

SSC-401

**STATE OF THE ART
IN
HULL RESPONSE MONITORING
SYSTEMS**

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<p>16. Abstract</p> <p>This report describes the commercial state of the art in Hull Response Monitoring Systems (HRMS) for open ocean and ice transit. Sources of information include secondary research into over 200 technical papers, plus surveys of current manufacturers and ship operators.</p> <p>The paper outlines the function of an HRMS in tactical ship handling decisions to reduce ship motions and hull stresses, including stresses during cargo loading. The paper also outlines the potential applications for HRMS in strategic voyage planning and optimization, including networking with remote sensor and data processing assets.</p> <p>The primary intent of the report is to educate prospective buyer/users about the available equipment and sensors, and which options will best serve their needs. The report appendices include sample screen displays and points of contact for HRMS and sensor manufacturers.</p> <p>Particular problems associated with ship transit in ice are addressed. Recommendations include new development of ship-mounted ice sensors, development of analytical/display software to allow prediction of ice thickness and lateral pressure trends as a function of time and ship speed. Until these tools are available, ice-class ship will have to rely on physical senses and hull rupture measures, such as flood alarms.</p>			
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STATE OF THE ART IN HULL RESPONSE MONITORING SYSTEMS

1.0 EXECUTIVE SUMMARY

The objective of this Ship Structure Committee-sponsored report is to describe the current state of the art in Hull Response Monitoring Systems (HRMS). Its explanatory format is intended to accomplish the following goals:

- Summarize the environmental threats posed by sea and ice loads to ship structures, and the types of hull responses that need to be measured;
- Describe the functional HRMS elements necessary to measure, display, and record ship hull responses;
- Explain how an HRMS, either alone or augmented by remote information, can be used to avoid or lessen the dangers associated with sea and ice loads; and
- Review currently available equipment and systems, and assist system buyers to select the options that best serve their needs.

In its most basic form, an HRMS is a system that measures and displays key ship motions and hull structural responses. By monitoring real-time motions and stresses, mariners can determine the onset and severity of hull structural response to the sea and, if suitably configured, ice. Hull response can be measured either directly by strain gauge or indirectly by monitoring pressures and motions (typical for slamming). Mariners can then initiate ship handling changes (course and/or speed) to mitigate dangerous stress levels and other hazards.

HRMS capabilities can be extended by measuring, recording, and analyzing hull stresses in conjunction with other ship motion, navigational, and performance data. Extended benefits include fatigue assessment, decision rules and guidance to assist the mariner in mitigating current dangers, and quantifying design constraints for future ships. In its most expansive form, an HRMS can be integrated with remote assets such as weather prediction to optimize routing on the basis of hull response, ship motion, fuel consumption, and other parameters.

An industry survey shows over 200 HRMS have been installed, and there are at least 11 currently active manufacturers. Past installations have been voluntary, by ship owners or researchers with specific needs and concerns. There are several ongoing efforts to institutionalize HRMS installation through regulation (IMO, Canadian Coast Guard) and classification society action. IMO is developing HRMS rules for bulk carriers, and ABS, Lloyd's Register, and DnV all offer HRMS guides and classification notations. All but one of the six firms responding to the Manufacturer's survey measure basic hull girder response with deck-mounted strain gauges. Most manufacturers offer additional sensors and capabilities, including position (GPS), motions (accelerometers, gyros), hull hydrostatic pressure (external and in-tank), weather and motion prediction, and linkage to other ship instruments such as speed, power, and cargo loading.

While HRMS applications to wave-induced structural response has matured as an industry, most applications on ice-class ships has been for research purposes. Attempts have been made to provide an “operational” display of measurements to assist safe navigation in ice.

Unfortunately, these systems have had limited practical use, and bridge displays are commonly turned off. A review of the requirements for ice-class vessels found that system response, sensor type, data acquisition, and environmental requirements are met by available open water systems. However, the arrangement and offsets of sensors, and the software requirements for ice load measurement and display are quite different from those for open sea loads. The ice application review has identified the following needs not met by the state of the art, for which R&D funding is recommended:

- Shipboard sensors to locate and measure ice in adverse conditions
- Either new hull response sensor development or new analytical software using existing sensor input to monitor, display, and perform trend analysis of ice loading.

Until this technology is developed, ice-class vessels must rely on hull integrity sensors (flood alarms, etc.) and remote sensor networks (satellite, aircraft, fixed stations) for safe navigation through ice.

An HRMS has three complimentary goals aboard ship:

- (1) minimize the risk of encountering dangerous seas and ice,
- (2) alert the mariner to the onset and severity of those conditions not avoided, and
- (3) provide ship handling guidance to mitigate their effect.

These operational goals strongly influence the display and remote sensing integration aspects of HRMS design. Shipboard users emphasize the clear presentation of a limited data set and system reliability. Shore-side maintenance support personnel use recorded HRMS data to monitor the condition of a ship’s structure. The design community uses HRMS data to quantify design criteria and improve structural design. For these reasons, shore-side users emphasize the importance of sensor accuracy, data storage, and long-term fatigue data acquisition. Optimal HRMS design must therefore be based on a number of factors:

- Type of ship and cargo
- Trade route characteristics
- User objectives.

This report explains the types of measurements and HRMS characteristics important to each application, and then describes the industrial state of the art and the equipment available to meet user needs.

2.0 INTRODUCTION AND INDUSTRY OVERVIEW

Although mariners have always monitored their ships through their physical senses, hull monitoring has only emerged as a separate technology over the last 30 years, in parallel with micro-computer technology. Developments have been spurred by regulatory bodies, classification societies, universities, and ship owner/operators.

2.1 Current and Future HRMS Applications

This report summarizes the current state of the art in Hull Response Monitoring Systems. It is based upon secondary research (including a review of over 200 technical papers) and on Manufacturer and Operator surveys. Assessments are made of the types of measurements, the equipment and sensors used, how the results are stored and displayed, and how these systems are linked into other information networks. This review of the industry reveals a current state of the art oriented toward the tactical (shipboard) level, and a developing role in computerized strategic voyage planning:

At-Sea Operational Guidance

The primary role of the HRMS is to alert ship's force to the onset and severity of hull structural risk. To the extent developed, the HRMS may provide ship handling guidance to lessen the severity of ship motions and hull stresses, including storm avoidance using weather predictions. These functions are fully supported by the current industry state of the art¹.

Route and Schedule Planning

When linked with remote sensing systems to project near-term weather predictions, routing and scheduling can be altered to minimize storm encounter and maximize trip efficiency. This function is theoretically complex, requiring the combination of ship response characteristics (either calculated or determined empirically through HRMS measurements) with weather predictions on some probability basis. Because of the statistical and random nature of ice loading, the use of an HRMS to record trends in ship response has been limited, the majority of successful systems being for research and development, including design data collection. Advances in satellite imagery for ice navigation, in concert with radar and onboard displays, have led to improvements in ice route selection that rely little on shipboard response sensors.

2.2 An Industry Overview by Survey

Brief surveys were conducted among HRMS manufacturers and users to determine the current status of HRMS deployment. The answers have been used throughout this report to describe the state of the art. Initial inquiries identified 11 manufacturers that currently market commercial HRMS. Appendix A contains a list and points of contact for all identified manufacturers. Seven manufacturers completed the survey, and limited information on two additional

¹ Robinson (ABS Surveyor, 1995) provides a general overview on how HRMS can be used in tactical situations to assist the mariner. He mentions the contributions an HRMS can make for crews that are less well trained, on ships where it is more difficult to physically feel hull structural response.

manufacturers was obtained by secondary research. Survey answers for the number of systems built and basic system cost (excluding installation) are provided in Table 2-1. The difference in cost among manufacturers is not statistically significant, since the question was phrased in \$50,000 price bands and there were variations in the equipment provided in basic systems.

Table 2-1: Number and Cost of Commercial Systems		
Manufacturer	No. HRMS Built	Basic HRMS Cost (excluding install.)
Ocean Systems	88	< \$50,000
BMT-SeaTech	63	< \$50,000
Straininstall	44	\$50,000 - \$100,000
SMS	21	< \$50,000
MCA Engineers	10	< \$50,000
Concept Systems	5	< \$50,000
SafetyOne	0	TBD

Note: Base systems varied -- a large number of Ocean System HRMS were weather service with no hull stress, SafetyOne offered fiber optics.

More interesting were results from both manufacturers and users (only 8 responded to the survey) concerning HRMS objectives, tabulated in Table 2-2. Results reveal some differences in manufacturer and user objectives. However, the user survey database is heavily slanted toward US ships and one company, and does not necessarily reflect world-wide or country wide statistics. Perhaps the only definitive conclusion is that US manufacturers and users do not yet seem overly concerned about meeting classification society requirements. One user did not believe classification society notation would reduce insurance rates, but believed that maintaining the class notation would incur additional survey and repair costs.

Table 2-2: Summary of Manufacturer and User Surveys on HRMS Objectives						
HRMS Objective	Manufacturers			User/Operators		
	Very Important	Desirable	Not Important	Very Important	Desirable	Not Important
Minimize slam/motions	7	-	-	2	5	-
Monitor hull stress	6	1	-	2	1	1
Optimize Routing	2	5	-	1	3	3
Engineering studies	4	3	-	4	-	-
Classification Society	3	2	2	-	-	1
Other (reduce repairs)	2					
Other (cargo loading)	1			1		

Note: Not all respondents checked all survey boxes.

One of the most important questions asked of mariners was the frequency that current HRMS were used during varying weather conditions. The results are shown in Table 2-3.

Table 2-3: HRMS Frequency of Usage			
Weather/Time	Often	Sometimes	Seldom/Never
Storm Seas - Night	5	-	-
Storm Seas - Day	5	-	-
Moderate Seas - Night	2	2	-
Moderate Seas - Day	2	2	-
Mild Seas - Night	2	3	-
Mild Seas - Day	2	3	-

Note: Not all responders checked all boxes. Support personnel did not answer this question.

Other interesting Operator Survey results included estimated cost (including installation) at an average of \$100,000. This is more than twice the Manufacturer Survey. Differences could be due to lack of information by the respondents or cost of installation. It is apparent that the cost of installing equipment and running cable can be a significant percentage if done in a shipyard, a factor to be considered when specifying an HRMS. Users were split 4-1-3 on whether the system justified the cost (4 yes, 1 no, 3 not sure).

Blank survey forms have been enclosed in Appendix D. These may prove useful as purchasing information checklists or user Quality Feedback forms.

3.0 THE SEA ENVIRONMENT AND VESSEL RESPONSE

Different ship types, cargoes, routes, and modes of operation represent different risks, and the optimal HRMS for a given application should consider all environmental factors and ship responses critical to ship safety and performance. The three key environmental factors are **wind, waves, and ice**. Hull response is characterized either directly or indirectly by ship motion (six degree of freedom), hull stress (global and local), stability, and powering performance.

Seas which are severe relative to the size and characteristics of a vessel can threaten its structural integrity, overwhelm its stability and buoyancy, impose damaging dynamic loads on the cargo, and result in motions that diminish the effectiveness and comfort of the crew and passengers. Ice hazards can sink a ship in a single catastrophic event. Although waves and ice are the primary sources of danger to ship structures, other environmental factors increase the potential danger. Wind impairs ship stability and available power. Impaired visibility (fog, storm conditions, or nightfall) - increases the probability of damage by waves and ice. Even less severe weather can cause structural damage (springing, fatigue, etc.) resulting in repair expense and lost productivity. Mitigating these danger and economic loss is a primary objective of an HRMS.

This chapter summarizes the external environment and typical responses for various ship types. By understanding the specific risks relative to their ship, the owner/operator can understand the key phenomena requiring monitoring. Section 3.1 describes environmental phenomena, and Section 3.2 describes typical hull response for several ship types.

3.1 Environmental Phenomena

The key environmental threats to ship safety are wind, waves and ice. Wind plays a role as the source of wave energy (most weather prediction codes are based on wind vector maps) and as a mitigating factor for stability and powering. It is not the intent herein to review the entire body of knowledge on weather, rather to explain how certain facets impact ship safety and performance.

3.1.1 Wind

Wind results from geographic differences in barometric pressure, generally caused by temperature differences. Storm waves are the result of wind, and wind measurements reported by ships (in the Volunteer Observation Ship program) and other sources form the basis for NOAA and National Weather Service marine weather forecasts. Wind also directly impacts stability and performance. The athwartship wind vector induces a relatively constant heeling moment which must be subtracted from the ship's dynamic righting energy curve. Wind heeling moment is a maximum typically when the ship is in a ballast (light) draft condition. Wind increases overall ship resistance, an effect that can be significant in storm conditions for ships with large above-water projected areas. Since the wind may not be aligned with the principle

wave direction, both ship motion and ship performance will favor one angle to the waves versus the symmetric direction. This fact has implications for computerized voyage optimization.

3.1.2 Ocean Waves

Ocean waves are generated by the transfer of energy and momentum from the wind to the sea². Wave growth is limited by the equilibrium between wind energy input and the energy loss due to breaking waves and non-linear transfer across the spectrum. In practice equilibrium can be approximated as a function of wind duration and fetch. The worst sea conditions are associated with sustained moderate winds followed by a cyclonic storm. The significant wave heights are typically more severe than those generated by hurricane-force storm winds (over 75 MPH) without prior sustained wind levels.³

Ocean waves are generalized into two broad categories. Storm waves (including extreme wave groups) are found near the source of the disturbance that generated the wave system and include the full range of possible frequency components. Swells are the longer period, more persistent components of the wave system which have propagated away from the storm. Both wave categories pose hazards for ships at sea, but can have differing impacts on HRMS design.

