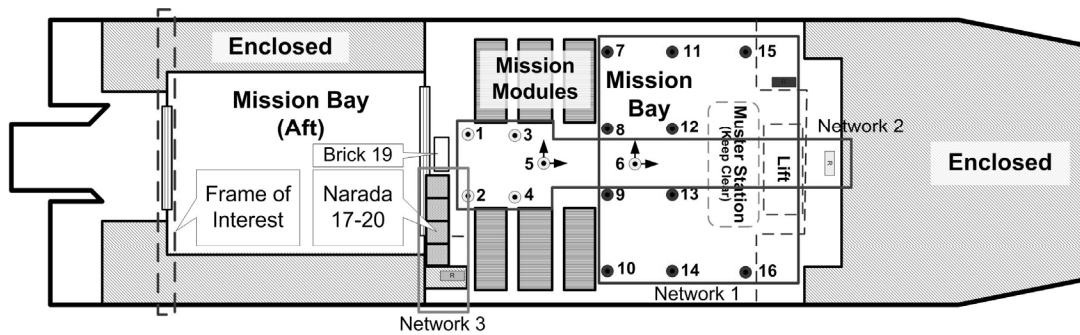
Figure 2. Wireless hull monitoring system proposed for the FSF-1 SeaFighter.

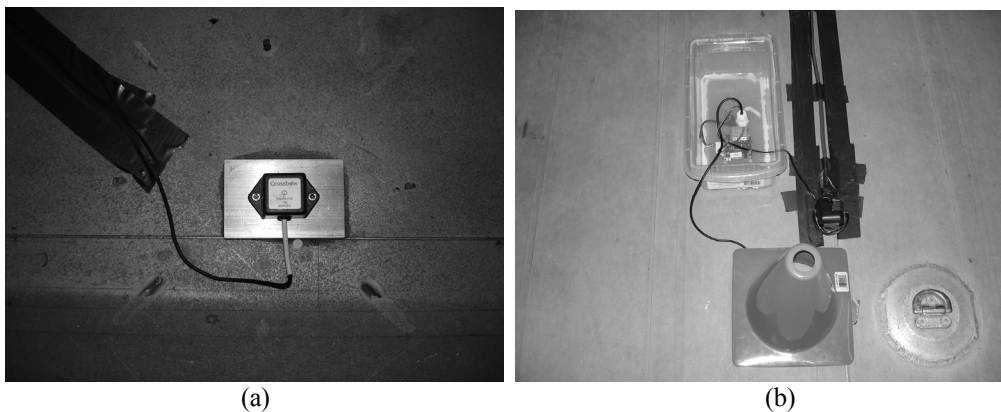(a)   (b)

Figure 3. (a) Accelerometer affixed to the mission bay deck; (b) *Narada* wireless sensor enclosed in a plastic enclosure.

In addition to acceleration, the strain response of the ship is monitored by the wireless hull monitoring system. The analog outputs of 8 metal foil strain gauges are spliced from the SPDAS hull monitoring system at brick 19 (Figure 2). The strain gauges utilized are physically mounted to a hull frame in the aft-section of the ship (Figure 2). Two Rosette patterns oriented to measure lateral, longitudinal, and 45 degree strain vectors measure plane strain on the shell and web of the frame (Figure 4a). Two additional strain gauges that measure the strain resulting from prying of the hull are also utilized. Before interfacing the output of each gauge's Wheatstone bridge, analog low-pass filters are used to de-noise each gauge output. A total of 4 *Narada* wireless sensors are used with each node recording the output of two gauge channels. To avoid issues associated with battery-operation, all *Narada* wireless sensors are powered by the ship's AC electrical system.

