Multi-Tiered Sensing and Data Processing for Monitoring Ship Structures

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Abstract

A comprehensive structural health monitoring (SHM) system is a critical mechanism to ensure hull integrity and evaluate structural performance over the life of a ship, especially for lightweight high-speed ships. One of the most important functions of a SHM system is to provide real-time performance guidance and reduce the risk of structural damage during operations at sea. This is done by continuous feedback from onboard sensors providing measurements of seaway loads and structural responses. Applications of SHM should also include diagnostic capabilities such as identifying the presence of damage, assessing the location and extent of damage when it does occur in order to plan for future inspection and maintenance. The development of such SHM systems is extremely challenging because of the physical size of these structures, the widely varying and often extreme operational and environmental conditions associated with the missions of high performance ships, the lack of data from known damage conditions, the limited sensing that was not designed specifically for SHM, the management of the vast amounts of data, and the need for continued, real-time data processing. This paper will discuss some of these challenges and several outstanding issues that need to be addressed in the context of applying various SHM approaches to sea trials data measured on an aluminum high-speed catamaran, the HSV-2 Swift. A multi-tiered approach for sensing and data processing will be discussed as potential SHM architecture for future shipboard application. This approach will involve application of low cost and dense sensor arrays such as wireless communications in selected areas of the ship hull in addition to conventional sensors measuring global structural response of the ship. A recent wireless hull monitoring demo on FSF-1 SeaFighter will be discussed as an example to show how this proposed architecture is a viable approach for long-term and real-time hull monitoring.

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1. Introduction

The advancement of technologies has made high speed and high performance ships increasingly common in both naval and commercial sectors. The U.S. Navy continuously seeks the ability to operate future ships with higher speed in higher sea states. These high performance goals resulted major and fast growing challenges for the US Navy for "Seakeeping[*]: the ability of our ships to go to sea and successfully and safely perform their missions under adverse environmental conditions." It is known that high-speed ships and crafts often employ novel and aggressive structural designs using composite, aluminum alloys, or high strength steel with innovative arrangements and fabrications to maximize weight reduction. These structural features and high-speed operating profiles may increase fatigue, buckling, and vibration problems as well as crew discomfort from increased wave slamming, acceleration levels, and higher working stresses in the structure, *Rawson and Tupper (2001).* As a result, structural damage due to wave impacts and slamming occur frequently and extensive damage can occur in a short amount of time while the ship is operating in heavy seas. To minimize the risk of operating high-speed vessels in an unrestricted manner will require the ability to monitor operational loads and to detect structural damage and structural performance degradation at the earliest possible stage, i.e., the ability to implement structural diagnosis in real time. This structural diagnostic information can then be used to predict the time to potential structural failure, and to provide strategies for corrective actions in order to support future Navy operation and maintenance.

The development of an effective structural health monitoring (SHM) system for condition-based hull maintenance is one of the important mechanisms to ensure structural performance over the life of a ship. An on board SHM system to monitor the response of the hull girder and secondary structure to the seaway loads was envisioned as early as two decades ago. The response data then will be continuously processed in real time to provide warnings and recommendations to the operators and/or engineering crews concerning structural integrity, required maintenance, as well as suggested operation modifications that may extend the lifecycle of Navy ships. The system will provide the means for safer ship operation by minimizing the possibility of structural damage and reducing structural fatigue damage accumulation. Although a series of efforts were undertaken since the mid 1990s to support this SHM vision, the development and implementation of such SHM systems are still in a very limited stage at the present time. An overview of the current status of monitoring marine structures and technologies required to realize real time structural diagnosis and prognosis vision as well as challenges for SHM shipboard implementation can be found in *Salvino and Collette (2009).*

The ultimate goal of a shipboard SHM system defines an integrated process, which includes continued and reliable measurements of load and usage in combination with structural diagnosis and prognosis components. Monitoring is defined as constant measuring or surveillance of ship structures to give actual time histories. The primary purpose is to be aware of what is happening to a structure. Although this information is useful in itself, load and structural response measurement systems are just a sub-set of a complete SHM process. The primary objective of a diagnostic task is to assess structural degradation by detecting, locating, and quantifying material or structural component damage using measured data (from past and present) and to establish state awareness through a diagnostic algorithm. Prognosis, on the other hand, aims to predict the future capability of structural systems using up-to-date diagnostic information and structural models in addition to estimating expected future loading. Prognostic information with some level of statistical confidence can be developed into decision-making tools to allow the appropriate authority to make intelligent deployment and maintenance decisions.

Various damage detection techniques and methodologies have been developed over the past several decades for aerospace, mechanical, civil, and ship structures. Numerous papers, books, and

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[*] VADM ADAMSON, COMNAVSURFLANT, Seakeeping Workshop, 1975.

specialized conference proceedings have been published and can be found, for example, in *Farrar and Worden (2007), Sohn et al. (2003), Chang (2003), Chang (2007).* Damage detection and structural diagnosis will remain an area of active research. Some damage detection methods and diagnostic techniques have demonstrated their feasibility in laboratory and controlled testing environments. However, the effectiveness of these methods for SHM of ship hull and local structure, which is similar to applications in aerospace and civil structure in general, is unknown. The reason that SHM application is particularly challenging because of the physical size of these structures, the widely varying and often extreme operational and environmental conditions associated with these ships' missions, lack of data from known damage conditions, limited sensing that was not designed specifically for SHM, and the management of the vast amounts of data that can be collected during a mission. This paper will discuss some of these challenges and several outstanding issues that need to be addressed. In section 2, structural performance evaluations for high speed ships will be introduced based on conventional verification sea trails on an aluminum high-speed catamaran, the *HSV-2 Swift*. An example of recent effort to develop hull monitoring system for Joint High Speed Vessel will be given. In section 3, a four-step SHM paradigm to guide the development of SHM system for ship structures will be discussed Continued onboard monitoring and SHM applications will also be discussed in the context of applying various SHM approaches to strain and acceleration data measured during the *HSV-2 Swift* sea trail. In section 4, a multi-tiered approach for sensing and data processing will be discussed as potential SHM architecture for future shipboard application. In particular, effective measurements to cover both global structural response and critical local area of concerns will be addressed. As an example of implementing the proposed multi-tiered sensing approaches, a recent wireless hull monitoring demo on *FSF-1 SeaFighter* in selected areas of the ship hull along with limited sensors measuring global structural response of the ship will be discussed. To conclude, this paper will discuss several outstanding issues that need to be addressed before SHM can be implemented on ships for long-term and real-time hull monitoring and condition-based hull maintenance.

2. Structural Monitoring and Performance Evaluations For High Speed Ships

Higher speeds and improved performance in rough seas are increasingly specified for new ships and craft, both naval and commercial. This development is consistent with international trends as navies of many countries are beginning to use higher speed designs for patrol and littoral duties. Although there is some experience in the commercial sector in managing high-speed aluminum hull forms, the relevance to naval application is limited. These commercial vessels had evolved through a variety of optimization processes to obtain the right combination of volume and strength to achieve speeds over 40 knots in moderate seaways (low to mid Sea State 4). Additional monitoring and testing is required to understand all of the construction practices used by commercial industry. In addition, commercial vessels usually operate on well-defined routes and have significantly different operational patterns compared to a navy vessel which is required to perform a range of tasks over wide and variable operational areas.