Storm Waves and Wave Groups

Storm waves are characterized by a full range of frequency components and confused direction. The superposition of short and long period wave components creates a multi-directional wave environment, possibly complicated by swells from other weather systems. These conditions create waves and wave groups capable of producing large vessel responses. Wave groups form from the interaction of waves of different speed, and are common in rising, narrow banded, storm spectra seas. Wave groups consist of a finite series of regular waves with heights that vary from a maximum at the center of the set to minimums at the two ends. Even if the wave heights are not large, their nearly equal periods may cause severe synchronous vessel response if encounter frequency is close to a ship motion natural frequency.

In addition to regular groups of larger amplitude waves, storms produce extreme wave groups (EWGs) with unusually energetic and possibly breaking waves⁴. Unlike the almost solitary

² Kroukovsky-Korvin, B. V.; "Theory of Seakeeping," SNAME 1961. Initially the energy/momentum exchange is linear, favoring waves traveling at the same speed as the mean wind. The process changes to include a coupling between wind turbulence and the existing or developing wave system, causing an exponential rate of wave growth and a large range of wavelengths. The sea continues to build until reaching a maximum somewhat beyond its equilibrium condition with the seas then declining to final form.

³ Ochi, Michel K.; "Marine Environment and its Impact on the Design of Ships and Marine Structures," SNAME Transactions Vol. 101, pp 673-704, 1993.

⁴ Ming-Yang Su; "Characteristics of Extreme Wave Groups, IEEE (Oceans '84). Both phenomena may be the result of sideband instabilities rather than a simple beat. Waves propagating together experience local energy level variation as they interact, due to the non-linearity of the free surface condition. In some cases, resonant coupling may occur between wave components so that the mean value is non-zero. In that case the direction of energy transfer between wave components depends on their phases and results in some components extracting energy and growing at the expense of adjacent waves. The highest or extreme waves are found within EWGs which are thought to develop from such resonant coupling between a central wave and its sidebands.

higher waves in a regular wave group, EWGs have a mean length of about three waves with a central extreme wave of unusual height and steepness. The central wave may be on the order of two to three times the height of waves outside the EWG, symmetrically positioned between at least two adjacent waves which are also higher than the significant wave height of the surrounding sea. The greater heights and close spacing of the three central waves in an EWG can suddenly produce multiple, closely spaced towering walls of water and deep troughs, with severe implications for ship safety.

Wave groups are also sites for breaking waves. Some observations suggest that more than two thirds of the breaking waves occur within storm wave groups. Breaking seems to occur most commonly in high energy waves near the center of wave groups and over a wide range of steepness. Recent analysis suggests that breaking irregular waves in a typical real sea may be a consequence of the resonant coupling between the central wave and its sidebands in an EWG⁵. Breaking waves are dangerous because of the energy transferred suddenly to a vessel. The energy from a breaking wave may be four times as great as for a non-breaking wave, possibly resulting in damage to a vessel's structure or capsizing. The prediction and avoidance (or mitigation) of storm sea phenomena is a primary objective for an HRMS. In particular, the ability to detect "monster" waves may be a worthy research objective for HRMS development, if detection (and response) can be initiated in time.

Swells

As a wave system propagates from its source, the shorter length, lower energy components dissipate, leaving a residue of longer waves segregated by wave period (longer waves move faster). These swells are the waves most commonly encountered at sea, accounting for notorious conditions like the rollers of the "roaring forties" in the Southern Ocean. Swells follow great circles and may travel great distances, especially in the Pacific Ocean. After traveling more than 90° of the earth's circumference, swell energy intensifies as alternate great circles converge toward the anti-focus at 180° from the site of the wave system's generation.⁶ Typically swell energy travels at a velocity on the order of about 50 km/hour, and within a few hundred miles of the source, waves with periods less than 12 seconds have disappeared. Swells may retain their characteristic form for great distances even after passing through regions of severe adverse winds. Swells of 12 - 15 second period are a major cause of fatigue damage in longer ocean-going ships, producing higher hull girder bending stresses in large ships than do moderate storms. The constant period nature of swells makes them a potential source of ship motion resonant response.

⁵ The resonant interaction between the central wave and its sidebands causes energy to transfer between the trough and crest and the back and front faces within the central wave. As the energy of the crest and front are simultaneously increased at the expense of the trough and back, the wave forms a steepening front face and the horizontal velocity at the crest increases until it exceeds the wave's celerity, forming a jet as the wave spills or breaks. The complex energy transfer between the core EWG waves and within the central wave may make it difficult to predict the likelihood of breaking waves by a single criteria such as wave steepness. For example, there is some evidence from sea data that suggests that waves may break at sea with steepness of about one third the value derived as a breaking criterion from laboratory tests.

⁶ Cartwright, D. E.; "The Science of Sea Waves after 25 Years: Theoretical and Technical Knowledge," RINA 1974.

3.1.3 Ice

There is an internationally accepted terminology for ice forms and conditions, coordinated by the World Meteorological Organization. The terminology is used as a basis for reporting ice conditions by the Ice Branch, Environment Canada, and is outlined in the seventh edition on MANICE (1989). Some of the more common ice types are described below:

Drift / Pack Ice: Term used in a wide sense to include any area of ice, other than fast ice, no matter what form or how it is disposed. When area concentration is high (70%), *drift ice* may be replaced by the term *pack ice*.

Fast Ice: Ice that forms and remains fast along the coast, and is attached to the shore, an ice wall, an ice front, between shoals, or grounded icebergs. If *Fast Ice* is thicker than 2 meters above sea level, it is called an ice shelf.

Floe: Any relatively flat piece of ice 20 meters or more across.

Other ice types include *ice island*, *ice shelf*, *icebergs*, and *nilas ice* (thin elastic crust of ice). *Ridged ice* is ice that has been piled haphazardly one piece over another in the form of ridges or walls, and is usually found in first year ice. The dynamics of *pack ice* may result in the ice being put under pressure, frequently leading to deformation of the ice cover (*ridged ice*). Both the lateral pressure and the deformed ice ridges can impact safe navigation.

Different forms of ice can be distinguished on the basis of their place of origin and stage of development, such as lake and river ice, sea ice, and glacier ice. Types of lake ice are identified as new (<5 centimeters), thin (5-15 centimeters), medium (15-30 centimeters), thick (30-70 centimeters), and very thick (>70 centimeters). Sea ice is categorized as new ice, young ice (10-30 centimeters), first-year ice (30-over 200 centimeters), and old ice, stronger and usually thicker than first year ice. Except for higher ice-class vessels, collision with old ice should be avoided. Excessive speed is considered to be a major cause of ship damage from ice.⁷

Ice imperils only the most northern and southern latitudes, and its presence is generally predictable on a seasonal basis along defined trade routes. Examples include freshwater ice in the Great Lakes and saltwater ice impeding trade in northeastern Canada and northern European sea ports (Russia, Baltic Sea, etc.). Satellites and aircraft-based radars can usually differentiate between first year and multi-year ice using scatterometry to measure the strength of the reflected signal.

3.2 Vessel Response

Given the dangers that exist in the marine environment, it is possible to define the types of hull response that may require monitoring.. This section describes general types of hull responses.

⁷ Ice Navigation in Canadian Waters, Canadian Coast Guard, Transport Canada Report TP5064E, 1992.

Table 4-1 in the next report section summarizes ship motions and stresses of importance to various ship classes. Hull responses can be categorized as follows:

- Ship motions
- Hull Stresses
- Stability
- Powering

3.2.1 Ship Motions

Ships respond to ocean waves in six degrees of freedom: three translational (surge, sway, and heave) and three rotational (roll, pitch, and yaw). Roll, pitch, and heave are generally of most concern from either a synchronous motion aspect or extreme motion aspect. Responses are a function of mass (including entrained water), damping (linear and nonlinear), restoring rates (i.e., spring rates determined by hull geometry), and degree of resonance. Principle of Naval Architecture (SNAME) contains a detailed explanation of ship motions. The implications of ship motion response for ship safety and performance can be summarized as follows:

Roll: Roll angle increases hydrostatic pressure head in fluid tanks, impairs reserve transverse stability, and causes crew discomfort. Roll acceleration induces lateral cargo loads that must be resisted by horizontal constraints. Excessive roll motions in a storm will usually cause the master to turn the ship into the waves, which usually increases hull girder stress. Since most roll damping is non-linear, synchronous roll can result in very large angles. Roll can also induce sloshing in cargo oil tanks.

Pitch: Pitch accelerations generate vertical loads at the ends of the ship. Extreme pitch angles result in slamming, which in turn induces both local and global stress distributions. Synchronous pitch is common in head seas in waves of length about equal to ship's length. Pitch (and trim) angles also induce hydrostatic pressure head increases at one end of fluid (cargo or ballast) tanks. Pitching induces longitudinal sloshing in tanks, particularly in partially filled tanks.

Heave: Closely coupled with pitch, heave resonance is common in head seas. The key impacts are vertical cargo acceleration and increased relative deck/wave velocity.

3.2.2 Hull Stress

Hull girder stresses can be classified as either global or local in nature. Global hull girder stresses can be further categorized as either quasi-static, whipping, or springing. Local hull stresses can be induced by a number of different phenomena, including cargo loads, wave refraction, slamming, and ice impact. Each of these types of hull response are explained in the following paragraphs.

Global Stress: Quasi-Static Hull Girder Stress

This term refers to both stillwater and wave-induced hull girder shears and bending moments that occur at the wave frequency. Stillwater loads accrue from differences in the loading curve and buoyancy curve along the ship. Maximum allowable stillwater stress values are established by the classification societies. Care must be taken during cargo loading and unloading that maximum allowable in-port values are not exceeded. Wave-induced hull girder shears and moments are caused by the cyclic buoyancy of the wave superimposed on the ship geometry in quasi-static balance with ship mass accelerations. The sinusoidal moment component is also typically estimated by classification society rules to facilitate calculation of hull girder stress. Moment values are more a function of the projected wave length superimposed on the hull (wave length / cosine of the heading angle) than on the encounter frequency. However, pitch and heave resonance (a function of encounter frequency versus motion natural frequency) can increase hull girder moment.

Large hull girder bending moments in response to extra-ordinary waves may result in structural damage that is global in nature, whereas smaller moments applied for millions of cycles may lead to fatigue at structural details.

Global Stress: Hull Girder Whipping

Whipping refers to vibration of the hull girder in its first (two-noded) vertical and lateral bending modes as the result of some impulse load, such as slamming or ice ramming. Slams occur on both the bottom and on the flare at the vessel's bow. Bottom slamming occurs when the relative motion between the vessel and the sea is severe enough to lift the forefoot clear of the sea. The slam occurs as the bow re-enters the sea. Flare slamming may occur as the result of relative motion between the vessel and the sea even without bow emergence, but can also occur with little relative motion between the vessel and the sea if the wave is steep enough. Bottom slams are usually of shorter duration than flare slams⁸. The dominant slam depends on the ship type. A high-speed containership with finer lines forward and a flaring bow may experience greater effect from a flare slam than a bottom slam, but the opposite will be true for a full-form tanker with little flare. Whipping moment components of the same order of magnitude as the quasi-static moment have been recorded on an aircraft carrier experiencing flare slam⁹. Whipping vibrations and decay mechanisms are not well understood, but are generally less severe in flexible (i.e., high L/D ratio) ships. The whipping moment components are usually small compared to the quasi-static moment, but their frequency is high. Some work suggests that whipping may increase fatigue damage by 20% to 30%.¹⁰

Global Stress: Springing

Springing is a steady state, two-noded vertical hull vibration excited by a wave encounter frequency at or near the primary hull resonant frequency. Springing frequencies are typically an order of magnitude greater than quasi-static bending (about one to two hertz), and the resulting superimposed moment contribution may be significant, especially with respect to fatigue.

⁸ Lewis, E. V.; "Structural Dynamics of Ships," Royal Institute of Naval Architects, 1974.

⁹ Lewis, E. V.; "Structural Dynamics of Ships," Royal Institute of Naval Architects, 1974.

¹⁰ Lacey, P. B. & Chen, H.; "Improved Passage Planning Using Weather Forecasting, Maneuvering Guidance, and Instrumentation Feedback," SNAME Los Angeles Metropolitan Section paper, 1993.

Springing is experienced by full-form ships with large L/D ratios (such as Great Lakes carriers) in small and moderate seas¹¹.

Local Stress: Cargo Loads

Cargo loading anomalies can often result in localized structural problems. Examples include uneven loading in bulk ships (hypothesized to be the source of a number of bulk ship losses) and unequal hydrostatic pressure heads across tank boundaries. The ABS SafeHull code specifically considers checkerboard loading in cargo and ballast tanks as a worst case. Loading sequence can result in temporarily excessive local and global stress problems.

Local Stress: Wave Refraction

Although hull girder stresses are not significant unless the wave projected length approximates the ship's length, smaller waves impinging on the sides of ship can cause localized long term fatigue damage and cracking. The effect is intensified by wave reflection in beam seas. This has been a problem on some TAPS trade tankers.

Local Stress: Slamming

In addition to exciting hull girder whipping, slamming causes damage to local bow structures. Bottom slamming in full-form ships usually results in dishing of the bottom shell plate, whereas flare slamming results in dishing of the side shell and sometimes loss of the flare strake.

Local Stress: Ice Transit

Local ice loads on a ship's structure are complex. The danger of pollution from structural damage is more a function of local ice loading than global ship hull loading. Shipboard measurements have shown that amidships hull girder stresses induced by ice are typically less than those induced by open-ocean waves. The pressure and force encountered during ship-ice impacts are random, and follow log-normal type probability distributions¹². The area of the hull that is highly stressed due to ice impact is dependent upon the type of operation (ramming, turning, etc.), and the local strength and geometry of the structure. Ice loads are non-uniform, such that high loads can be applied to a relatively small area of the hull (i.e., 0.5 m²). In addition, these loads can occur at a number of locations on the hull, predominately over the bow area. In this respect, local ice loads are more difficult to "measure" than slamming loads. Table C-3 (Appendix C) provides information on ice loading strain rates. The table values indicate that strain rates for ice loading in the local structure are similar to those for the global response, and that both of these are not significantly different from those experienced from sea loading.