With a total of 28 sensor channels sampled at high-rates (100 to 1000 Hz), wireless bandwidth limitations prevent all 20 *Narada* wireless sensors from communicating within the same network. To alleviate this problem, the wireless hull monitoring system is divided into three separate networks (Figure 2). Each network has one receiver unit that can command the *Narada* wireless sensors and retrieve their data. Network 1 consists of the 10 *Narada* nodes (7 through 16) which record vertical accelerations of the hull. Network 2 represents a combination of uni- and tri-axial
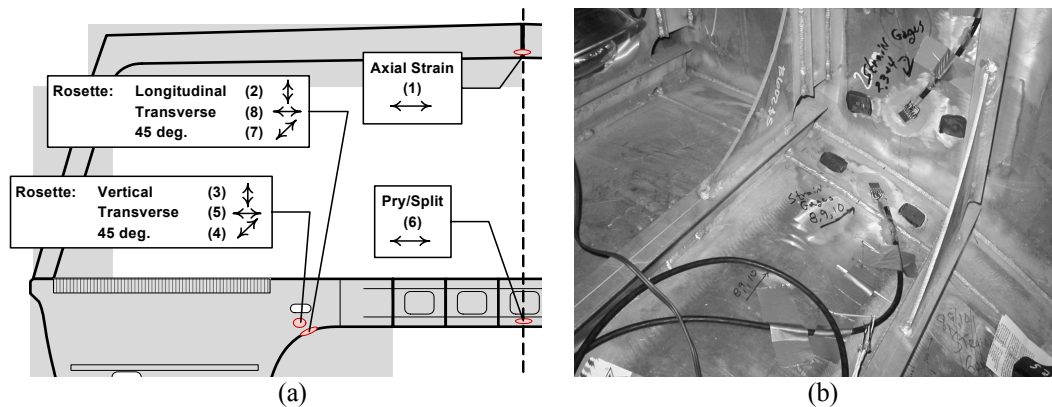
Figure 4. (a) Schematic of frame 20 where 8 strain gauges are installed (two Rosette triplets and two single gauges); (b) typical installation of strain gauges on the SeaFighter.

accelerometers (nodes 1 through 6). Finally, Network 3 records data from the 4 *Narada* nodes measuring the 8 hull strains. All three networks operate concurrently by operating on three different channels of the IEEE802.15.4 2.4 GHz radio spectrum.

Each network is operated as a star network with one wireless receiver (Texas Instruments CC2420DB radio board) coordinating the activity of the network. Each receiver is connected to a serial-ethernet converter (Moxa NPort DE-311) so that the receiver can be commanded by the system data server which is remotely located on a different level of the ship. The data server commands all three networks over the ship's fiber optic network, time synchronizes the three wireless sensor networks, and stores all measurement data collected.

RESULTS FROM SEAKEEPING TRIALS

Extensive seakeeping trials are conducted on the SeaFighter in 2008 during a one-month voyage from Panama City, Florida to Portland, Oregon. During the transit from Panama City to the Panama Canal, the ship experiences relatively calm seas. However, during the Panama Canal-Portland leg, the ship experiences severe sea conditions with wave heights in excess of 3 m. During these conditions, slamming events (*i.e.*, impulsive wave loading on the bow) are common. The wireless hull monitoring system is operated in both automated and user-operated modes. During automated operation, the wireless hull monitoring system is run at 100 Hz continuously. The user-operated mode allows the system user to select a number of sensors to collect data from at higher sampling rates. When user-operated, sampling rates ranging from 200 to 1000 Hz are utilized. Especially during slamming events, higher sample rates are desired. The wired SPDAS hull monitoring system is operated at 200 Hz.

To assess the performance of the wireless hull monitoring system, the strain and acceleration response of the ship as recorded by the wireless monitoring system are compared to those collected by the SPDAS system. First, the strain response of the ship is analyzed. The strain time histories recorded during rough seas on the Pacific are shown in Figure 5. Strain time histories are shown for both channels 2 (longitudinal strain of the ship) and 3 (vertical strain in the frame itself) recorded by
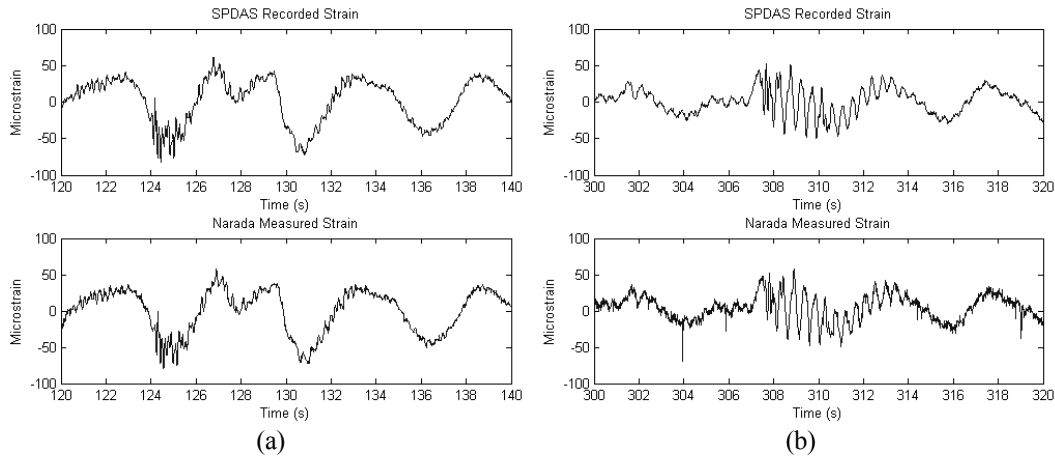
Figure 5. Strain response on SeaFighter frame 20: (a) channel 2 (longitudinal hog-sag flexural strain); (b) channel 3 (vertical strain).
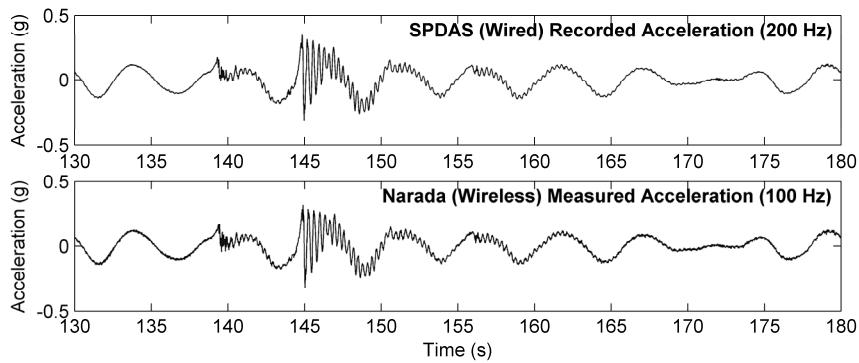