In the early 2000, the US Navy has begun technology evaluations of high speed ships and crafts such as the Joint Venture (*HSV-X1*), followed by other aluminum catamaran such as *HSV-2 Swift* (Fig. 1) and Sea Fighter (*FSF-1*, also known as *X-Craft*). More information on these vessels can be easily found in the public domain such as http://www.globalsecurity.org/military/systems.

Fig. 1: All aluminum high-speed vessel *HSV-2 Swift*

The initial evaluations of *HSV-X1*, *HSV-2* and *FSF-1* were to monitor structural responses during dedicated rough water trials. In each case the trial objectives were to determine if the responses were nominal or acceptable when the ship is operated within the Safe Operational Envelop (SOE) defined by American Bureau of Shipping. The SOE provides guidance for the operation of the vessel since it is not permitted to operate unrestricted in the open ocean. *Thomas et al. (2003),* presents an example of such a trial conducted during the delivery voyage of a high-speed ferry, while *Pegg, Gilroy, and Kumar (1995)* give an overview of conducting a sea trial and finite element model verification through natural frequency predictions of a SWATH vessel. Such design verification is fairly routine practice today, however, both the sea condition and structural response monitoring equipment are typically removed or de-activated at the completion of the trial.

2. 1. *HSV-2* sea trials

To determine seaway loadings and to quantify structural performance as a function of sea state, speed, and heading, the *HSV-2* sea trials were conducted during winter/spring 2004, *Brady et al. (2004*). The vessel was instrumented with various types of sensors, placed throughout the ship, to monitor and evaluate response and performance at sea trials. The hull response gages were basically identified and segregated into three groups: primary load, global T1, stress concentration, local T2, and wave impact response T3, strain gage measurements. The global T1 strain gage locations were chosen based on a full-ship finite element model to capture primary load response. The local T2 strain gage locations were chosen to indicate the level of structural response in known or suspected areas of high stress. Few T2 gages are labeled as A-B pair located on the frame web, adjacent to cutout details (Fig. 2).

Fig. 2: Examples of local high stress T2 A-B pair strain gages

During the sea trials, the ship was operated in such a manner as to collect data at specific speed and heading combinations. By traversing an octagon course relative to the predominate wave direction, at certain speeds, strain data were collected at headings of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and so on. Wave height characterizing each test condition was measured with an on-board over-the-bow wave height system installed on the centerline bow of the ship. A wave buoy positioned within the octagon with the ship at low speed in head seas prior to each octagon was also used. In addition to the eight headings associated with the octagon course, data were collected at speeds of 10, 15, 20, 30, and 35 knots. Tie-ins to the ship's GPS and gyro systems provided verification of ship track course and speed.

There were a total of sixteen T1 strain measurements, twenty-three T2 strain measurements, and ten T3 measurements collected during the trials. T1 and T2 gages, continuously recorded data from the start until the end of each trial run (about 30 minutes), and were sampled at 100Hz. In addition, accelerometers were used to record ship motion in *e.g.* vertical and longitudinal directions in several locations. Fig. 3 shows an example of recorded global strain T-1 and vertical acceleration, which can be used to correlate high strains at a given time, in the bow area in one of the trial runs.

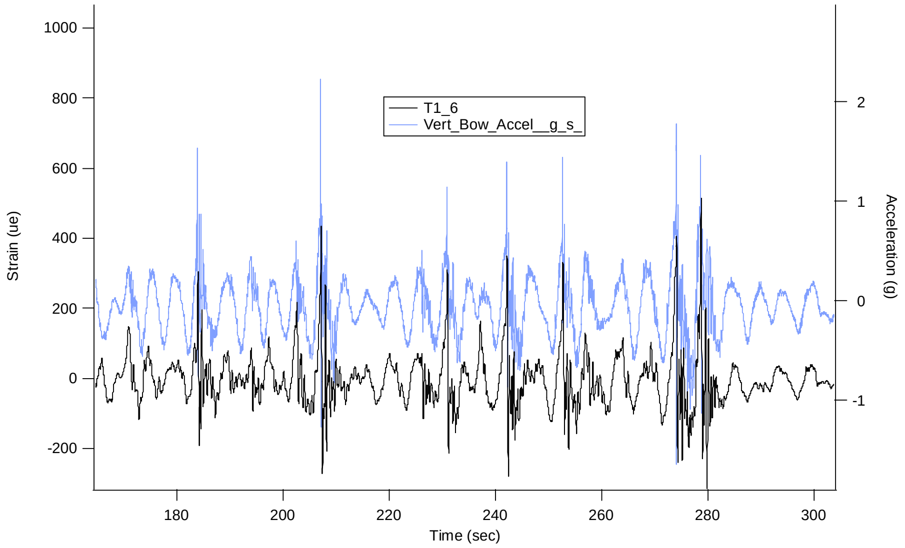


Fig. 3: Example of recorded global strain and vertical acceleration in the bow area.

The wave impact T3 measurements were made with strain gage located above the waterline in the bow region. These strain gages were installed to measure differential bending along selected T-bars or longitudinal stiffeners. In order to capture wave slamming, much higher sampling rate such as in kilohertz range is needed. As the result, much larger dataset will be generated. In the *HSV-2* trial, T3 measurements were sampled at 2,000 Hz and designed to be "event-triggered" recordings, that is the system will record data only when wave impact larger than predefined amplitude to capture slamming local responses. Examples of few T3 data in a 25 second time window are given in Fig. 4. It's evident that a wave slamming can induce large strain response of hull structure. From the recorded strain data, it is likely the large peak represents an overloading incident due to slamming. To monitoring such overloading event through an appropriate sensing system is very important for high speed vessels because slamming often occurs during normal operations at high sea state. Obviously, each overloading incident contributes to the overall ship structural fatigue.

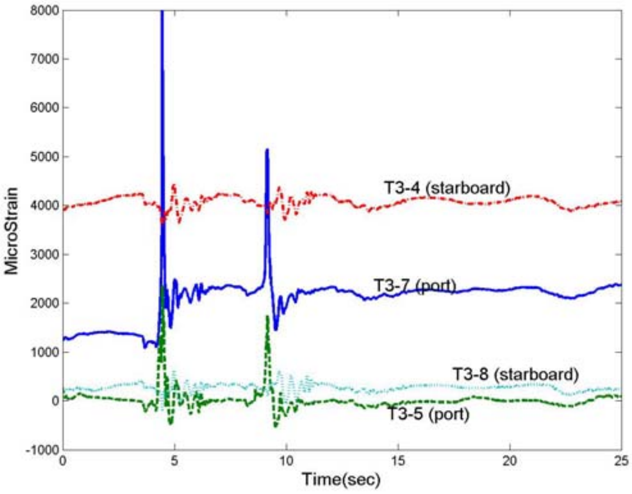


Fig. 4: Examples of T3 data in a 25 second time window.