3.2.3 Stability

A ship's stability is a function of its geometric form, weight distribution, watertight integrity, and tank arrangement. Stability can be adversely affected by a number of environmental

¹¹ Robinson (ABS Surveyor, June 1995) briefly describes the role of HRMS in analyzing springing problems on Great Lakes ships.

¹² St. John et al, "Ice Impact Load Measurement Aboard the *ODEN* During the International Arctic Ocean Expedition (1991)," SNAME Ictech '94, March 1994.

factors. Severe roll angles may lead to flooding of open ports or spaces as well as transverse shifting of cargo. Green water and icing may add topside weight. Ships perched on wave crests may lose a significant amount of form derived stability, and be susceptible to broaching or capsizing. Hull breaches during ice transit may lead to flooding or pollution, and possibly to sinking. Long-term averaging of roll angle can identify combinations of wind heel and permanent list. Roll period averaging can deduce changes in metacentric height. The key point is that stress monitoring is not necessarily the only benefit of HRMS.

3.2.4 Powering

Ship power plants are often based on calm water power curves plus allowances for losses in wind and waves. In fact, ship schedule and fuel performance are highly dependent upon the selected routing. Voyage planning based on predicted weather and known ship characteristics can result in significant fuel savings and reduced repair bills, and sometimes result in earlier arrival. HRMS can be used to determine the relationship between ship performance (added resistance, power) and weather (wind, sea state) on a full scale basis (see Section 5).

4.0 HRMS FUNCTIONAL REQUIREMENTS

When developing an HRMS for a specific ship installation, a number of questions must be considered:

- What types of environmental loading is the ship susceptible to?
- Who are the system users (or “customers”), and what are their needs?
- What measurements are required to provide the necessary data?

The answers will drive the specification of all HRMS subsystems. This chapter briefly categorizes HRMS along these dimensions, and will provide a functional subsystem breakdown of a typical HRMS.

4.1 Ship-Based HRMS Functional Requirements

Many of the critical HRMS measurements are specific to ship type. Table 4-1 provides a summary list of key hull responses based on ship type, some obvious and some subtle. The key point is that ship characteristics should be reviewed when determining HRMS requirements.

4.2 HRMS Functional Requirements Based on Route

Trade routes have a significant impact on the loads that may be critical for a given ship design. For example, ship scantlings developed using ABS rules are generally based on North Atlantic service with a cosine-squared wave heading distribution. This is a relatively conservative design basis for ship class designs where actual trade routes are not known, or no fixed route will apply (typical for Military SeaLift Command charters). However, certain repetitive routes may emphasize structural susceptibility to certain types of loads. Examples include:

- Ships intended to operate in polar regions will be subject to ice. HRMS sensing considerations could include hull stresses in ice zones, detection of floating ice, and remote sensor networks warning of ice pack / free ice locations.¹³
- Ships operating in tropic climates usually do not have wave-induced fatigue problems because of the large time spent in calm conditions. Key concerns may be limited to weather updates (for major storms), stresses during cargo loading, and ship motions under certain swell conditions.
- TAPS trade tankers are subject to high winds, frequent storm seas, and very directional sea states.¹⁴ Cargo runs are made south with principal seas to starboard, ballast runs with seas to port, sometimes resulting in localized fatigue patterns.
- North Sea ships often see very steep waves due to shoaling effects on regular sea waves. Hull girder bending, slamming, and green water are all key concerns.

¹³ In order to maintain year-round port access, remote sensing / icebreaking networks have been formed in the Baltic and Northeastern Canadian regions. The existence and location of ice is continually monitored by shore, sea, and aircraft assets, and icebreakers are dispatched as necessary to open shipping lanes.

¹⁴ Witmer, D. J. & Lewis, J. W.; “Operational and Scientific Hull Structural Monitoring on TAPS Trade Tankers,” SNAME Transactions Vol. 102, pp. 501-533, 1994

- Great Lakes bulk ships, typically designed with high Length/Depth ratios, are susceptible to springing under certain lake wave conditions.

It is not possible to list all ship route variations herein. It is important for HRMS specification to consider the types of environmental loads peculiar to the ship trade routes, and to include sensors to monitor the resulting key hull responses. Part of this research includes investigating past structural problems on the ship(s) in question as well as other similar ships involved in the same trade.

Table 4-1: Common HRMS Requirements by Ship Type	
Passenger Ship	<ul style="list-style-type: none"> • Ship Motion (roll) • Bow Flare Slam
Tanker/Products Carrier	<ul style="list-style-type: none"> • Midship Hull Girder Stress • Bow/amidships Side Shell Stiffeners • Forefoot Slam • Explosive environment
Bulk Ships	<ul style="list-style-type: none"> • Stillwater Hull Girder Stresses (cargo loading) • Cargo Hold Frame Stresses • Stress Concentrations at Hatch Corners • Forefoot Slam
Container Ships	<ul style="list-style-type: none"> • Stress Concentrations at Hatch Corners • Hull Girder Torsion • Bow Flare Slam • Green Water over Bow • Whipping / Cargo Accelerations
LNG / Internal Tank	<ul style="list-style-type: none"> • Forefoot Slam • Temperature / Explosive Atmosphere • Sloshing
Barges / Platforms	<ul style="list-style-type: none"> • Towline / Mooring Tension • Motions & Inertial Forces • Lateral Motion
Naval Combatant	<ul style="list-style-type: none"> • Bow Flare Slam • Firing Control Plane Deflections

4.3 HRMS Functional Subsystem Breakdown

Although commercially available HRMS's can vary widely in sensor type, overall design intent, and general design, they can be functionally segmented into the following subsystems.

Sensors

The sensor subsystem includes all measuring devices provided with the HRMS, including local power supplies, distributed signal processing, and test equipment. Power is often supplied locally to avoid the cost of running cable from the CPU. However, the quality of power at some shipboard locations may be poor due to the size of other equipment in the area. A typical example is a strain gauge installed near the bow. Power surges associated with winch and windlass operation may adversely affect sensor performance. Decisions must also be made concerning sensor output signal processing. If this function is performed at the CPU, then the costs associated with multiple sensor installation can be reduced. However, analog signals are very sensitive to degradation from cabling and junction box connections.

Input/Output

The I/O subsystem consists of the data transmission network between sensor output and CPU, or between the CPU and remote network, and includes any signal conversion equipment inherent to the transmission method. There are three available methods of data transmission: cabling, fiber optic cable, and radio link. Cabling is the most common method, and is relatively simple on ships with protected passageways running between the Deck House (CPU) and sensor locations. However, ships carrying explosive cargoes require intrinsically safe cabling installations, and standard high-voltage cable may not be possible. Fiber optic cable data transmission has been successfully proven in experimental trials, but the higher cost (due mainly to signal conversion) and lack of prior commercial applications are drawbacks. SMS and MCA offer short-wave radio transmission, and have successfully installed this I/O variation on several barges and tankers. The only reported field problem has been occasional signal "spikes" due to radio interference (walkie-talkie, etc.).

CPU

The Central Processing Unit (CPU) is the heart of any HRMS, consisting of the central computer hardware and software used to transform sensor signals into user-friendly data displays, to store certain data sets, and to transmit information into remote networks. All of the manufacturer survey responders currently use 486 or Pentium personal computers running on Microsoft DOS or Windows. Data storage varies in type and capacity among manufacturers, including magnetic disk, tape, and optical disk.

One key aspect of an HRMS CPU is its ability to link with other shipboard systems, including navigational systems (particularly GPS if installed), cargo loading computers, ship powering monitors (RPM, SHP), environmental sensors (wind), and communication networks (including MARSAT or other).

Display

Although data display is normally considered a part of the CPU function, we list it as a separate functional subsystem due to a number of specific design criteria. Displays must be user friendly to control, easy to read, provide all relevant data to the user, and not interfere with night-time vision. An HRMS display competes with other bridge equipment for space and the mariner's attention. It should therefore be unobtrusive until such time as realistic safety limits are exceeded, when the nature and severity of the alarm should be clearly and rapidly assimilated.

Remote Network

Although this subsystem extends beyond the physical limits of the ship and therefore the basic definition of an HRMS, the integration of the shipboard system with both remote sensor networks and information distribution systems represents the future of the industry and the ultimate goal of the system -- to reduce danger to the ship. Section 5.0 briefly summarizes the current status of remote sensing and communication networks.

The remainder of this SSC report describes HRMS requirements and current industrial state of the art in terms of the preceding functional subsystem breakdown structure. Section 6.0 describes sensors, Section 7.0 describes Input/Output, Section 8.0 describes CPU functions, Section 9.0 discusses Display issues, and Section 5 summarizes remote sensing.

5.0 REMOTE SENSING AND INFORMATION NETWORKS

The basic HRMS described in Section 4.0 is a ship-based unit with limited (line of sight) sensor range that provides the mariner with environmental and hull response data on a real-time basis. As such, it is a tactical system, capable of alerting the mariner to immediate dangers and assisting with ship handling decisions. However, a ship-bound HRMS does not provide strategic data, and cannot show the best course to avoid future storms, ice, or other dangers to navigation and operation. By combining shipboard systems with remote sensor platforms through information/communication networks, it is possible to optimize ship routing on the basis of weather predictions, ship motion, fuel economy, and/or other constraints. Although a detailed discussion of remote sensing is beyond the scope of this report, this section briefly describes the state of the art and the potential to improve ship performance through optimized voyage planning.

5.1 Remote Sensor Platforms

There are a number of environmental sensor platforms deployed throughout the world to provide data for both generalized and specific maritime purposes. These include fixed land stations, ocean buoys, ships, aircraft, and satellites. The capabilities and roles of each sensor platform are described in the following paragraphs.

Fixed Land Sensors

Although mostly limited to meteorological measurements (wind speed and direction, temperature, precipitation), land-based stations can provide Over-the-Horizon wind estimates using high frequency (6-28 Mhz) radio waves reflected off the ionosphere.¹⁵ Current usage is generally limited to meteorological reports, water depth¹⁶, and ice sightings.

Ocean Buoys

The Ocean Data Acquisition System (ODAS) is a network of buoys anchored in the deep ocean areas off North America. Operated by the National Data Buoy Center (NDBC), more than sixty buoys routinely provide weather and oceanographic data from stations in the Atlantic, Pacific Gulf of Mexico and Great Lakes via satellite transmissions to the National Weather Service (NWS). The buoys process twenty-minute sensor data sets and transmit the results each hour to the NDBC for further processing and weather/wave forecasting. The data from the ODAS buoys is reported to be accurate within +/- one meter per second and +/- 10 degrees for wind speed and direction.

¹⁵ Georges, T. M. & Harlan, J. A.; "Ocean-Monitoring Tests with the US Air Force Over-the-Horizon Radars"

¹⁶ Tessier et al (1993) and Smith (1993) describes the development of COWLIS (Coastal Ocean Water Level Information System, now called ODIN), a remote water-depth sensor information network developed to improve the safety and efficiency of shipping along the St. Lawrence Seaway and eastern Canadian ports. Shippers can optimize cargo load draft for current navigable river depths on a near-real-time basis.

Ships

Weather reports are routinely forwarded every six hours to NOAA from ships participating in the US Voluntary Observing Ship Program. Observations include weather (temperature and wind speed) and best estimates of sea, ice, and visibility. The Voluntary Ship Observation Program provides about 30,000 reports from about 1000 ships each month. The data is distributed by the national Ocean Weather Service via the Global Telecommunications System to most countries, and is routinely used for weather forecasting¹⁷. The program has existed for several decades and is a lineal descendent of the USCG Ocean Weather Station ships established about fifty years ago. Wave prediction is the most important use of this data for HRMS. State of the art wave forecasting can predict enroute wave conditions from a geographic grid of barometric pressure or wind conditions over the ocean as much as five days in advance, making it practical to avoid the worst seas by prudently choosing course and speed.

Aircraft

Although the most publicized use of aircraft involves hurricane tracking, they are also used routinely to scout ice conditions in polar regions¹⁸. Aircraft have also been used as Synthetic Aperture Radar (SAR)¹⁹ platforms for estimating sea states, but applications to date have been experimental in nature.

Satellites

Although satellite sensing technology has progressed rapidly since its inception in the 1960's, the accuracy and data processing capabilities have only recently been sufficient to support accurate weather forecasting. Sensor development has been focused in three areas: AVHRR to sense sea temperature and map sea currents, radar altimetry to measure wave height, and scatterometry to indicate wind vectors and ice.

AVHRR (Advanced High Resolution Radiation) sensors have been flown on satellites by NOAA since 1978. AVHRR sensors detect infra-red radiation as a measure of the sea surface temperature. There are usually two AVHRR satellites in polar orbit on 24 hour cycles, phased 12 hours apart for day and night readings. AVHRR data is most helpful to oceanographers for tracking ocean currents, but it has been used to assist ocean racing yachts. Clouds interfere with AVHRR sensors, but useful information can sometimes be obtained by constructing a composite image from multiple images.

¹⁷ Baron (1990) provides an overview of the VOS program, including VOS/GOS, GTS (Global Telecommunications System), and GDPS (Global Data Processing System). Szabados (1985) describes the semi-automated data collection and transmission system installed aboard some ships to improve the quality and timeliness of weather reports from VOS ships.