Figure 6. Acceleration response of the SeaFighter measured at the center of gravity. Both wired (SPDAS) and wireless (Narada) time histories are shown.

both the wireless and wired monitoring systems. The wireless time histories are recorded at 100 Hz while those collected by the wired SPDAS system are collected at 200 Hz. The peak strains observed in these time histories are approximately ± 50 $\mu\varepsilon$. The strain time-history recorded by channel 3 reveals the strain response of the frame during a slamming event at roughly 307 seconds. As can be seen in Figure 5, the time history responses recorded by both hull monitoring systems are identical. This validates the high-resolution data collection capabilities of the wireless hull monitoring system. In addition, no data is lost during wireless communications. Both hull monitoring systems also have high-precision accelerometers installed at the center of gravity of the ship. The acceleration time history response of the ship is compared using the acceleration measurements independently recorded by both monitoring systems. As shown in Figure 6, the acceleration time histories measured at the SeaFighter's center of gravity are identical. Again, a slamming event is observed at roughly 145 seconds.

Modal analysis is conducted using the acceleration data recorded by the wireless hull monitoring system during slamming events. Here, it is assumed slamming events are relatively broadband due to their impulsive nature. The output-only frequency domain decomposition (FDD) modal analysis method [6] is employed to derive the operational deflection shapes of the SeaFighter. While the operational deflection

Narada Operation Deflection Shape, 2.25 Hz

Narada Operational Deflection Shape, 3.30 Hz

(a)

(b)

SPDAS Operational Deflection Shape, 2.19 Hz

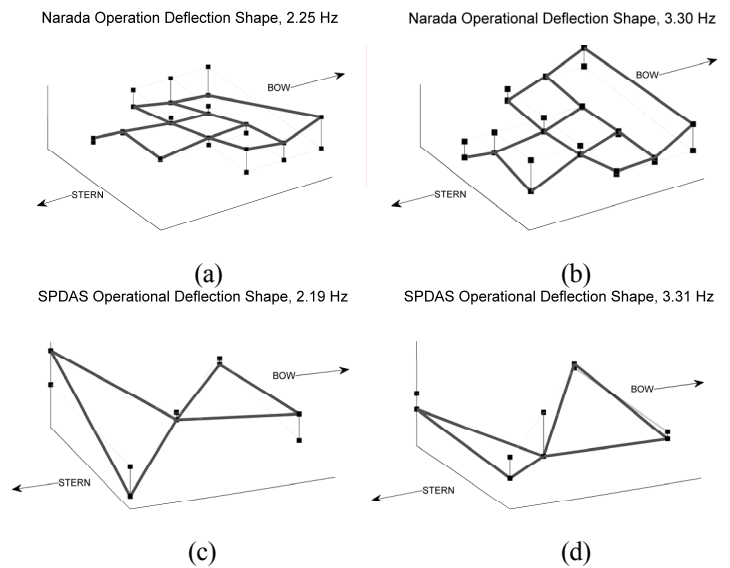SPDAS Operational Deflection Shape, 3.31 Hz

(c)

(d)

Figure 7. Operational deflection shapes: (a) 2.3 Hz and (b) 3.3 Hz (wireless); (c) 2.3 Hz and (d) 3.3 Hz (wired).

shapes will be strongly correlated to the ship's mode shapes, the lack in knowledge of the system inputs prevents the analysis from deriving the mode shapes.