In all evaluations of *HSV-X1*, *HSV-2* and *FSF-1*, the SOE was adequate in defining the space of operation as defined by speed and wave height. However, trial results did show that these vessels can endure significant wave impact loadings, at high speed, when operated near the edge of the SOE. Not all wave impacts, including slamming events, are detrimental but those that are can produce local damage that could go unnoticed until the next visual inspection. It is very difficult to determine the severity of these wave impacts during high-speed operations. Moreover, it is impossible to assess the effect of these wave impacts on local structure without a continued shipboard hull monitoring system. At a very basic level, a monitoring system would indicate to the operator when or if an overload has occurred. Knowing when to inspect after operation in high seas can save inspection time and help assess operational readiness.

2. 2. Development of continued structural monitoring

In the effort of further structural performance evaluation to support the on going acquisition of aluminum high speed vessels, the Joint High Speed Vessel (JHSV) program funded a spectral-based fatigue analysis for *HSV-2*. The findings are summarized in *Kihl (2006).* This report indicates that crack initiation could begin early in the life of the vessel. It is accepted that aluminum does not have the same fatigue strength as steel. *Sielski (2007)* stated that aluminum has a crack propagation rate under fatigue loading that can be as much as 30 times greater than that of steel under the same applied stress. In addition, marine grade aluminum will become sensitized over time when exposed to high temperatures. The sensitized material forms a continuous film along the grain boundaries of the material. It is possible for corrosion to rapidly spread along this film, resulting in a network of gaps in the material. These gaps can lead to stress corrosion cracking and exfoliation in the alloy resulting in total material/structural failure, *Wong et al. (2006).* At the present time, no techniques exist to indicate if the on board aluminum is sensitized. These facts greatly accelerated the interest in equipping Navy aluminum ships with an operational real-time monitoring system to find cracks and structural anomalies early or at least to provide structural response data that can be useful in identifying portions of the structure that require a more rigorous visual/local non-destructive evaluations. Although visual inspection cannot detect newly formed cracks, or cracks under insulation and machinery, it is the only means to identify flaws in practice today. Obviously, a rigorous inspection will be time consuming and costly so it should only be performed as needed. It is an important step forward if the information derived from the hull monitoring database can assist the maintainers so that they execute inspections and maintenance as required. Recently, few US Navy acquisition programs invested in the development of long-term hull and structural monitoring systems. An example is a hull condition-monitoring project for the JHSV program. Some of the details for JHSV hull monitoring system will be discussed in the context of addressing important issues for future ship board SHM implementations. In particular, the focus will be on current work that addresses issues regarding sensing architecture and data management for global response measurement and performance evaluation as well as for structural damage detection in critical areas.

It is important to note that the measurement system, both hardware and software, used for short term trials does not have the same constraints as a long-term monitoring system. It has become apparent through similar efforts that the hull monitoring system hardware must be relatively small in foot print and weight. Since these systems are being added on late in construction, the weight of the system will combine with other add-ons to reduce speed, payload, and endurance. A robust procedure/method needs to be in place to ensure sensor arrays and data acquisition systems function properly and generate valid data continuously. Software design architectures must be suitable for permanent use by the operators, maintainers, and ships force. A continued load and usage monitoring system will generate a large amount of data and information about the vessel constantly. These data are required not only to address the needs of real time operation and provide instantaneous feedback, they are also needed to maintain information for in depth analysis and potential future development needs. The information technology required handling real time data collection, analysis, display, transmission, and storage demands much more difficult tasks to perform compared to short-term verification trials.

2.3. JHSV hull monitoring system

In this section, a recent effort is discussed for the improvement of data acquisition software so that the systems can be used not only for short-term trials but the architecture will be suitable for long-term hull monitoring. In order to provide overload indicators for operators and condition based monitoring for maintainers, the system is being developed on two levels. The first level determines exactly what structural measurements are needed, providing only pertinent data that can be matched with the necessary analysis or assessment programs. The results of these analyses and other information including relevant data will be compiled and sent to the shore-based authorities through an automated reporting process. The return path for any necessary actions or requests for the crew will eventually be identified and added. The second level determines the information that must be displayed to the operator on the bridge. This would assist the operator to achieve the best speed and heading and to remain within the SOE. It will be most useful at night or in confused seas to guide the operator into the best speed and heading combination and possibly to achieve the lowest structural responses for the conditions at hand. It is understood that the need for this display will be limited to a few times during a transit. The display will also indicate that the system is functioning, which is very important and will probably be noted in the ships log. Having the crew monitor the system will also ensure that good data is collected and good information is supplied to the shore based maintainers.

The display screens must be relatively simple and updated in real-time allowing the operators to obtain pertinent data of structural response in an active seaway. On the other hand, the monitoring software includes a set of background processes to provide additional analyses and information as needed. More details of these background processes, also known as the Analysis Engine, include statistical calculations, load and fatigue damage accumulative estimations, and periodic reporting, *Hildstrom (2007).* This hull monitoring software is designed in tiers providing details as needed. Fig. 5 shows overall forms and functions of the current implementation.

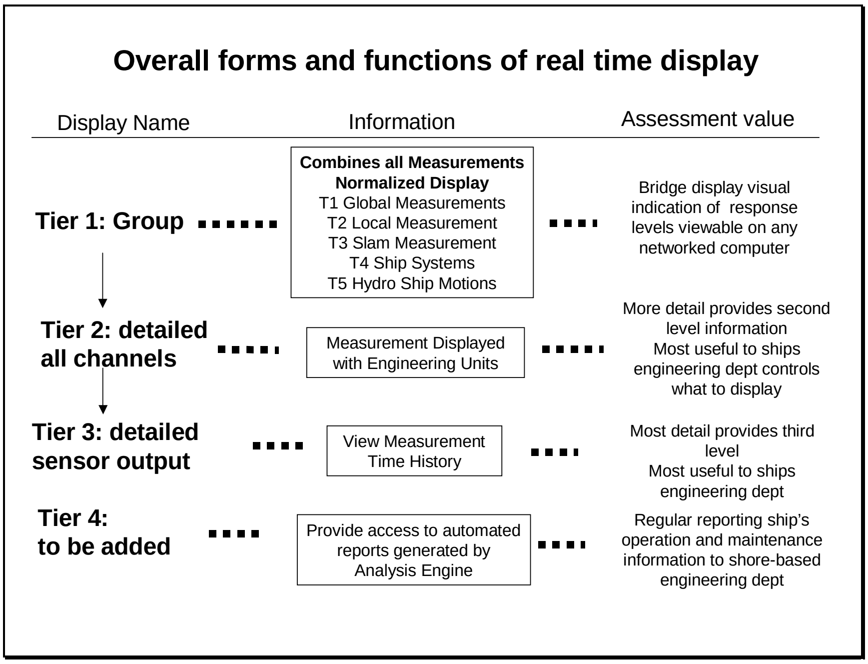


Fig. 5: overall forms and functions of the current software implementation

An example of the display process for the global stress T1 group is shown in Fig. 6, demonstrating how all tiers of infomation can be accessed using the bridge monitor. Starting from Tier 1, the overall sensor and data information can be viewed in whole. Tier 1 should be the only screen an operator would need. If an operator needs more information, he/she can select more detail using buttons on the left. If there is concern that a redline indicator is false the detailed displays can help support that decision and remove the sensor from the display group. Ideally, the operator on the bridge could ask for additional analysis from the duty engineer or crew member. The crew member would interrogate the system using the detail button to determine if a sensor is bad or if there really is an overload to the structure. The screen can provide the operator with the ability to detect overloads and track current trends with historical data (Red X). Bars move at or near real time and can be used by the operator to adjust speed or heading. The display runs on the dedicated bridge display screen or an existing computer connected to the monitoring system and it can run at multiple locations. If needed, detailed data for all channels of T1 group can be obtained in Tier 2. Tier 2 group can be used to remove faulty sensor output and to add or remove sensors to be used in averaging data (maximum, mean, minumum, etc) of this group. Each channel time history can be viewed from Tier 3 level. This display is useful to spot bad sensor signals quickly.