¹⁸ "Ice Performance and Navigation," Ice Tracks-Summer 1996, a Canarctic company publication, summarizes ice tracking. Canarctic equipped the MV Arctic with down-link stations for SAR and NOAA imagery. Leavitt, E. D. & McAvoy, G.; "Remote Sensing in Ice Navigation," MTS Journal Vol 21 (1987) briefly summarize typical airborne sensors, including pulse radars for measuring ice thickness.

¹⁹ Alpers (1992) provides an overview of SAR measurement of wave spectra, particularly the growing consensus in signal processing to obtain accurate wave data.

Radar altimetry is measurement of the distance between the spacecraft and the wave profile by radar. First demonstrated aboard NASA's GEOS-3 in the mid 1970's, altimetry accuracy was not sufficient until the 1990's to support HRMS objectives. Accurate measurement requires accurate knowledge of the satellite orbital variations, and in cloud conditions, the ability to correct for electrons in the ionosphere and water vapor in the atmosphere. Errors as great as ten meters were not uncommon until the launch of TOPEX/Poseidon in 1992. Its orbit is known within +/-10 cm and it carries two pulse-limited radar altimeters capable of reducing antenna pointing angles and atmospheric interference. As a result, TOPEX/Poseidon can measure sea surface distances within three centimeters and wave heights within thirteen centimeters. Significant wave height can be determined from the shape of the radar altimeter return pulse (calm seas with low waves return a condensed pulse, rough seas with high waves return a stretched pulse). Since there is a high degree of correlation between wind speed and wave height, altimetry measurements should improve future forecasts. There is only one TOPEX/Poseidon satellite currently on line, directed primarily towards research. Applications to state-of-the-art route optimization is likely within the next decade.

Satellite radars can measure sea wind vectors using a process called scatterometry. Scatterometry measures the strength of the return pulse of a radar altimeter to infer the roughness of the observed segment of the sea surface. A calm sea is a good reflector and returns a strong pulse, but rough seas scatter the signal and weaken the return pulse. Speed is estimated from empirical correlation between return signal strength and wind speed. The wind vector (speed and direction) is determined by using multiple beams that look at the same spot on the sea surface from two orthogonal directions. The concept of satellite radar anemometry using scatterometry was first demonstrated aboard Skylab in the 1970's and has since matured as a technology. It was found that wind speed (rather than wave height as previously supposed) correlated well with the loss of return signal strength. Scatterometry requires intensive computer reduction into wind speed and wave forecast, a barrier to real-time processing that continues to erode with advancements in computer technology. Scatterometry accuracy suffers from the double-inference and also from rain, which reduces surface signal reflection. However, the most recent technical papers indicate the potential for satisfactory results²⁰.

Satellite-mounted radars have also proved effective in monitoring the ice pack. The strength of the return signal is often effective in differentiating between first-year and multi-year ice.

²⁰ Luscombe and Montpetit (1992) summarize the state of the art in satellite-based SAR (Synthetic Aperture Radar) and supplementary sensors as applied to the Canadian Ice Community.

5.2 Communication/Information Networks

Data transfer among ships, sensor platforms, and shore-side computer processing assets²¹ has evolved from an HF Radio infrastructure to a combined communication satellite -telephone (including the Internet²²) infrastructure.

The current (but retiring) state of the art consists of Inmarsat A analog satellites in high geosynchronous orbit. Four satellites are sufficient to cover the earth at its 22,000-mile orbit, but earth antennas are larger (and time delays longer) because of the distance. Inmarsat B, C, and M satellites featuring higher data transmission rates are now being added. Inmarsat B will replace Inmarsat A over the next few years, and Inmarsat C is expected to satisfy Global Marine Distress and Safety System (GMDSS) regulations. Inmarsat M is similar to B, but slightly slower and less expensive. Inmarsat P is a future service under development to compete with the non-geosynchronous Low Earth Orbiting Satellites (LEOS)²³. With 10 satellites at 6,400 miles and 12 ground stations, communication is immediate with smaller equipment than the other Inmarsat services. GM/Hughes is expanding its Spaceway geosynchronous orbit system to nine satellites for full earth coverage as a response to competition from the LEO projects.

Several LEOS-based communication systems are currently in development. ORBCOMM has launched the first of its 600-mile orbit satellites. A network of 36 satellites, accessible with a hand-held transmitter, will be suitable for digital data and limited packet size since ground communication is not continuous. IRIDIUM is the Motorola-Lockheed-Sprint system consisting of 66 LEOS orbiting at 500 miles. The system includes inter-satellite linking and a paging service. Since LEOS are not geo-synchronous, marine users benefit from systems developed to compete in the land-bound cellular phone market. Globalstar is a 48 satellite system that relies on ground "gateways" for linkage. At the far end of LEO technology is Teledesic, an 840-satellite network flying at 700 km (435 miles)²⁴. This brainchild of Bill Gates (Microsoft) and Craig McCaw will reportedly cost \$9 billion and will not be in place until 2001. Of all the LEO projects, it is most acclimated to high-volume computer data transfer.

The current challenges facing the communications infrastructure are transmission rate, cost, and standardization. It would appear the existing competitive pressures to improve satellite communication performance will match development efforts in ship voyage planning.

²¹ Viehoff (1990) discusses the advantages and disadvantages of downlinking satellite AVHRR directly to the ship versus to a shore data processing facility.

²² McClain (1993) describes the California State University-Fresno WeatherLink networking tool for maintaining and updating its selective weather database, including reports and satellite images.

²³ Story, Eugene D., "Future Prospects for Maritime Data Communications," SNAME California Joint Sections Meeting, 21 April 1995. Mr. Story, president of Marine Management Systems Inc., provides an excellent synopsis of communications satellite systems and some of the standardization problems facing the marine shipboard information industry.

²⁴ Gilder, George, "Ethersphere," Forbes ASAP, October 10, 1994. Gilder provides a thorough discussion of the competition between cellular/digital satellite consortiums, with extensive comment on the *Teledesic* system.

5.3 Integration of Weather Forecasting and Ship Response.

The ideal integration between remote sensing and ship routing would consist of general (strategic) voyage route optimization based on weather predictions and calculated ship response²⁵, updated and modified by an HRMS feedback loop at the ship (tactical) level to adjust ship handling for optimal performance and hull response in actual conditions. A number of the key elements to this ideal system are already state of the art, including:

- Weather prediction (wind vectors and waves) using meteorological computer models. These models currently use buoy data and ship reports to generate wind vector grids and ultimately storm movement and wave height estimates. The current buoy/ship data source preference will probably swing to satellite assets as cost and computer processing time drops, and satellite area coverage and sensor reliability increases.
- Characterization of ship wave response using SMP and related ship motion programs,
- Improved computer software and hardware, and
- HRMS systems capable of measuring local phenomena and the resulting ship response.

The missing elements are primarily system integration assets, including low-cost real-time data transmission and processing, and software capable of projecting an optimum route through predicted weather on the basis of known wind and wave performance. It should be possible using probability decision trees to develop an optimal voyage, including heading and speed, to reach a destination with minimum hull response and fuel consumption within a given time. Such a program would need continuous updating, but could be run ashore with results and expert guidance forwarded to the ship. Optimization programs could be analyzed for design constraint sensitivity to determine what ship changes would most improve economic efficiency (such as adding anti-roll devices to improve resistance to beam seas).

The potential of voyage planning was best demonstrated by ARCO Marine in 1993²⁶. Two TAPS trade sister tankers departed San Francisco for Valdez at the same time and in the same ballast condition. Operating within a narrow corridor where timing and speed were the primary control variables, the ship with voyage planning arrived 21 hours earlier (it departed a few hours earlier), and the ship without voyage planning absorbed \$400,000 in repair costs due to wave-induced damage.

Special-purpose integrated remote sensor networks are already in use to improve accessibility to ice-bound ports in both Canada²⁷ and the Baltic Sea. Aircraft, shore, and shipboard sensor

²⁵ Dr. Henry Chen (1988) has been a lead proponent of this approach, describing the general methodology in *Sea Technology* (1988) and reducing it in practice to shipboard equipment installation (Ocean Systems, Inc.).

²⁶ Lovdahl, Lacey, and Chen, "Advances in Computer Based Onboard Voyage Planning," SNAME 1995 California Joint Sections Meeting, April 22, 1995. Voyage planning was performed using weather predictions (wave height and direction) from Ocean Systems.

²⁷ ENFOTEC operates the ICENAV information service, which collects information on ice movement, ice edges, current dynamics, and other weather data using satellites (RADARSAT, ERS-1), aircraft SAR, and other remote

and processing assets are linked to map real-time ice conditions and to dispatch ice breakers when and where necessary to open shipping lanes. Application of networked remote and local sensor platforms to optimize routing for wind and waves is still developmental as an overall technology, but several companies have initiated R&D efforts to correlate HRMS sensor readings with sea state, a key step in characterizing ship response to weather²⁸

assets, and transmits the assembled information to ships (letter from David Green, ENFOTEC to Bruce Cowper, Fleet Technology Limited, dated June 13, 1996).

²⁸ MCA Engineers has found strong correlation between forefoot pressure sensors and bow accelerometers in LNG HRMS data for regular seas. Both SMS and MCA have ongoing R&D efforts to back-calculate sea state from HRMS sensor readings, and SMS has experimented with route optimization for TAPS trade tankers.

6.0 HRMS SENSORS

Sensor selection is the foundation for HRMS effectiveness. Sensors must be carefully designed and located to provide useful data. For example, strain gauges must be configured and located properly to measure the desired stress component, and wind sensors must be located clear of airstream altering shapes that distort measurement of true wind velocity. Sensors also must be designed for reliability and maintenance access, since their need is greatest when the weather is worst.

This report section provides a brief description of commercially available sensors, typical ranges and accuracy, and limitations. This description should allow an HRMS buyer to specify the characteristics suitable to his application at reasonable or optimal cost.

Table 6-1 summarizes the sensor suite offered by the manufacturers responding to the project survey. None of the responders manufactured systems developed specifically for ice. However, a number of experimental systems have been installed on ice breakers, cutters, and similar vessels. Sensor characteristics and performance are described in a separate section unique to ice environs.

Table 6-1: Summary of Manufacturer Survey Sensor Availability									
Company	Navi- gation	Ship Motion s	Ship Accel.	Pressure	Hull Stres s	Slam	Weathe r Predict	Wind/ Waves	Ship's Power
BMT-SeaTech		X	X	Flare/ Bow	Deck, Side, Tank	X		Wave	Speed HP RPM
Concept Systems	X	X	X	Side/ Bottom	Deck, Tank, Shell	X		Wave	
MCA Engineers	X	X	X	Bottom	Deck	X		Wind	Speed HP RPM
Ocean Systems*		X	X			X	X	Wind Wave	
SafetyOne	X				All Zones	X		Wind	Speed HP RPM
SMS	X	X	X	Side/ Bottom	All Zones	X	X	Wind Waves	Speed HP RPM
Straininstall			X	Flare/ Bow	All Zones	X			HP RPM

* Offered as part of Sperry Integrated Bridge package containing other sensors

6.1 Strain Gauges

Strain gauges are the primary method of evaluating the stress condition in the hull material. Although foil (electro-resistive) and long baseline gauges have long dominated shipboard installations, new technologies have been proven to provide equivalent technical performance though possibly at higher cost. For purposes of this discussion, strain gauges are categorized as:

- Short baseline (measuring strain in material samples less than 1-inch long)
- Long baseline (typically 2 meters long, oriented along stress axis of interest)
- derived (estimated hull girder bending moment and stress using motion sensors)
- Developmental (proven technology but not yet commercial state of the art)

6.1.1 Short Baseline (SBL) Strain Gauges

Short baseline gauges are typically 1/4-inch wire grids either bonded or welded to the structure. Foil resistance changes as the foil is stretched, providing a corresponding linear electrical signal using a Wheatstone bridge. Strain displacements are typically measured along one, two, or three axes, depending on the type of data required (axial strain can be read from a single axis). SBL gauges are the only reasonable option to derive shear stresses.

Relative advantages include low component cost, universal acceptance in the engineering community, and the ability to install in small spaces, particularly where a direct measurement of localized “hot spot” stress is desired. Disadvantages include directional accuracy (the foil element must be properly aligned), installation-related bond failure (particularly in tanks)²⁹, short fatigue life, and analog signal degradation at cable junctions.³⁰ Analog signals can be adversely affected by electrical noise and stray magnetic fields. Foil gauges are subject to temperature errors because of dissimilar metal temperature coefficients, but these effects can be compensated electrically using a temperature-compensated gauge with Wheatstone wiring.

Most foil gauges are bonded to the target structure using an epoxy. Weldable strain gauges are a sub-group of the foil type, and are spot welded to compatible materials when epoxy bonding is not feasible or reliable.

The small voltages and currents used in electro-resistive SBL gauge design make them intrinsically safe in explosive atmospheres (but the power supplies may not be).

6.1.2 Long Baseline (LBL) Strain Gauges

²⁹ Conversations with several “foil” strain gauge installers indicates reliability is highly dependent on the quality of the installation, including surface preparation, proper epoxy procedures, and the gauge/cable connection.

³⁰ Sensors provided with A/D conversion as close as possible to the gauge reduce the potential inaccuracies associated with electrical cabling.

Long Baseline (LBL) strain gauges are the configuration typically specified and provided for hull girder stress measurements on commercial ships. They consist of long rods (about two meters) fixed at one end to the deck structure. Strain is measured by measuring displacement of the rod free end relative to a fixed point on the structure. The length of the gauge allows relatively accurate uniaxial stress, provided the gauges are located so as to exclude secondary or tertiary stress distributions. Rod displacement is typically measured using one of three techniques:

- Linear potentiometer - this method is simple and uses low voltage and current. However, resistor life is limited (about 1 year), and contact problems often lead to noise spikes in the output.
- Linear Variable Differential Transformer (LVDT) - because this sensor has no contacts, it exhibits longer life and very precise measurement. However, the higher power requirements make it difficult to pass stringent intrinsic safety standards.
- Linear Displacement Transducer (Magnetostrictive Sensor) - this device measures the time interval between an interrogating pulse and a return pulse, generated by a magnet connected to the rod free end. This device has longer life (no contacts) and is available with an Intrinsic Safety rating for use in hazardous materials, but is relatively expensive (about \$1500).