Output acceleration time histories are converted to the frequency-domain through the use of standard discrete Fourier transform techniques (*e.g.,* FFT, windowing, filtering). The output spectra are analyzed in order to identify modal peaks. For the SeaFighter, the spectra is dominated at low frequency by the rigid body motion of the ship as it travels over sea waves. The wave height measurement system on the bow of the ship provides quantitative information on the wave environment, thereby allowing wave-induced peaks in the acceleration spectra to be identified and removed from consideration. At identified modal frequencies, the output Fourier spectra are assembled into the output-only power spectral density (PSD) matrix. Singular value decomposition (SVD) is performed on the PSD matrices with the first singular vector corresponding to the ship operational deflection shape at that frequency. The magnitude of the first singular value is compared to the second and third singular vectors to ensure only one dominant operational deflection shape is present.

Using the wireless acceleration response data, dominant peaks are observed in the frequency-domain at approximately 0.2, 2.3 and 3.3 Hz. The peak at 0.2 Hz is consistent with sea waves which are measured to have a period of roughly 5 seconds. The FDD analysis is conducted at 2.3 and 3.3 Hz. As shown in Figure 7, the two operational deflection shapes at 2.3 and 3.3 Hz correspond to torsion and bending modes of the ship, respectively. It should be noted that the accelerometers interfaced to the wireless hull monitoring system correspond to the central section of the ship. However, the SPDAS hull monitoring system has accelerometers at the four corners of the ship, as well as at the center of gravity, which would provide a more comprehensive view of the global operational deflection shape. The operational deflection shapes obtained by applying the FDD method on the SPDAS acceleration measurements are also shown in Figure 7. The two operational deflection shapes obtained from the SPDAS system confirm the findings obtained by the wireless hull monitoring system.

CONCLUSION

A wireless hull monitoring system for high-speed aluminum littoral combat ships is proposed. By eliminating the cost and effort required to install a wired system, the wireless hull monitoring system allows for a dense installation of sensors in a single ship without incurring an exorbitant cost. A series of metal foil strain gauges and accelerometers are interfaced to 20 *Narada* wireless sensor nodes for high-resolution digitalization and reliable wireless communications. The proposed wireless hull monitoring system is installed on the FSF-1 SeaFighter. In total, 8 channels of strain and 20 channels of acceleration are collected by the system. During seakeeping trials in the Atlantic and Pacific Oceans, the wireless monitoring system proved robust service (with no system failures observed). Side-by-side comparisons of ship responses measured by the wireless and wired hull monitoring systems revealed the accuracy of the wireless sensor nodes. Using acceleration data collected by the wireless and wired monitoring systems, the operational deflection shapes of the ship were obtained with strong agreement again observed between the two systems. Future work is needed to create even larger wireless hull monitoring systems defined by more than 100 sensor nodes. Second, the embedment of data interrogation algorithms should be explored to allow the wireless hull monitoring system to process its own measurement data. Sensor-based data processing would enhance the functionality of the wireless hull monitoring system.

REFERENCES

1. Hess, P. E. 2007. "Structural health monitoring for high-speed naval ships," presented at the 7th International Workshop on Structural Health Monitoring, Stanford, CA.
2. Zimmerman, A. T., M. Shiraishi, R. A. Swartz, and J. P. Lynch. 2008. "Automated modal parameter estimation by parallel processing within wireless monitoring systems," *J. Infrastruct. Syst.*, 14(1):102-113.
3. Lynch, J. P., and K. J. Loh. 2006. "A summary review of wireless sensors and sensor networks for structural health monitoring," *Shock Vib. Dig.*, 38(2):91-128.
4. Swartz, R. A., D. Jun, J. P. Lynch, Y. Wang, D. Shi, and M. Flynn. 2005. "Design of a wireless sensor for scalable distributed in-network computation in a structural health monitoring system," presented at the 6th International Workshop on Structural Health Monitoring, Stanford, CA.
5. Bachman, R. J., Woolaver, D. A., and Powell, M. D. 2007. *SeaFighter (FSF-1) Seakeeping Measurement*, Report NSWCCD-50-TR-2007/10, Naval Surface Warfare Center, Carderock, MD.
6. Brincker, R., Zhang, L. and Anderson, P. 2001. "Modal identification of output-only systems using frequency domain decomposition," *Smart Materials and Structures*, 10(3), 441-445.