The Analysis Engine reports are to be added under detail button in Tier 4. Additional measurements, analysis algorithms, damage diagnosis, and prognosis tools that developed specifically for SHM can be added as they become available as Tier 5, Tier 6,... etc. Examples of possible future additions are discussed in sections to follow.

To summarize, knowledge and experience gained through sea trials can provide valuable information for the development of a hull condition monitoring system to perform functions such as continued load and usage monitoring. A major improvement of software design and data management issues is addressed for the current JHSV hull condition monitoring system. Most importantly, the current system is designed for easy future upgrade as more advanced SHM technologies such as, statistical feature extraction algorithms, and real time damage detection and diagnostic tools that can identify early signs of cracks and other structural damage become mature.

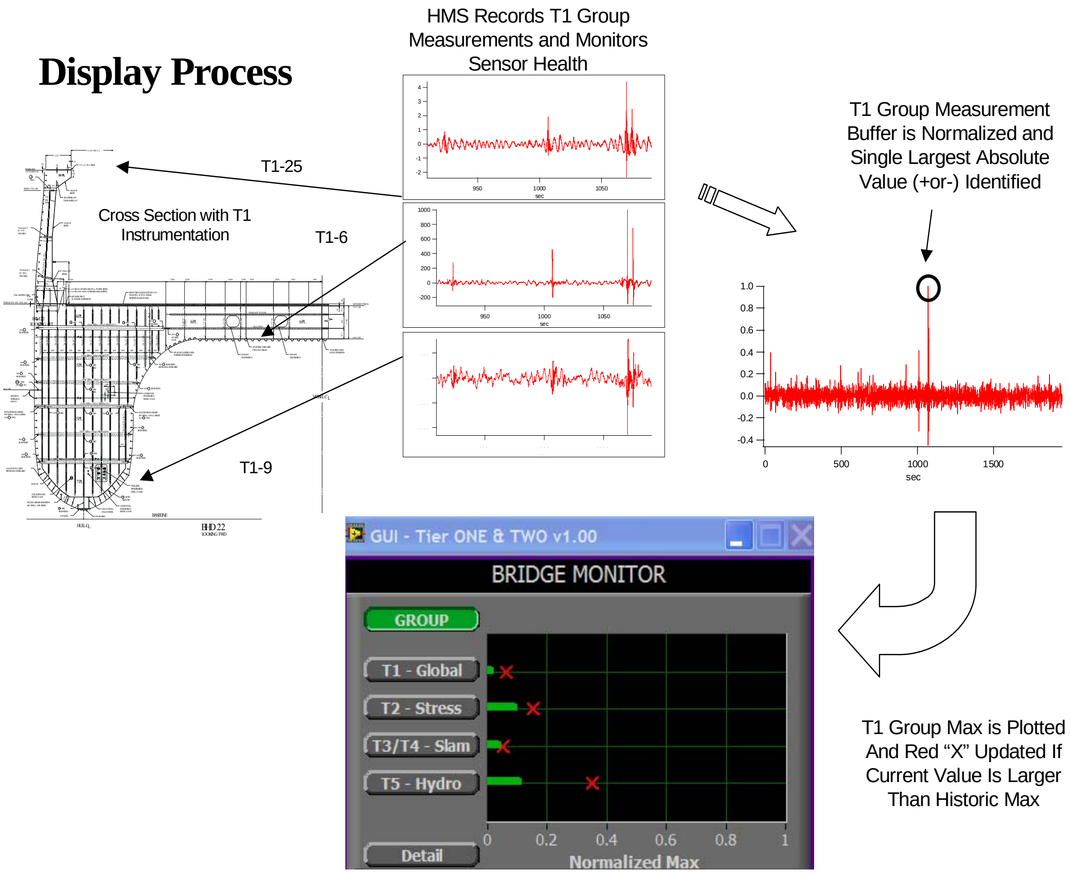


Fig. 6: Example of measurement and information display

3. Structural Health Monitoring for Ship Hull and Structural Components

As discussed previously, the US Navy has been monitoring ship structures for decades during short dedicated rough water trials. These efforts provided valuable experience for the development of real-time on board SHM systems that are capable of assessing structural degradation by detecting, locating, and quantifying material or structural component damage using measured data (from past and present) and to establish real time state awareness through a diagnostic and prognostic algorithms and analysis tools to allow the appropriate authority to make intelligent deployment and maintenance decisions. However, this envisioned SHM system is particularly challenging because of the physical size of ship structures, the widely varying and often extreme operational and environmental conditions associated with these ships' missions, lack of data from known damage conditions, limited sensing that was not designed specifically for SHM, and the management of the vast amounts of data that can be collected during a mission.

One of the SHM methodologies available for ship structures implementation is vibration-based damage detection, which is based on the principal that damage in a structure, such as material yielding, a loosened connection or a crack, will alter the dynamic response of that structure. There has been much recent work in this area that is summarized in detailed reviews of vibration-based SHM *Sohn et al. (2003).* Because of random and systematic variability in experimentally measured dynamic response data, statistical approaches are necessary to ensure that changes in a structure's measured dynamic response are a result of damage and not caused by operational and environmental variability. Although much of the vibration-based SHM literature focuses on deterministic methods for identifying damage from changes in dynamic system response, we will focus on approaches that follow a statistical pattern recognition paradigm for SHM, *Farrar and Worden (2007*), which is directly applicable for structural response data recorded during a sea trial. This paradigm consists of the four steps of 1. Operational evaluation, 2. Data acquisition, 3. Feature extraction, and 4. Statistical classification of features. Each portion of the paradigm will now be discussed in the context of applying it to damage detection in ship structures using *HSV-2 swift* sea trail data.

3.1. Operational evaluation

Operational evaluation attempts to answer four questions regarding the implementation of a damage identification capability: 1. What are the life-safety and/or economic justification for performing the SHM? 2. How is damage defined for the system being investigated and, for multiple damage possibilities, which cases are of the most concern? 3. What are the conditions, both operational and environmental, under which the system to be monitored functions? 4. What are the limitations on acquiring data in the operational environment?

Operational evaluation begins to set the limitations on what will be monitored and how the monitoring will be accomplished. This evaluation starts to tailor the damage identification process to features that are unique to the system being monitored and tries to take advantage of unique features of the damage that is to be detected.