6.1.3 Derived Moment and Stress Measurements

Significant research has been conducted into predicting hull girder moments and stresses using ship motion sensor readings in combination with calculated hull response characteristics³¹. Although this approach simplifies the sensor suite and support equipment required onboard the ship, the accuracy is not within ABS guidelines for either real-time stress (strain) display (+/- 5 micro-strains³²) or fatigue “bin” sorting (50 micro-strain). Derived measurements have shown close correlation in some applications³³

6.1.4 Developmental Strain/Stress Measurement

This final category incorporates several emerging technologies with the potential for shipboard application. These include fiber optics, acoustic, and laser/radar ranging. The following paragraphs provide a brief explanation and potential application for each.

³¹ Lovdahl, Lacey, and Chen, “Advances in Computer Based Onboard Voyage Planning,” 1995 SNAME Joint California Sections Meeting, April 22, 1995. The authors acknowledge the contributions in hull stress prediction by Dr. Paul Kaplan of Hydromechanics, Inc. See also Kaplan, P., “Computer Simulation/Prediction of Ship Motions and Loads in a Seaway,” Seakeeping and Weather Symposium, RINA, London, 1995.

³² Micro-strains are the change in length of a gauge element normalized (divided) by the gauge length.

³³ Cheung and Vo at MCA Engineers have found close correlation between bow forefoot pressure and bow vertical acceleration on an LNG tanker in regular waves. The correlation was sufficiently close to use bow acceleration for slam prediction while the forefoot pressure gauge was awaiting installation.

Fiber Optics:

Fiber optic strain gauges have been deployed and demonstrated at sea experimentally³⁴. They are susceptible to the same temperature errors as SBL gauges. Although the fibers and gauges are relatively inexpensive to procure and install, the coupling requirements render them expensive, beyond “commercial state of the art” for conventional metal ships.

There are two primary types of fiber optic gauge design. The Bragg’s grating style³⁵ measures the length change between two transverse “scores”, or grates. The distance between scores establishes whether the gauge is SBL or LBL in nature. Multiple gauges can be installed on a single fiber, keyed by differing lengths between scores. Because of this feature, the Bragg’s Grate type gauge could be considered in applications where a large number of collocated strain gauges are required, such as instrumentation of large panel areas for localized ice-induced stresses. However, reliability would become a major factor, since fiber failure could cause “Christmas Light” failure of a large number of gauges. The I/O coupling problem is more complex for this style than for the second type. The Fabray-Perot gauge is an SBL style gauge measuring the length change between opaque bands at the end of the fiber. Only one gauge is possible per fiber, but the coupling problems are not complicated by multiplexing.

Because of the I/O coupling cost, fiber optic strain gauges should be considered beyond the commercial state of the art. Far less expensive and reliable gauges are available for typical strain measurements. Specific applications favoring the use of optic fibers include:

- Applications requiring large numbers of gauges in an explosive or liquid-immersed environment
- Military applications sensitive to Electro-Magnetic Pulse (EMP)
- Unusual size or weight constraints
- Availability of existing fiber optic trunk lines/coupling equipment³⁶
- Strain in composite materials, where conventional strain gauges are unreliable and difficult to install. The composite materials community may drive fiber optic strain gauge development over the next decade.

Acoustic Strain Gauge

Acoustic strain gauges³⁷ measure sound waves induced into metal structures using electromagnetic acoustic transducers (EMATs). Developed specifically for instrumenting and inspecting bridges, they do not need to be in direct contact (i.e., they work through paint and rust) and are portable. Even if cost is not commercially competitive with other types of strain

³⁴ Most noticeably, hundreds of fiber optic strain gauges were installed on the propeller on the USCGC Polar Star. Fiber optics were used to overcome problems of size and cable routing associated with standard strain gauges.

³⁵ Xu et al (1994) describe temperature-insensitive installations of Bragg type gauges. Background on optic fiber gauge types and applications was obtained from Dr. John Kosmatka, University of California - San Diego.

³⁶ Metre and Curran (1990) describe an optic fiber data network for a submarine combat system. SafetyOne, in responding to the manufacturer’s survey, described their development of a fiber optic I/O network as a prelude to their HRMS.

³⁷ The only manufacturer found to date is SonicForce Corporation, 30 Adrian Court, Burlingame, CA 94010, (415) 692-4477.

gauges, acoustic gauges may be extremely valuable for calibration and verification. The first commercial units are anticipated to be available in late 1996.

Laser/Radar Ranging

The current state of the art in surveying and ranging, whether by laser or radar, is about +/- 1 mm (this equates to about +/- 1,000 psi over a 30-meter gauge length. Greater accuracy by radar would require shorter wavelength and/or phase measurement. However, radar wavelengths this short are impacted by atmospheric moisture. It is possible to measure with greater accuracy using lasers, but at the expense of greater power and also with the risk of moisture-induced errors.

The measurement of strain over large distances is of limited value, since only average stress is derived over the measurement length. However, a single transmitter illuminating multiple targets could be used to derive the stress distribution over the length of the ship, using only one instrumented emitter and receiver. We found no instances of near-term commercial application of this concept.

6.2 Ship Motion Sensors

Ships respond to a wave environment in six degrees of freedom: three translational and three rotational. Although roll, pitch, and heave are the most extreme and therefore the motions most often measured, the other motions (particularly surge) may become important in quantifying ship powering performance in waves. Ship motions represent key limits to operation for many types of ships. Considerations include:

- Roll - crew comfort, stability, cargo loads, hydrostatic pressures
- Pitch - hull girder stress, slam, green water, cargo loads, hydrostatic pressure
- Heave - springing, cargo loads, hydrostatic pressure

Because ship motions are six degrees of freedom, it is often difficult to separate individual motions, particularly if sensors are not located at the center of rotational motion. The use of accelerometers to separate motion components is often complicated by local structural resonance problems. For instance, bow accelerometers often exhibit high readings when lowering and raising the anchor. The current state of the art for motion sensors is summarized in Table 6-2³⁸

³⁸ The table format and comments are adapted from a paper by Ashcroft, Goebel, and Hennessy, "Technology Integration for Vessel Operations," SNAME 1995 Joint California Sections Meeting, April 22, 1995.

Table 6-2: Summary of Ship Motion Sensor Technology			
Motion	Sensor Type	Advantages	Potential Problems
Roll & Pitch	Vertical Gyro	Reliable, may be able to use existing ship unit.	Drift, cost, power
	Magnetometer	Moderate cost	Calibration on steel ships
	Solid State Gyro (crystal)	Low cost & power, units packaged with integral rates & displacements	Sensitive to external vibration
	Solid State Gyro (Optic Fiber)	New laser ring technology, no moving parts	Expensive, not yet commercialized for ship use
	“Watson Meter”	Reliable, accurate for pendulum-based design	Moderate cost (\$2500)
	Bubble / Simple Pendulum	Low cost	Inaccurate when not at center of motion.
Yaw (Heading)	Gyro Compass	Current state of the art	Expensive, frequent service
	Solid State Gyro (KVH)	Low cost combination of rate gyro and flux gate compass.	Unproved, unknown life and reliability
	Solid State Gyro (Optic Fiber)	New laser ring technology, no moving parts	Expensive, not yet commercialized for ship use
	Flux Gate Compass	OK for small vessels once compensated, low cost	Difficult to uses effectively unless able to swing vessel for compensation
	Magnetometer	Moderate cost	Calibration on steel ships
Surge Sway Heave	Piezoelectric Accelerometer	Good for machinery vibration measurements	Unsuitable for ship response frequencies
	Piezoresistive Accelerometer	Low cost, OK for short term ship motions	Subject to temperature, cross-axis errors
	Servo Accelerometer	Excellent stability, accuracy, reliability	Expensive
	Capacitive Accelerometer	Moderate cost, performance nearing that of servo accelerometers	Cross axis sensitivity higher than for servo accelerometers

6.3 Environmental Sensors

This category includes all sensors that take direct measurements of the environment, including wind, waves, temperature, ice, and location (navigation). Shipboard environmental sensors are usually less accurate than ship response (motion) sensors, and in many cases the remote sensing technology is more accurate. Ice sensors are non-existent beyond visual observation, remote

sensor (aircraft or satellite) radar scatterometry, or sonar. Remote sensor platforms (NOAA buoys, weather prediction services) also dominate wave height measurement beyond visual observation, although several HRMS manufacturers are back-calculating sea states as a function of ship motions.

Table 6-3: Summary of Shipboard Environmental Sensors			
Category	Sensor	Advantages	Potential Problems
Navigation	GPS	State of the art, low cost, accuracy improved in coastal areas with DGPS	100 m away from DGPS shore stations unless multi-antennas installed
	SatNav	Low cost, reasonable accuracy	Long time between fixes, obsolete technology
	Loran	Low cost, reasonable accuracy in served areas	Not effective in northern or offshore areas, obsolete
Wind	Solid State Thermal Array	Reliable, low degradation in freezing weather	More expensive, less tested technology
	Vane/Cup Anemometer	Low cost, accurate when new, widely used	Icing, long-term reliability and accuracy
	Sonic	Accurate	Expensive, fragile, icing, must be compensated for temperature
Waves	Derived (from motions)	No separate sensors	Works best in swell conditions, emerging technology
	Laser/Optic Wave Meter	Direct measurement	Expensive, inaccurate in precipitation
	Radar	Directional information	Not accurate for wave height or in confused seas.
Ice	Radar	Using existing systems	Need ice “mast” to work
	Sonar	Able to see larger berg keels	Reduced accuracy in higher seas, unreliable for smaller ice, cost, exposed sensors.
Temperature	Thermocouple	Inexpensive, standardized	Connections, nonlinear over wide range
	RTD	Accurate, easily integrated into existing circuits	Expensive compared to thermocouples
	Optical/Infrared	Portable, non-contact, excellent troubleshooting	Too expensive for permanent installations

Although sea-state information may be available from satellite tracks and ground references (buoys, ship reports), an onboard wave height sensor can help define ship motion RAO's with greater accuracy. A number of radar and acoustic designs have been developed, but seem to

work best for fixed platforms. An over-the-bow unit was developed using a Thorn/EMI pulsed infrared band laser mounted over the bow (looking forward, at a 12.5° angle from vertical) conditioned to remove ship motions from the relative motion readings.³⁹ The Russians have also pioneered development in this area.⁴⁰ Pulsed laser wave height gauges range in cost from \$15K to \$30K, depending on the amount of signal conditioning and modification.

Shipboard wind measurements form the backbone of the VOS program. Thousands of reports are collected for meteorological forecasting. Wind measurement accuracy suffers from airstream flow interference by the ship's hull and house, and by distance above sea level. Selecting and documenting the least impacted sensor location is important. Locations atop the mast are best, but suffer impaired maintenance access. Table 6-3 summarizes the current state of the art for shipboard environmental sensors.

6.4 Other Sensors⁴¹

Other sensors that may either be a part of an HRMS or may need to be integrated include:

- Ship performance measurements, including shaft RPM, Horsepower, and speed through the water, will provide measures of propulsion efficiency relative to environmental conditions. Speed and heading (covered under yaw sensors) are important marks to evaluate the relative effectiveness of ship handling changes.
- Pressure gauges are used in an HRMS most frequently to measure slamming pressures and in-tank loads. Germanische Lloyd's is initiating a project to instrument hydrostatic pressures on a bulk ship. Underwater gauges should be replaceable without entering drydock. Pressure gauges should not be overly damped if slam pressure accuracy is desired. The user surveys indicated that pressure sensors were the most frequent HRMS equipment failure.⁴²

6.5 Sensors for Ice-Class Vessels

Ice sensors can be grouped into two categories: avoidance sensors for open ocean transit and hull stress monitors for transit through sheet ice. The first category is beyond the scope of this project, but current technology is summarized for reference.

³⁹ Ship Structures Committee Report No. 362.

⁴⁰ Sviridov, S. A.; "States of Arts on Laser Remote Sensing Techniques of Sea Surface Roughness in Russia," IEEE Oceans '93, page I-473.

⁴¹ Ashcroft, Goebel, and Hennessy (Scientific Marine Services, Inc.) provide an excellent summary of the current design status of a number of miscellaneous ship sensors in "Technology Integration for Vessel Operations."

⁴² Most of the surveys came from ships using one specific pressure gauge model: replacement units have been much more reliable.

Remote Sensing

A number of countries maintain an iceberg surveillance and notification system for alerting marine traffic to the presence of icebergs. The emphasis is shifting from terrestrial sensor assets (ships, buoys, and aircraft) to satellites⁴³ as the technology matures.

Visual / Radar

Visual lookout is still the most reliable sensor for ice of all sizes, but is of course limited by darkness and weather. Radar is effective in identifying ice with a large above-water profile, but not for barely awash ice (particularly as the weather rises). Pulse radars are under evaluation for measuring ice thickness, but dependability is questionable⁴⁴.

Sonar

Success has been mixed. Although sonar can identify larger ice keels if the waves are not too high, effectiveness decreases with decreasing ice size. Sonar sensors are also in an exposed location, and will likely be damaged during transit of sheet ice⁴⁵.

It is apparent that prudent mariners must use all available resources to avoid ice in open waters, including visual, radar, and remote networking.