For most large defense systems, the lifetime maintenance costs typically exceed the purchase price of those systems. Therefore, there is significant economic advantage to be gained by reducing these maintenance costs, which motivates the development of SHM systems for ship structures. Clearly, because people will be operating these ships in adverse environments, both man-made and natural, a robust SHM system can potentially prevent harm to the crew by alerting the operators to damage before it reaches a critical state. Therefore, there is also a life-safety motive for developing SHM systems for these ships.

For the *HSV-2 Swift* ship it is anticipated that three types of damage are of interest: 1. Yielding of structural elements, 2. Crack initiation and propagation (particularly at joints), and 3. Corrosion. However, there is no *a priori* knowledge of where this damage might occur and no definition of critical levels of damage that must be detected. Corrosion is not considered in any of the subsequent analyses of the sea trials primarily because it was felt that the instrumentation system used was not adequate to detect this type of damage and because the age of the ship and the short duration of the sea trials make corrosion an unlikely damage condition.

During the sea trials data were acquired in a variety of operational and environmental conditions including different ship speeds, different heading relative to the wave direction and different sea states as shown in section 2. Similar variations will be encountered when ships are deployed on their various missions. Other than variations in fuel loads, the mass of the ship does not appear to have changed in these sea trials and this variable has not been considered in the analyses of these sea trials data. However, careful consideration of variable mass loading will be necessary for an operational vessel carrying different military stores, and particularly if ice buildup is a possibility. Note that many of the ship’s operational parameters (e.g. engine rpms, and ship speed) are currently monitored and can be recorded along with the primary SHM sensor readings. Such operational data will be key to the data normalizations process.

Because the current study did not design the data acquisition system, but rather is analyzing previously acquired data, answers to most of the operational evaluation questions regarding deployment of the data acquisition system were not addressed. For an aluminum structure limitations associated with data acquisition result from the physical size of the structure, wire maintenance, difficulties with wireless data transmission in metallic structures and issues such as insulation covering the structural elements. It is anticipated that a significant outcome of this study will be insight gained from analysis of these sea trials data that can be used to answer the operational evaluation questions when a system designed specifically for ship SHM is developed in the future.

3.2. Data acquisition, normalization and cleansing

The data acquisition portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware. This process will be application specific.

Economic considerations will play a major role in making these decisions. The intervals at which data should be collected are another consideration that must be addressed. Data utilized in this study represent dynamic ship structure response measurement including strain and acceleration intended to capture both local and global ship structure response. However, as previously mentioned, this sensing system was not designed with on board SHM in mind. There is a clear need for developing an optimal SHM sensing strategy based on the defined threshold levels of damage (identified during Operational Evaluation), anticipated loading and in consideration of a fixed sensing budget. However, currently a significant gap in SHM technology is the lack of any validated sensor network design procedure.

Because data can be measured under varying conditions, the ability to normalize the data becomes very important to the damage identification process. Fig. 7 shows an example of two different strain measurements made while operating the ship at different speeds. A robust damage detection system will have to be able to normalize the data to account for such sources of variability. As it applies to SHM, data normalization is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. When environmental or operational variability is an issue, the need can arise to normalize the data in some temporal fashion to facilitate the comparison of data measured at similar times of an environmental or operational cycle. Sources of variability in the data acquisition process and with the system being monitored need to be identified and minimized to the extent possible. In general, not all sources of variability can be eliminated. Therefore, it is necessary to make the appropriate measurements such that these sources can be statistically quantified. Variability can arise from changing environmental and operational conditions, changes in the data reduction process, and unit-to-unit inconsistencies. For the *HSV-2* trial data such as ships speed, fuel levels and headings relative to the wave direction are measured and can be use to develop a data normalization scheme.

Data cleansing is the process of selectively choosing data to pass on to or reject from the feature selection process. The data cleansing process is usually based on knowledge gained by individuals directly involved with the data acquisition. Signal processing techniques such as filtering and re-sampling can also be thought of as data cleansing procedures. In this study we have relied upon our familiarity with these sea trials to select specific data sets for subsequent analyses.

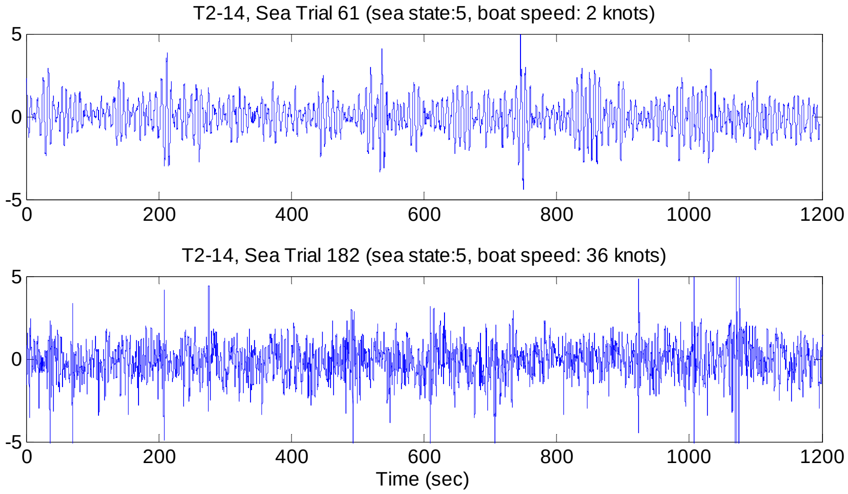


Fig. 7: Variability in dynamics response resulting when measurements were made with the ships operating at different speeds.

3.3. Feature extraction and information condensation

A damage-sensitive *feature* is some quantity extracted from the measured system dynamic response data that is used to indicate the presence of damage in a structure. Identifying features that can accurately distinguish a damaged structure from an undamaged one is the focus of most SHM technical literature. Fundamentally, the feature extraction process is based on fitting some model, either physics-based or data-based, to the measured system response data. As an example, an autoregressive time series model AR(p) of order p is given in Eq. (1). The parameters of these models, *i.e.*, ϕ_j, or the predictive errors associated with these models *i.e.*, e_i, then become the damage-sensitive features.

$$x_i = \sum_{j=1}^{p} \phi_j x(i-j) + e_i \tag{1}$$

Fig. 8 shows the prediction of order 15 autoregressive time series model to the measured strain gage from the *HSV-2* trial. As can be seen in this figure, the time series model accurately models the response data and subsequent changes in this modeling capability can be used as an indicator of damage. An alternate approach is to identify features that directly compare the data waveforms or spectra of these waveforms.

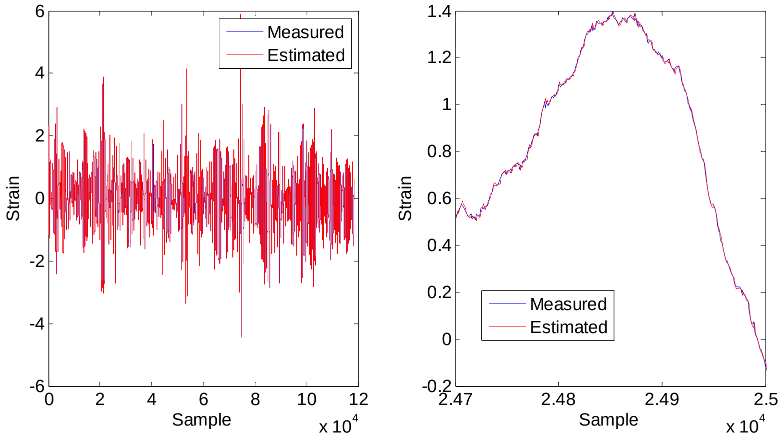


Fig. 8: Comparison of the measured and estimated time histories using the AR(15) model fit to Run 61 from strain gage T2-14.

Ideally one should select a feature that is sensitive to the presence of damage in the structure and insensitive to all forms of operational and environmental variability. However, in most real-world applications, features that are sensitive to damage are also sensitive changes in the dynamic system response not related to damage, *Worden, K., Farrar, C. R., Manson, G. and Park, G. (2007)*. If multiple type of damage are possible, as is the case with ship structures, it may require different features to be extracted from the data in an effort to identify these different types of damage.

One of the most common methods of feature extraction is based on correlating observations of measured system response quantities with the first-hand observations of the degrading system made by the system operators or maintenance personnel. Another method of developing features for damage detection is to apply engineered flaws, similar to ones expected in actual operating conditions, to systems and develop an initial understanding of the parameters that are sensitive to the expected damage. The flawed system can also be used to validate that the diagnostic measurements are sensitive enough to distinguish between features identified from the undamaged and damaged system. The use of analytical tools such as experimentally-validated finite element models can be a great asset in this process. In many cases the analytical tools are used to perform numerical experiments where the flaws are introduced through computer simulation. Damage accumulation testing, during which significant structural components of the system under study are subjected to a realistic degradation, can also be used to identify appropriate features. This process may involve induced-damage testing, fatigue testing, corrosion growth, or temperature cycling to accumulate certain types of damage in an accelerated fashion. Note that any such destructive testing approaches to feature identification can be costly and are typically prohibitively expensive for large capital expenditure systems such as ship structures. Insight into the appropriate features can be gained from several sources and is usually the result of information from some combination of these sources.

With the *HSV-2 Swift* in mind, crack formation will be accompanied by local strain relief that manifests itself as a DC offset in the local strain gage readings. However, based on St. Venant's Principle, this strain relief will not be observed at any significant distance from the crack location. Yielding is also associated with DC offsets in local strain readings resulting from the permanent deformation that characterizes this phenomena. Yielding is particularly difficult to detect in metallic structures based on dynamic response measurements because once the load that produced yielding has been removed, the structure typically exhibits similar stiffness properties as it did prior to yielding. If crack opens and closes under subsequent loading then there will be specific features such a harmonic generation that are indicative of this process. Also, crack initiation and growth is usually accompanied by the propagation of an elastic wave and the transient response associated with such an event can be detected with a strain gage, acoustic emissions sensor or accelerometer given appropriate location of these sensors, appropriate sensitivity of the sensors and appropriate sampling parameters.

3.4. Statistical model development

Statistical model development is concerned with the implementation of the algorithms that operate on the extracted features to quantify the damage state of the structure. The algorithms used in statistical model development usually fall into three categories. When data are available from both the undamaged and damaged structure, the statistical pattern recognition algorithms fall into the general classification referred to as *supervised learning*. *Group classification* and *regression analysis* are categories of supervised learning algorithms. *Unsupervised learning* refers to algorithms that are applied to data not containing examples from the damaged structure. *Outlier* or *novelty detection* is the primary class of algorithms applied in unsupervised learning applications. All of the algorithms analyze statistical distributions of the measured or derived features to enhance the damage identification process.

The damage state of a system can be described as a four-step process to answers the following questions: 1. **Existence**: Is there damage in the system?; 2. **Location**: Where is the damage in the system?; 3. **Type**: What kind of damage is present?; 4. **Extent**: How severe is the damage? Answers to these questions in the order presented represent increasing knowledge of the damage state.

In this study we are primarily concerned with identifying the *Existence* of damage in an unsupervised learning mode. The use of unsupervised approached is motivated by our lack of knowledge regarding the damage condition corresponding to any of the data sets made available for this study and by the fact that a SHM system deployed on a ship will most likely have to function in an unsupervised learning mode. Because three of the damage types identified as concerns for aluminum ship structures (corrosion, cracking and yielding) have distinct characteristics, we believe it is possible to address the *Type* of damage question as well. Because the ship is sparsely instrumented relative to its size, it is not clear if the *Location* question can be adequately addressed if damage has the potential to occur at random locations over wide areas of the ship's structure. Most structural systems have areas that are more susceptible to damage than other, and ideally instrumentation is concentrated in these areas. In the case of the *HSV-2 Swift*, the local T2 strain gages has been placed with this consideration in mind, but it is possible that additional locations of concern were not instrumented due to hardware (number of channels) limitations.

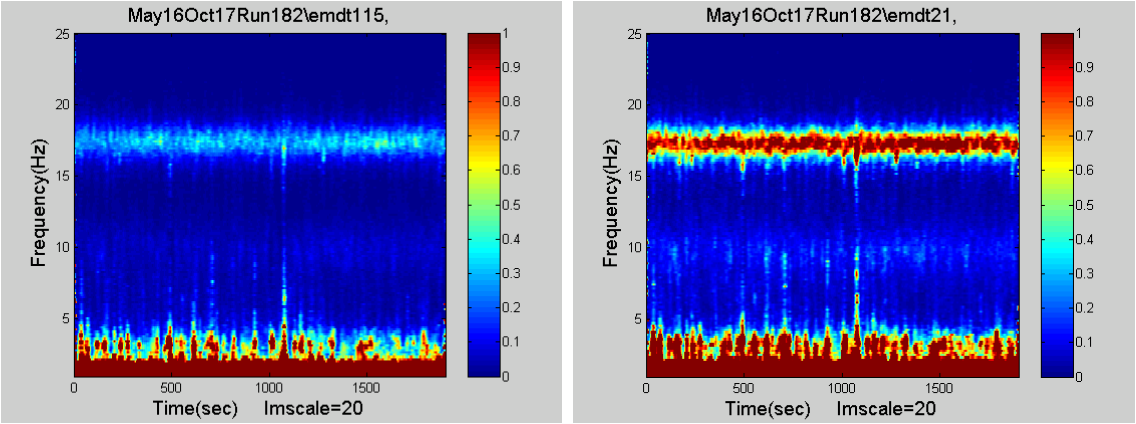
4. Hull Monitoring and Damage Detection via Optimal Sensing Strategy

Like most large and complex civil and aerospace structures, ships can only be sparsely instrumented relative to its size. Therefore, it is critical to develop an optimal SHM sensing strategy to support structural monitoring needs as discussed in section 3.1. It may be necessary to implement a multiple stage / multiple tier sensing and data processing plan for SHM. On the global level, a real-time, onboard sensor network combined with dynamic based damage detection algorithm can pinpoint possible problems and identify their approximate locations in timely fashion. Then, further evaluations are justified using more localized techniques as well as incorporate sensor and inspection information into fracture-based fatigue models to evaluate details of known or suspected flaws. In addition to sensing systems, data acquisition such as intervals at which data should be recorded, interrogation methods for local damage detection and diagnostics, as well as data transmission, storage, and processing all needs to be appropriately considered. Mostly likely, an effective on board SHM system will contain multi-tiered sensing and data processing architecture.