Hull Stress Monitoring for Ice-Induced Loads

None of the respondents to the manufacturer's survey provide ice-induced hull response sensors or support equipment beyond what is normally provided for open ocean operations. The most common use of HRMS on ice-class vessels has been for research purposes, though attempts have been made to provide an "operational" display of the measurements to assist in safe navigation in ice. As part of this project, Fleet Technology Limited conducted a literature search and informal industry survey to evaluate and define the current state of the art in ice hull monitoring. Tables C-1 and C-2 in Appendix C summarize their findings for both localized and global hull responses on a number of vessels. Key findings included:

- Localized hull structure stresses frequently exceed material yield strength during icebreaking. An ability to adjust strain gauge zero-offsets must be provided for reset after plastic deformation.
- Amidships hull girder stresses are generally less in icebreaking conditions than during typical open ocean storm transit. Maximum hull girder stresses during ice operations may occur well forward of amidships, a consideration if hull girder strength is tapered fore (and aft) of the amidships 40% length.

⁴³ Blackford et al (1994) describe the use of SAR and AVHRR satellite sensors to guide yacht racers and oceanographic ships clear of ice in the southern polar area. McIntyre et al (1994) provide an excellent summary of ice measurement and discrimination using various satellite radars.

⁴⁴ Leavitt & McAvoy (198?) describe helo-mounted pulse radars in the VHF band to estimate ice thickness, including problems with accuracy. Echert et al (1992) describe their results in measuring ice thickness using the EM31 Ground Conductivity Meter. Accuracy is less for thinner ice, since the unit depends on differences in conductivity between the ice and the water underneath. Future developments of this device may lead to satisfactory on-the-go measurements.

⁴⁵ Leavitt & McAvoy (198?) also summarize work in hull-mounted ice-sensing sonars.

- Strain rates for ice loading in the local structure are similar to those for the global response, and both are not significantly different from global responses experienced from open sea loading.
- Localized ice loads (and potential hull breach) are not uniform and not well correlated with average loads (hence breach is difficult to predict from trend analysis). In other words, it is not uncommon to breach the hull even though a distributive strain gauge grid indicates stresses have not exceeded yield.
- The location and orientation of strain gauges depends on the ship structural arrangements. Therefore a specific requirement is not feasible.
- It would be prudent to measure local loads at areas other than the bow, where ice damage can occur (midship waterline, etc.).
- The required number of sensors is dependent on a number of factors, therefore it is better to specify the area of coverage rather than the number of sensors.
- A system measuring noise or other indicator of total energy expended during icebreaking may offer an alternative means of covering large hull areas. Such a system is not state of the art, and must be developed.
- Current HRMS hardware and data acquisition equipment used in non-ice applications is suitable or adaptable to ice operation. However, sensor offset, arrangement, and analytical/display software is quite different than for open sea loads.

These findings suggest the following developmental needs for ice-class vessels:

- (1) Development of ship-mounted all-weather equipment capable of detecting ice masses in sufficient time to take corrective action (changing speed and/or direction). Ship-mounted systems should be integrated with remote systems capable of displaying regional ice conditions.
- (2) Development of sensor grids and analysis/display software capable of predicting pack ice characteristics, such as thickness and lateral pressure, as a function of speed and direction.
- (3) Development of sensor grids or new sensors capable of detecting hull structural yield and rupture. In the interim, ships operating in pack ice must rely on reactive measures such as flood/other alarms for breach warning, inner hull separation of pollutants, ice-class scantlings, and similar measures.

Sensors and foundations installed on ships operating in arctic regions have additional requirements, including:

Temperature:	+30°C to -50°C
Icing:	Up to 1 meter thick in exposed locations
Accelerations:	+/- 2.0 g's
Sampling Frequency	100 Hz for global and regional structure
Material:	Nil Ductility transition temperature of -50°C

for critical structural applications

6.6 Recommended Sensor Range and Accuracy

It is not possible to fully specify the sensor suite characteristics for all applications. Common sense must be applied to specifying sensors and HRMS capabilities. If the HRMS objective is to provide bridge personnel with visual indications of ship response, then the required accuracy and sampling rate are relatively low. If HRMS objectives include determination of maximum values for establishing operational policy and future design criteria, then accuracy and sampling frequency must be better. Table 6-4 provides recommendations for three levels of purpose: ABS minimums (as indicative of classification society requirements), a minimum based on manufacturer practice and bridge visual requirements, and one based on research objectives. The table values should be considered guidance only, and individual specifications should be based on user need.

Table 6-4: Recommended Sensor Accuracy			
Sensor	ABS Requirement	Visual/Mfr	Research
Navigation	None	100 m	As required
Roll/Pitch: Range:	None	+/- 45.0 degrees	+/- 45 degrees
Accuracy:	None	+/- 1.0 degrees	+/- 0.5 degrees
Yaw/Hdg: Range:	None	360 degrees	360 degrees
Accuracy:	None	+/- 1.0 degrees	+/- 0.5 degrees
Accel. : Range:	None	+/- 1.0 g	+/- 5 g's
Accuracy:	+/- 0.01 g's	+/- 0.02 g's	+/- 0.005 g's
Frequency:	3X req'd response	5 Hz	As required
Strain Gauge (no ice):			
Range:	Yield	Yield	Ultimate
Accuracy:	+/- 5 micro-strain	+/- 25 micro-strain	+/- 5 micro-strain
Sampling Frequency:	5 Hz	5 Hz	100 Hz
Fatigue - bin size	50 micro-strain	50 micro-strain	10 micro-strain
Strain Gauge (ice):			
Range:	No difference	Yield	Ultimate
Accuracy	No difference	+/- 25 micro-strain	+/- 5 micro-strain
Sampling Frequency	No difference	100 Hz	100 Hz ⁴⁶
Wind: Speed	None	0-40 m/sec	0-50 m/sec
Accuracy	None	+/- 2.0 m/sec	+/- 0.5 m/sec
Angle	None	+/- 5.0 degrees	+/- 1.0 degrees
Wave: Height	None	+/- 0.5 m	+/- 0.1 m
Period	None	+/- 0.5 sec	+/- 0.1 sec
Ship Perf. Accuracy:			
Speed	None	+/- 0.5 knot	+/- 0.1 knot
RPM	None	+/- 1.0 rpm	+/- 0.1 rpm
HP	None	+/- 2%	+/- 1%
Hydrostatic Pressure:			
Range:	None	0 - 0.5 MPa	0 - 0.5 MPa
Accuracy:	None	+/- 1.0%	+/- 0.1%

⁴⁶ It may be necessary to sample at much higher frequencies if performing research on individual hull panels subject to high frequency impulse loading, such as HI-Shock. NAVSEA recommends sampling frequencies at least twice the anti-aliasing filters. Sampling rates are part of a trade-off with data storage space and hardware/software capability.

7.0 SHIPBOARD DATA TRANSMISSION

The cabling infrastructure required to route power to CPU and sensor modules, and to transmit data from sensors to the CPU, is the most straightforward (but often the most expensive) part of an HRMS. There are a number of factors driving the selection of the power/data transmission subsystem:

- Number, location, and power/signal requirements of sensors
- Signal degradation due to power variance, cable length, terminal corrosion, etc.
- The presence of existing passageways or cable trunks in which to run new cable
- Explosion hazards in various parts of the ship
- Installation costs for new cable

Given these design factors, there are only a few options for the data transmission system:

1. Hard wiring
2. Radio link between some or all modules
3. Optic fiber network
4. Combination

This report section briefly examines the advantages and disadvantages of each approach, delineating key options.

7.1 Hard Wiring

Hard wiring is the most common approach to installing hull monitoring systems. Protected longitudinal passageways require the least cable and installation expense, but such passageways do not exist on many ship types, including tankers and product carriers. Several types of shielded and grounded cable are available, and low-smoke manufacture is recommended for passageways. Cables need to be grounded to prevent the possibility of static charge, particularly in an explosive atmosphere. Prior opinion (and USCG rules) indicated armored cable for external applications. Long cable lengths and end connections sometimes lead to signal degradation. Where applicable this can be overcome by providing pre-processors near the sensors.

7.2 Radio Link

Radio links between sensors and the CPU are only offered by two of the HRMS manufacturers responding to the survey. Radio links have the advantages of eliminating spark hazard in an explosive atmosphere and eliminating the cost of running wire (but at the expense of the radio transmitter and antenna installations). This advantage is significant when cabling must be run in exposed areas where no existing cable trunk exists. However, radio linking becomes less advantageous in systems with a large number of distributed sensors, requiring multiple radio transmitters. Radio transmission is susceptible to signal interference, causing erroneous data

blips. If needed, these blips can be removed from data storage by filtering or by a verification protocol between transmitter and receiver.

7.3 Fiber Optic Network

Fiber optic strain sensors have been used on an experimental basis for propeller blade stress monitoring and by SafetyOne for hull girder stress sensors. However, there are no commercial systems that currently feature fiber optic data transmission. Potential advantages include inherent safety in explosive atmospheres and light weight/small size applications. Fiber optics are being introduced into large numbers of military applications because of the inherent resistance to electro-magnetic pulse. The military development may ultimately push the cost of optic signal connectors and decoders down until a shipboard HRMS network is economical.

7.4 Power Supply and Distribution

Some HRMS manufacturers fully power all components from the CPU. This sometimes requires the installation of additional, heavier cabling over long distances. Alternatives include local power supplies taken from the ship's existing power distribution system. The risk in this approach is the quality of the supplied power - voltage spikes are common, particularly in forward areas where limited power may be supplied for large machinery. Power supplies must therefore incorporate sufficient filtering and choking to maintain sensor power supply within manufacturer's specified limits. ABS requires a minimum 4-hour Uninterruptible Power Supply (UPS) for units meeting the requirement of HM3-Voyage Data Monitoring.

Table 7-1: Summary of Manufacturer's Survey on Input/Output Characteristics			
Company	Data Xmission Method	I/O Channels	Intrinsically Safe?
BMT-SeaTech	Hard Wire	17 - 32	Yes
Concept Systems*	RS485 Data Link*	> 64	Yes
MCA Engineers	Radio Link Hard wire	9 - 16	Yes
Ocean Systems	Hard Wire	9 - 16	No
SafetyOne	Optic Fiber	> 64	Yes
SMS	Hard Wire Radio Link	> 64	Yes
Strainstall	Hard Wire	9 - 16	Yes

* Concept Systems offers radio link and fiber optic compatibility for some applications

8.0 CENTRAL PROCESSING UNIT (CPU)

The CPU is the central processing unit for the distributed HRMS. It queries the sensors, collects and processes the readings, and displays (and stores) the results in a user-friendly format.

8.1 CPU Hardware & Operating System

All respondents to the Manufacturer's Survey supply IBM-compatible personal computers (most currently supply 486-66 or Pentium units) running on either MicroSoft DOS or Windows. None of the respondents listed either Apple or RISC/Workstation equipment. Buyers often have the choice of having the computer dedicated to the HRMS or being available for other shipboard purposes. However, manufacturers prefer dedicated PC's to maintain configuration control over the HRMS. The cost of a single service call to reconfigure a sailor-modified system will generally be more than the cost of another PC. Table 8-1 summarizes the manufacturer's survey responses for CPU questions.

Table 8-1: Manufacturer CPU Specifications		
Manufacturer	Hardware	Operating System
BMT-SeaTech	Pentium	MS/DOS & Windows/NT
Concept Systems	Pentium	MS Windows/NT
MCA Engineers	486-66 Mhz	MS/DOS & Windows/NT
Ocean Systems	486 or better	MS/DOS & Windows
SafetyOne	IBM Compatible	MS Windows/NT
SMS	486-66 Mhz	MS/DOS
Strainstall	486-66	MS/DOS & Windows

8.2 Software Considerations

Manufacturers generate their own proprietary codes to convert sensor readings, perform real-time calculations in support of display functions and statistical summaries, estimate sea-state characteristics from ship motions, and perform other specialty functions. Portions of the software related to special purpose "cards" can be procured off-the-shelf. Specifically, cards and software that poll sensors at rates up to 100,000 Hz are available. However, such high-rate polls exceed the capacity for hard disk transfer, and will fill available buffer storage rapidly. It is possible to trigger high polling rates for limited periods of time, subject to buffer storage limits.

The most serious issues related to operating and specialty software are compatibility and configuration control. It is not atypical for HRM systems to be specially configured on a ship-by-ship basis, providing different sensor suites, alarms, and display screens. These differences sometimes result in problems for systems that use the same operating systems and specialty packages. A change in operating system software (such as from Windows 3.1 to Windows 95

NT) will often impact other functions, sometimes disabling existing specialty codes and HRMS entirely. It is therefore preferable to obtain a system completely assembled and tested using dummy sensor inputs. It is critical to record the exact versions of all computer hardware and software to maintain configuration control.

8.3 Data Storage

CPU data storage must be configured to meet a number of conflicting requirements. Relatively modest data storage (< 100 Mbytes) is acceptable for real-time HRMS purposes. However, any requirement to store data for later retrieval and analysis will increase minimum data storage capacity. Trade-offs between voyage (or record) length, storage medium (optical disks, tapes, etc.), sensor sampling rate, ability to download data by satellite to another storage device, etc. must be made to determine the optimal data storage capacity. Table 8-2 summarizes the data storage capacity currently offered by survey respondents. If an HRMS serves as a data storage receptacle for Voyage Event records (ABS HM3 - Voyage Data Monitoring or similar), then interfaces to other data (engine performance, radar sweeps) must be provided and storage space allocated. The cost of PC data storage (hard drive, optical disk, tape) has dropped dramatically the last two years, and greatly increased capacity is readily available. When increasing available storage in existing systems, software compatibility to existing or new operating systems must be evaluated.

Table 8-2: Summary of Manufacturer's Survey on Storage and Sampling Rate			
Company	Data Storage Capacity	Data Sample Rate	Satellite Link
BMT-SeaTech	100 MB - 1 GB	10 - 50 Hz	Upload data*
Concept Systems	> 1 GB	> 100 Hz	
MCA Engineers	> 1 GB	6 - 10 Hz**	
Ocean Systems	100 MB - 1 GB	10 - 50 Hz	Up/Download
SafetyOne	> 1 GB	10 - 50 Hz**	Up/Download
SMS	100 MB - 1 GB	6 - 10 Hz	Up/Download
Strainstall	< 100 MB	6 - 10 Hz	Upload data

* BMT will have this ability soon.

** MCA provides >100 Hz for 2 seconds during slam. SafetyOne plans a similar capacity.

8.4 Networking

The issue of satellite communications was addressed in Chapter 5. Data transmission using existing Inmarsat A equipment is somewhat slow and expensive, but is vital to HRM systems providing periodic weather updates and recommended voyage route changes. As the Low Earth Orbit (LEO) satellite communication systems come on line, data transmission abilities will start to mimic current cellular telephone capabilities. T-1 data transmission rates may become viable if Teledesic comes on line in 2001 as currently promised. Current HRMS satellite links are summarized in Table 8-2.

9.0 DISPLAY

An HRMS display includes the graphic user interface (GUI) between the system and the user, plus any audio alarms. Modern computer programs allow the combination of real-time sensor data feeds with realistic visual displays that convey a high quality of information to the user.

Display considerations include:

- Regulatory/classification society requirements
- Concise information transmittal to all system users
- Alarm needs and effectiveness
- Human factors

This report section provides a framework for evaluating display requirements. Sample color plots for several commercially available systems are provided in Appendix B.

9.1 Regulatory Requirements

Although Lloyds, DnV, and other regulatory agencies also have requirements for HRMS, we will summarize American Bureau of Shipping requirements since they will most likely drive US installations in the near future. ABS requirements are relatively few and not overly restrictive, and include:

- Real-time or near-real-time display of critical parameters (slam warnings, green water warnings, motions, accelerations) on the bridge. The display must show trend over time as related to warning levels. Warning levels must generally be developed on the basis of ABS rule-allowable values or comprehensive analysis and/or testing, and must be submitted for approval.
- Hull girder stress displays must show both stillwater and wave-induced components. Stresses must be shown as a function of time and longitudinal position. A display for stillwater stresses must be provided at the cargo operations area. Displays must show the effects of speed or heading change over a relatively short period (10 minutes) to indicate to the helmsman how ship handling changes are affecting stresses.
- Intensity reduction and revised color schemes must be provided for night-time operation so as not to impact mariner night vision.
- Alarms must not be overly sensitive or unnecessarily worrisome to prevent helmsman “sensory overload.” Sensory overload has been a significant problem for ice-induced hull stress monitoring systems.

Although the ABS Guide is not overly restrictive on display format, the requirements are difficult to meet using only one screen, or two screens with minimal switching. User-oriented display requirements are reviewed in the following section.

9.2 Display Design Driven by Users

The manufacturer's survey indicated that most HRMS manufacturers provide five or more screens, including real-time sensor displays, statistical averages, and replay (not real time) capability. Table 9-1 summarizes the results for several manufacturer survey questions.

An HRMS buyer should consider the needs of all system users. Users will certainly include ship's force, but may also include support personnel tasked with developing operating policy and future ship design specifications. Different users will have different HRMS display priorities, such as:

Bridge Personnel

- Emphasis on real-time data display
- Minimum number of screens with maximum quality of information
- Intuitive screens with simple shapes and pictures
- Easy-to-see warning or alarm conditions
- Simple controls

Cargo Loading Personnel

- Single screen showing hull girder stress versus limits

Shore Support Personnel

- Multiple screens with "data mining" options
- Ability to replay and summarize
- Emphasis on statistical measures
- Ability to back-track responses to original sensors & wave conditions

Ship's force and shore personnel will often have different display needs, and they may not be able to articulate specific needs until they have some operational experience with the system. In general, shipboard user needs will take precedence, but it is apparent from the manufacturer's survey that all needs can be met.

Table 9-1: Summary of Manufacturer Survey on Displays					
Company	No. of Sensors	Real-Time Disp. Per.	Statistical Per. Avg.	Replay Period	No. of Screens
BMT-SeaTech	All	> 60 min	5 min-1 day	> 2 hr	> 10
Concept Sys.	All	1 min	5 min	> 2 hr	1-4
MCA Engineers	All	1 min	5 min	> 2 hr	1-4
Ocean Systems	All	1-60 min	5 min-1 day	> 2 hr	5-10
SafetyOne*	On dmd	On dmd	On dmd	On dmd	On dmd
SMS	All	> 60 min		< 2 hr	> 10
Straininstall	All	1-60 min	5 min	> 2 hr	> 10

*SafetyOne has not yet built a commercial system, but offers any range of display.

Other companies will provide additional display capability if tasked as well.

Different HRMS manufacturers have resolved the display design problem in different ways. Appendix B contains display screens for several manufacturers. MCA provides a primary operational screen (Appendix B, page B-2) that displays the real-time value of all sensors using relatively simple shapes. Individual sensor traces are plotted in detail on secondary screens (page B-3), and trip summary experience for any sensor can be plotted as a function of ship position trace (page B-4). Ocean Systems emphasizes weather prediction and voyage routing, and several of their screens (provided as part of an integrated Sperry Bridge design) are shown on Appendix page B-5. SMS emphasizes the use of simple hull shapes and bar graphs in their screen designs (page B-6). SafetyOne has developed display screens suitable for a large number of strain sensors as well as classification society style hull girder bending moment and fatigue plots (pages B-7 and B-8). Straininstall provides one of the more intricate views of a hull girder with its CAD-style hull and bar graph plots (pages B-9).

9.3 Warnings, Alarms, and Event Predictions.

All surveyed manufacturers included visual and audible alarms. Table 9-2 summarizes the functions provided with alarms (visual and audible) and predicted on the basis of trend analysis, ship motion calculation, or other procedure.

Company Name	Warnings (Visual/Audio)				Event Prediction				
	Slam	Hull Stress	Pitch Accel	Load Plan	Slam	Ship Mot'n	Weather Response	Arrival Time	Fuel
BMT-SeaTech	X	X	X	X	X	X	X		
Concept Systems	X	X	X						
MCA Engineers	X	X	X		X				
Ocean Systems	X	X	X		X	X	X	X	X
SafetyOne	X	X			X	X			
SMS	X	X			X	X		X	
Straininstall	X	X							

Ice Alarms - The user's survey indicated no specific complaints about HRMS alarms for typical ocean-going systems. This was not the case for systems developed to measure ice-induced hull stresses. Interviews with personnel aboard ships fitted with ice hull monitoring systems indicated that systems had been disconnected, primarily because of constant alarms signals from local stress sensors. Bridge personnel tended to use physical indications of overall ice resistance, primarily sound and ship motion, to determine ice-breaking limits. If one defines localized hull failure as a breach in watertight integrity, then there is no dependable correlation between global and local ice-induced hull stresses. Local yielding and failure can occur under relatively light ice conditions, or may not occur in ice thick enough to stop the ship. There is a need for further ice-class vessel sensor development as outlined in Section 6.5.

9.4 Human Factors

There are a number of human factors to be considered in any HRMS system. The best designs typically result from an interactive development process that teams the designer with the user. Witmer and Lewis⁴⁷ credit much of their success in introducing HRMS onto BP tankers to the interactive process between SMS engineers and ship's force in developing the display screens. Key HRMS considerations include:

Night-time Operations

An HRMS is most valuable at night in storm conditions, when bridge personnel cannot see the wave environment. It is important that the system have color schemes and light intensity controls to prevent interference with the watch-stander's night vision. These requirements place a premium on lower frequency colors (red) and simple shapes that require a minimum of contrasting.

Color Selection

Mariners have natural and trained perceptions of the relative importance of colors. In the United States, red and orange are associated with danger, whereas blue and green are associated with acceptable or non-threatening conditions. Many, but not all, other cultures share these color preferences, and crew nationality should be considered in control and display design. Display screen color selection can generally be changed with very minor software changes. HRMS buyers should not be hesitant to request color changes for screen graphics and sensor displays.

Screen Location

Screen location will typically be a function of bridge layout, and is best determined by the customer rather than the manufacturer. When considering or specifying a system, the ability to view the HRMS screens on other video display terminals (possibly port navigation ECDIS) would be beneficial, particularly in crowded bridge arrangements. Screen location should also be considered in the context of priority during storm situations. Those sensors the crew consider most important should be located most central to the helmsman's field of view.

Heads-Up Display (HUD)⁴⁸ is not yet state of the art for shipboard bridge controls. We anticipate the automotive industry will lead commercial HUD development, and most auto makers already have HUD's in the R&D stage.

⁴⁷ Witmer and Lewis, "Operational and Scientific Hull Structural Monitoring on TAPS Trade Tankers," SNAME Transactions Volume 102, 1994.

⁴⁸ Heads-Up Display is the process of superimposing optically generated images, such as gauge displays, with line-of-sight vision using an intervening glass surface.

10.0 LOGISTIC SUPPORT

Most marine organizations (including the US Navy) have learned that an integrated Logistic Support Plan is necessary for the successful introduction of new hardware at sea. Success in HRMS implementation and logistic support depends greatly on management support at both the corporate and shipboard level. Maintaining HRMS equipment in proper running order is necessary not only to support ship handling decisions but also to maintain classification where applicable⁴⁹. Section 10.1 describes the logistic support facets to be considered by a buyer, and lists some of the options available. Sections 10.2 and 10.3 summarize the manufacturer and operator survey responses respectively.

10.1 Logistic Support Procurement Considerations

Integrated Logistics Support refers to the overall design and system attributes necessary to operate and maintain the equipment. In new one-off systems, it is not unusual for ILS costs to approach those of the equipment procured. The following paragraphs summarize the ILS considerations for the HRMS.

Training

Training in system use, maintenance, and repair should be provided to all applicable crew members, including those with purchasing or supervisory control of the system. The best training includes actual use under adverse environmental conditions, whether simulated or actual. However, this type training is also the most expensive. The ship operator/owner must assess their own programs and personnel when deciding on training plans. Several levels are possible:

- (a) Shoreside Training - this is generally the least expensive approach, since a large number of personnel can be accommodated at one time. However, it is often the least effective since the training environment is usually not realistic and crew attentiveness may be lacking.
- (b) Computer-based training (CBT) - CBT has several advantages. It allows the operator/user to train at their own speed and schedule. Although more costly initially, there are no follow-on costs for new crew members or refresher training unless the system is changed significantly. It facilitates at-sea training using the actual equipment. Disadvantages include the loss of interaction with manufacturer's personnel and loss of system use during training periods. CBT requires personal discipline to make time to complete the training evolution. CBT effectiveness is enhanced through feedback on trainee problems and performance.
- (c) At-Sea Training - Because of the individualized attention and realistic operating conditions, properly developed at-sea training will provide the best quality. However, it must be

⁴⁹ The ABS "Guide for Hull Condition Monitoring Systems" specifies yearly surveys plus calibration and special survey requirements. The unqualified requirement to maintain all HRMS gear in full operating condition may preclude an owner's desire to obtain classification society notation unless other conditions (such as a reduction in insurance rates) apply.

repeated for new crew members, and cost is usually higher because of the large amount of consulting time required.

- (d) Operating Manuals - Operating manuals should be a part of any training program. The US military has MIL-SPECS defining minimum content and standards. ABS requires an Operating Manual containing instructions on HRMS use, how to interpret results, maintenance and repair, sensor set-up and calibration, and verification procedure. Technical Manual quality is best when verification testing is invoked. Manual medium (hard copy, CD-ROM) should be consistent with other manuals on the ship. Hard copies take up room, but are accessible in the event of power or computer failure.

Reliability

Equipment reliability is a function of operating environment, equipment design, component procurement, and system manufacture and installation. Lack of attention in any area can result in poor system performance. There a number of ways a purchaser can evaluate and/or specify the level of reliability in an HRMS:

- Interview other customers with parallel applications
- Specify warranty, burn-in, and/or delivery/acceptance testing
- Review manufacturer's written QA plan (ISO 9000, MIL-I-45208, etc.)
- Review/define levels of redundancy in combination with in-port and at-sea repair capability.
- Review components against applicable "Qualified Parts" lists.
- Require validation proof for minimum figure of merit, such as MTBF (Mean Time Between Failures).

Reliability specifications involve cost, and the buyer must evaluate the relative importance of various portions of the system. For example, the required reliability for data storage will differ for a user interested in real-time ship handling versus one interested in Voyage Event Records.

Maintenance & Repair

An HRMS buyer must be concerned with both scheduled and unscheduled maintenance requirements. Scheduled maintenance can be performed by either the manufacturer or by ship's force. If ship's force is responsible, then Technical Manuals must provide complete procedures, including safety, tools and equipment, performance standards, and frequency. Well designed systems consider ease of maintenance, including access, modular replacement, tool clearance, and component interchangeability. Although onboard maintenance and repair capability may be desirable from the standpoint of cost or operational flexibility, the increased ship's force workload may not be acceptable.

Maintainability is often measured by MTTR, or Mean Time To Repair. Technical Manuals can be improved by invoking verification testing to identify missing information or unforeseen maintenance problems.

Spare Parts

It is critical that either the manufacturer or user maintain a reasonable spare parts inventory, especially for long-lead or proprietary items. The need (and expense) of spare parts inventories can be reduced by making maximum use of interchangeable components, “off-the-shelf” components, and components common to other systems. Spares inventories should be updated to reflect system modifications.

Configuration Management

The rapid pace of computer hardware and software development combined with emerging sensor and network technologies invokes a requirement for Configuration Control.