4.1. Global vs. local structural monitoring

Sensors used for global load and structural response monitoring of a ship can be relatively sparse. In particular, traditional mono-hull ships require relatively low sensor densities to capture the global behavior. Although data should be recorded continuously, sampling frequencies can be relatively low.

As discussed for *HSV-2* instrumentations, the global T1 strain gage locations were chosen based on a full-ship finite element model to capture primary load response. The local T2 strain gage locations were chosen to indicate the level of structural response in known or suspected areas of high stress. Examples of T1 and nearby T2 data are shown in Fig. 9 in the form of time-frequency spectra, which displays structural response frequency as a function of time with the normalized response amplitude distributions. These time-frequency spectra were calculated using Empirical Mode Decomposition and Hilbert-Huang Transform, *Huang, N.E., et al. (1998).*



(a) **(b)**

Fig. 9: Time-freqeuncy spectra of measured global strain (a) and local strain (b)

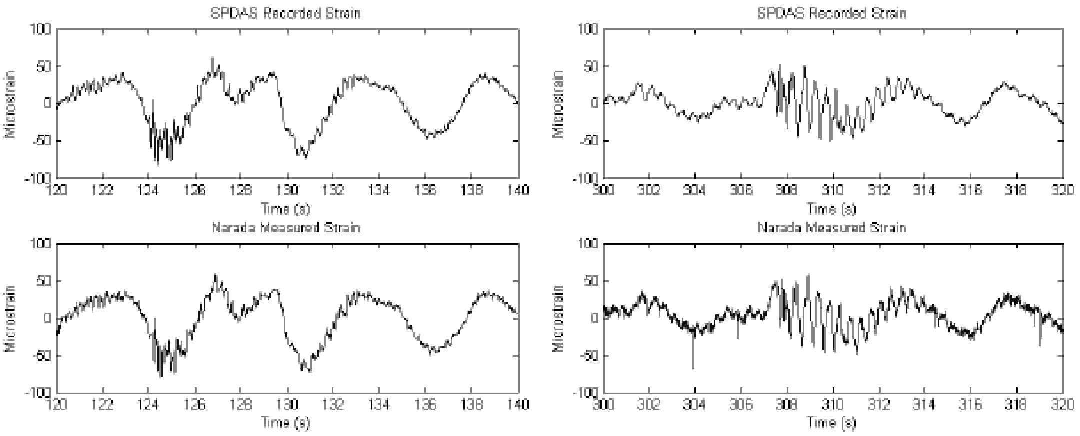
The global strain T1 and local strain T2 in Fig. 9 (a) and (b), respectively, clearly indicates that most local structural response frequencies are between 15Hz to 20 Hz, while the global responses are below 5 Hz. In addition, as shown in recent studies using time-frequency analysis by *Salvino and Brady (2007)*, local structural response due to wave-slamming depends on both wave impact magnitude and time duration. In contrast, hull and structural component responses due to seaway loading, in general, can be considered as time invariant. Long term hull monitoring sensing and data acquisition system should be designed to include both global and local structural monitoring needs in an efficient manner.

4.2. Dense sensor array using wireless transmissions

Monitoring ships with more complex hull forms such as those often seen for high speed vessels require a higher density of sensors to capture the vessel global behavior. With structural damage detection in mind, sensors such as strain gages need to be located in the vicinity of crack formation sites. Although it is possible that damage has the potential to occur at random locations over wide areas of the ship's structure, our experience base as well as numerical analysis tools can provide sufficient knowledge to indicate the areas that are more susceptible to damage. Therefore, SHM and specialized on board sensors can be densely placed in these areas to detect structural damage.

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 wired (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 and bridges. In this study, a low-cost wireless sensor platform developed at the University of Michigan is used 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, *Swartz, et al (2005)*. 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.

A recent wireless hull monitoring demo is discussed below to provide an example for dense sensor array monitoring options. This dense network of wireless sensors (Narada) is installed on the *FSF-1 SeaFighter* to measure its strain and acceleration response during ship transits in the Atlantic and Pacific Oceans. Recorded data from Narada in comparison with existing measurement system - The Scientific Payload Data Acquisition System (SPDAS) which is wired backbone system are shown in Figs. 10 and 11. Detailed descriptions of this entire experiment can be found in *Lynch et al (2009)*.



(a) (b)

Fig. 10: Strain response on SeaFighter Frame 20:
(a) channel 2 (longitudinal) and (b) channel 3 (vertical)

The strain time histories recorded during rough seas on the Pacific are shown in Fig. 10. Strain time histories are shown for both channels 2 (longitudinal strain of the ship) and 3 (vertical strain in the frame itself) recorded by 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 με. 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 Fig. 10, 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 Fig. 11, the acceleration time histories measured at the *SeaFighter*'s center of gravity are identical. Again, a slamming event is observed at roughly 145 seconds.

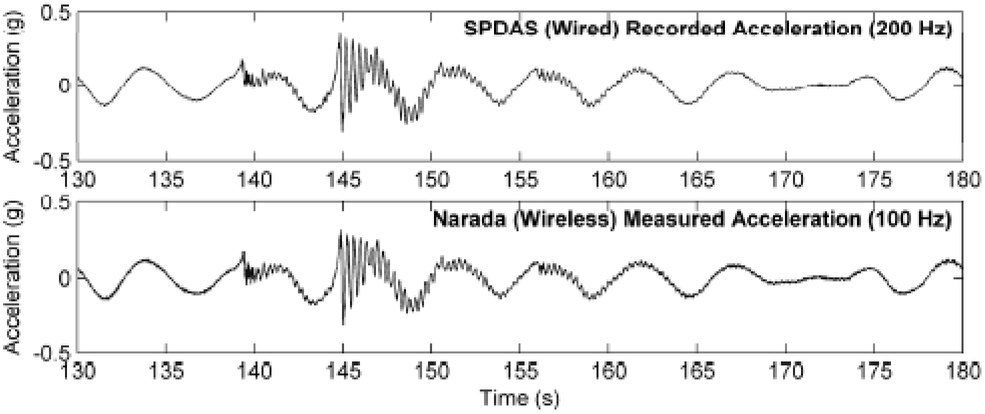


Fig. 11: Acceleration response of the *SeaFighter* measured at the center of gravity.

4.3. Embedded data processing for hull monitoring

Costs and weight savings are known benefits of wireless sensors. Aside from cost, other long-term benefits associated with a wireless system include flexible topology formation that can self-heal during battle damage and embedded computing with each sensor. Unlike wired sensors that centralize data storage and processing at a single central unit, wireless sensors can conduct data processing at the individual sensor nodes. The intelligent wireless sensors can process their own data for signs of damage represent a powerful and scalable approach for SHM, *Lynch and Loh, (2006).* Examples of embedded local processing for wireless sensors are to compute fast Fourier transforms, to determine model properties, to compress data using wavelet transforms, and to identify damage based on autoregressive time series models such as shown in Eq. (1).

Examples of sensor-node-capable computations are to perform modal analysis using the wireless acceleration response data collected during *SeaFighter* transient on Pacific. An output only frequency domain decomposition (FDD) analysis method is employed to derive the operational deflection shapes of the *SeaFighter*. The spectra are dominated at low frequencies by the rigid body motion of the ship as it travels over sea waves. In particular, 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 Fig. 12, 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. The wired SPDAS 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 Fig. 12. The two operational deflection shapes obtained from the SPDAS system confirm the findings obtained by the wireless hull monitoring system.

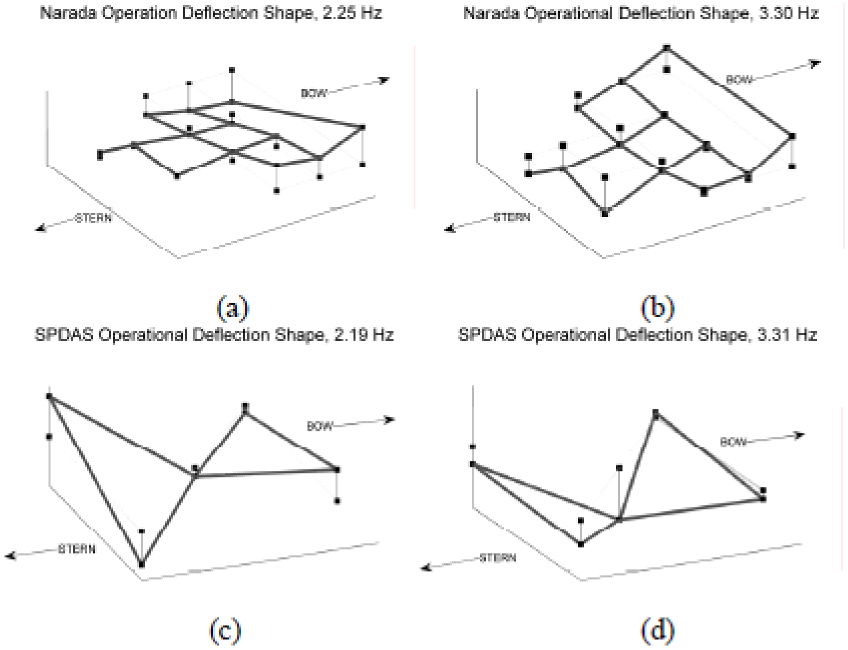


Fig. 12: Operational deflection shapes:
(a) 2.3Hz and (b) 3.3Hz (wireless); (c) 2.3Hz and (d) 3.3Hz (wired)

As mentioned previously, known structural hot-spots such as joints and weldments can be instrumented with closely spaced strain gages to record the hull response under cyclic wave loading. Currently, strain data is measured for storage and future analysis. However, sensors such as wireless sensors couple intelligence (*i.e.* computational power) at the sensor. Computing resources collocated with the sensor allows the sensor to continuously process measurement data for signs of damage. Another advantage of this is the sensor is effectively converting high-bandwidth data streams into low-bandwidth streams. A potential future work is to perform fatigue analysis at the wireless note. For instance, the classical rain flow counting algorithm can be embedded into the sensor to continuously and autonomously count strain peaks. Using peak amplitude strains (S) and the accumulated number of peaks (N), Miner's rule and the appropriate S-N curve for the ship's aluminum alloy are embedded to roughly track the fatigue life of the instrumented hull detail.

To summarize, the global/local multiple stage sensing approaches can enhance the potential for finding damage early in the damage progression as well as perform the assessment for the entire ship to support remaining life or time-to-repair prediction, and to prevent catastrophic failure. As technologies become more sophisticated, such an approach could also provide feedback on how to operate the vessel for a given damage condition and provide the opportunity to greatly improve operability, maintenance and repair strategies.

4. Summary and Discussions

SHM technologies are needed to monitor ship hull and structural integrity as U.S Navy and maritime industry designs increasingly rely on lightweight materials such as composites and aluminum for high speed and high performance ships. Although ship structures have been monitored for decades during short dedicated design verification trials by measuring seaway loading to quantify structural performance as a function of sea state, speed, and heading, the continued load and usage monitoring are still very much new endeavors for the U.S Navy. While these structural and load monitoring systems can provide useful data and are growing in complexity, most of them do not make any attempt to diagnose the current health of the structure or detect and localize early-stage damage such as fatigue crack propagation. Likewise, prognosis applications of the current generation systems tend to revolve around recording strain cycles and estimating the percentage of a pre-determined fatigue budget that has been consumed to date.

On board SHM systems, both hardware and software must be suitable for permanent use by the operators, maintainers, and ships force. The basic architecture can be developed based on verification trial measurement systems. An example of such development for a hull condition-monitoring project of the JHSV program has been discussed in this paper. It is important to note that systems used for short term trials do not have the same constraints as long-term functions. In particular, sensing and data processing design architectures need to be able to incorporate new technologies as they become mature. SHM data are required not only to address the needs of real time operation and provide instantaneous feedback to the operators, they are also needed for longer-term maintenance considerations as well as more in depth analysis and potential future development. These considerations are being implemented in the current JHSV hull-monitoring program. Software of this hull monitoring system is designed in tiers, which will provide needed data and information about the ship. This development effort, although incremental, will provide valuable experience for future Navy SHM development needs.

This paper also presented a four-step SHM paradigm that the authors believe must be used to guide the development of SHM system for ship structures. There are many technical challenges associated with this SHM application. These challenges include but certainly are not limited to the ability to define the damage to be detected in a quantifiable manner *a priori*, the ship's physical size and structural complexity, designing the optimal SHM data acquisition system, the widely varying operational and environmental conditions, and the management of the large data volumes that will be obtained with an SHM system.

It is critical to develop an optimal SHM sensing and data processing strategy for ship structures. A multi-tiered sensing and data processing plan is discussed. On the global level, a real-time, onboard sensor network combined with dynamic based damage detection algorithm can pinpoint possible problems and identify their approximate locations in timely fashion. Then, further evaluations are justified using more localized techniques as well as incorporate sensor and inspection information into fracture-based fatigue models to evaluate details of known or suspected flaws. A wireless hull monitoring system allows for a dense installation of sensors in a single ship without incurring an exorbitant cost and weight. Demo wireless hull monitoring system is installed on the *FSF-1 SeaFighter*. During ship transient 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 sensors 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 can be performed to embed data interrogation and processing algorithms at the sensors note to allow the wireless hull monitoring system produce SHM function in near real time.

To minimize the risk of operating high-speed vessels in an unrestricted manner will require on board SHM system. The long-term goal of real-time structural health monitoring and diagnosis is to identify signs of fatigue or structural overload damage, *i.e.* to detect structural anomaly at the earliest possible stage through on board sensor networks and diagnostic algorithms. This structural diagnostic information can then be used to predict the time to repair or potential structural failure, and to provide strategies for corrective actions in order to support future Navy operation and maintenance needs.

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