Configuration Control is necessary at both the system and component level, to insure all subsystems function properly with each other, and that spares and other ILS assets (particularly Technical Manuals) are up-to-date.

10.2 Manufacturer Survey Results

All manufacturers responding to the survey offered training and Technical Manuals. Results are listed in Table 10-1. A prudent buyer would examine examples of training plans and Technical Manuals as an indication of ILS quality.

TABLE 10-1: Manufacturer Logistic Support Services						
Manufacturer	Training		Operating Manual		Maint/Repair Manual	
	Ashore	Aboard	Hard Cpy	CD-ROM	Hard Cpy	CD-ROM
BMT-SeaTech	X	X	X	X	X	X
Concept Systems	X	X	X		X	
MCA Engineers	X	X	X		X	
Ocean Systems	X		X		X	
SMS	X	X	X	X		
Strainstall	X	X	X		X	

BMT and Ocean Systems offer On-line Help functions. SafetyOne is not listed since they do not have any production units in place.

10.3 Operator Survey Results

The response rate to the Operator Survey mailing was less than 10%, with only eight responses. Two came from ship’s force on TAPS trade tankers, one from shore support and three from ship’s force on LNG tankers, and one from shore support on container ships. The results, although not statistically significant, are provided in Table 10-2 and 10-3 as empirical evidence of user perceptions.

TABLE 10-2: Operator Rating of ILS Products			
ILS Product:	None or Not Applicable	Poor or Marginal	Good or Excellent

Vendor Training	1	5	2
Operating Instructions/Manual		5	3
Maintenance/Repair Manual	6		
Spare Parts Availability	1		5
Answers Questions Promptly			6
Field Service			8
“User Friendly”		1	7
Overall Reliability		1	7*

* The most frequently cited equipment problems were pressure sensors and satellite link.

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APPENDIX A
LIST OF HRMS MANUFACTURERS

UNITED STATES

MCA Engineers

2960 Airway Avenue #A-103

Costa Mesa, CA 92626

Phones: Voice (714) 662-0500
 FAX (714) 668-0300
 Email tvo@mcaengineers.com

Contact: Tim Vo, HMS Manager

Ocean Systems, Inc. / Sperry

1330 Broadway #952

Oakland, CA 94612

Phones: Voice (510) 835-5431
 FAX (510) 835-4202
 Email 74354.1064@compuserve.com

Contact: John Murk

Scientific Marine Services, Inc. (SMS)

101 State Place, Suite N

Escondido, CA 92029

Phones: Voice (619) 737-3505
 FAX (619) 737-0232
 E-mail fdebord@scimar.com

Contact: Frank DeBord, Jr., President

UNITED KINGDOM

BMT Seatech Ltd.

Grove House, 7 Ocean Way

Ocean Village, Southampton

Hampshire S014 3TJ, U.K.

Phones: Voice (011) 44-1703-635-122
 FAX (011) 44-1703-635-144

Contact: Dr. Phil Thompson

**** Broadgate Ltd**

Unknown address

Phone: Voice (011) 44-
 FAX (011) 44-1454-617-310

Contact: Chris Winkley

UNITED KINGDOM (Continued)

Concept Systems

1 Lobie Mill, Beaverbank Business Park,
Logie Green Road,
Edinburg EH7 4HG, U.K.

Phones: Voice (011) 44-1315-575-595
 FAX (011) 44-1315-572-367
Contact: Mr. David Phillip/David McOmish

Strainstall

Denmark Road, Cowes,
Isle of Wight, PO31 7TB, U.K.

Phones: Voice (011) 44-1983-295-111
 FAX (011) 44-1983-291-335
 E-mail 100616@compuserve.com
Contact: Mr. Bryan M. Harden or Terry Lewis

NORWAY

* **Kvaerner Ships Equipment A.S.**

Joseph Kellers vei 20, Tranby
P.O.Box 19
N-3401 Lier, Norway
Phones: Voice (011) 47-3285-9310
 FAX (011) 47-3285-4370
Contact: Mr. Knut Kildahl Hansen

* **Moland Automation A.S.**

Liaveien 5, P.O.Box 44
N4815 Saltrød, Norway
Phones: Voice (011) 47-3703-0666
 FAX (011) 47-3703-0220
Contact: Mr. Otto Knudsen

SafetyOne A.S.

P.O.Box 250, Vagsbygd
N-4602 Kristiansand S., Norway
Phones: Voice (011) 47-3800-2580
 FAX (011) 47-3800-2585
Contact: Mr. Sten Hellvik

FINLAND

* **SAJ Instrument AB**

PO Box 176
FIN-22101 Mariehamn Finland

Phones: Voice (011) 358-28-16100
 FAX (011) 358-28-23199

A-2

Notes concerning HRMS Manufacturers:

1. Manufacturer names and points of contact are provided for information only. The inclusion of any manufacturer does not represent a recommendation or guarantee of any kind. Readers and buyers should perform their own determination of equipment suitability for purpose.
2. Ocean Systems now provides their weather prediction system as part of the Sperry Integrated Bridge
3. Companies marked with “*” did not respond to the Manufacturer’s Survey
4. Broadgate did not respond to the survey. Their primary product was described by secondary sources as a Voyage Event Recorder. The VER is able to interface with a number of systems and sensors, including the Straininstall HRMS.
5. SAJ did not respond to the survey. Their product is described in the May 1996 issue⁵⁰ of *Shipping World and Shipbuilder*. Their system consist of two dynamic trim/heel measuring sensors installed at either end of the cargo block, allowing measure of the relative trim and heel angles. These can be used to calculate average bending moments and torsion. They also offer a through-hull pressure sensor to measure draft.

A-3

⁵⁰ We extend our appreciation to Robert Sedat at the USCG R&D Center for furnishing this information.

LIST OF STRAIN GAUGE SENSOR MANUFACTURERS

Bonded Foil Style Strain Gauges:

JP Technologies, Inc.

1430 Cooley Court
P.O. Box 6002
San Bernardino, CA 92408
Tel: (909) 799-8000
Fax: (909) 799-1904

Omega Engineering, Inc.

One Omega Drive
Box 4047
Stamford, CT 06907
Tel: (800) 826-6342
FAX: (203) 359-7811

Measurement Group, Inc.

PO Box 27777
Raleigh, NC 27611
Tel: (919) 365-3800
FAX: (919) 365-3945

SAJ Instrument AB

PO Box 176
FIN-22101
Mariehamn Finland
Tel: 358-18-16100
Email: Sales@saj.pp.fi-personel.eunet.fi/pp/saj

Welded Strain Gauges:

JP Technologies, Inc.

1430 Cooley Court
P.O. Box 6002
San Bernardino, CA 92408
Tel: (909) 799-8000
Fax: (909) 799-1904

Linear Potentiometers (LBL Strain Gauges):

BEI Duncan Electronics

15771 Red Hill Avenue
Tustin, CA 92600
Tel: (714) 258-7500
FAX: (714) 258-8120

LVDT's:

Lucas Shaevitz

7905 N. Route 130

Pennsauken, NJ 08110-1489

Tel: (609) 662-8000

FAX: (609) 662-6281

Omega Engineering, Inc.

One Omega Drive

Box 4047

Stamford, CT 06907

Tel: (800) 826-6342

FAX: (203) 359-7811

Fiber Optic Strain Gauging:

MetriComp Systems Ltd

5608-37th Street SW

Calgary, Alberta

Canada

T3E 5M6

Tel: (403) 246-1983

FAX: (403) 240-1512

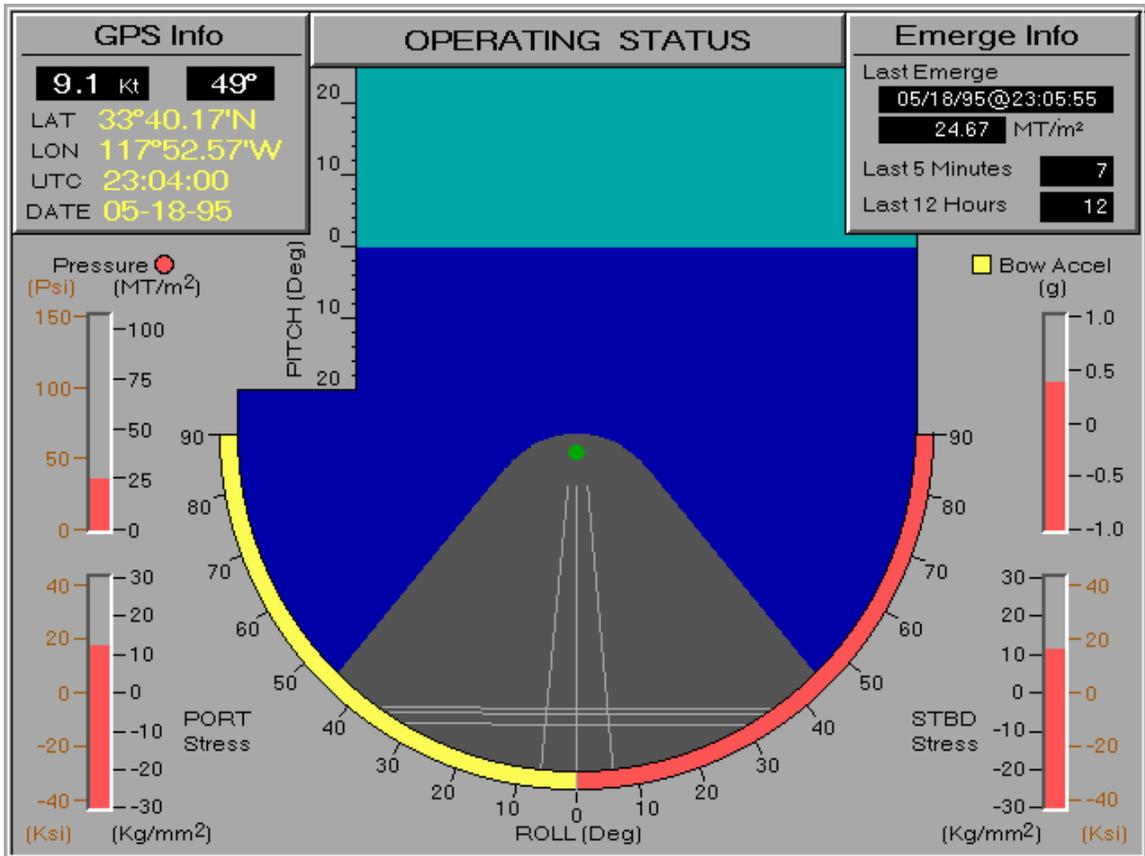
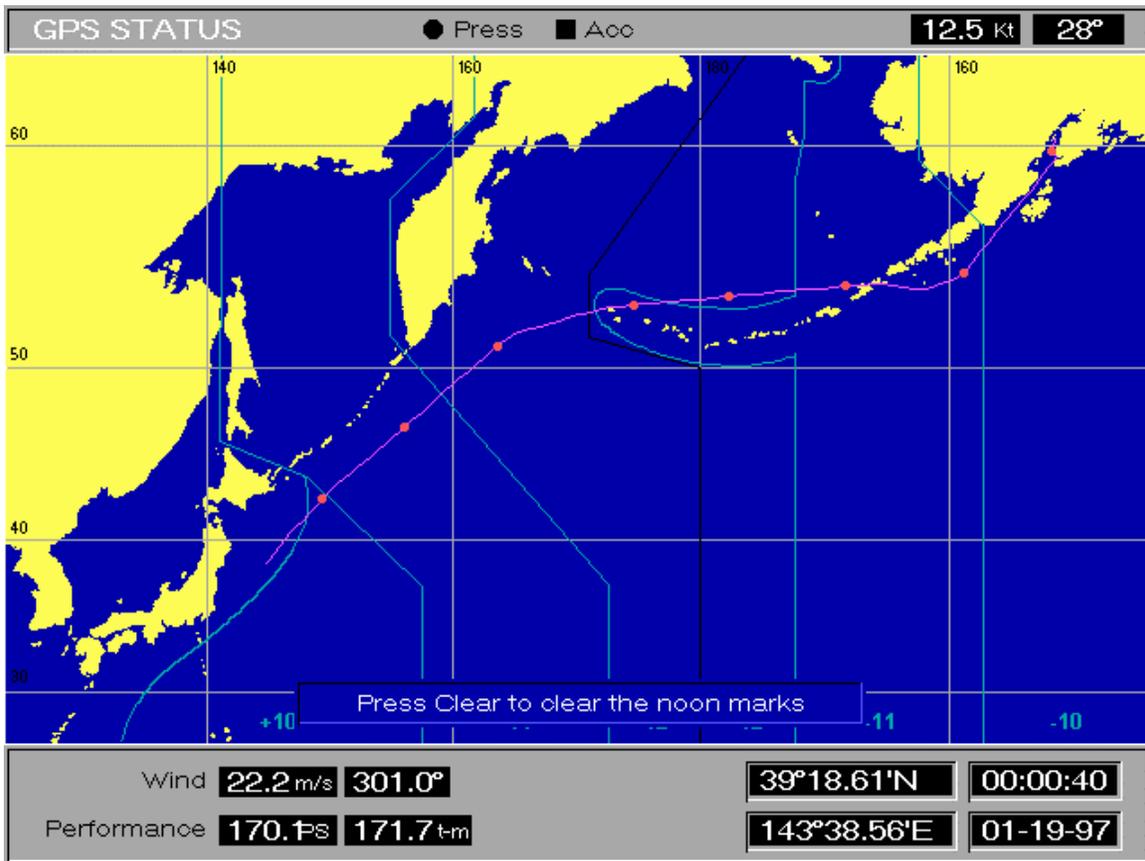
Pulse-Laser Wave Height Sensor

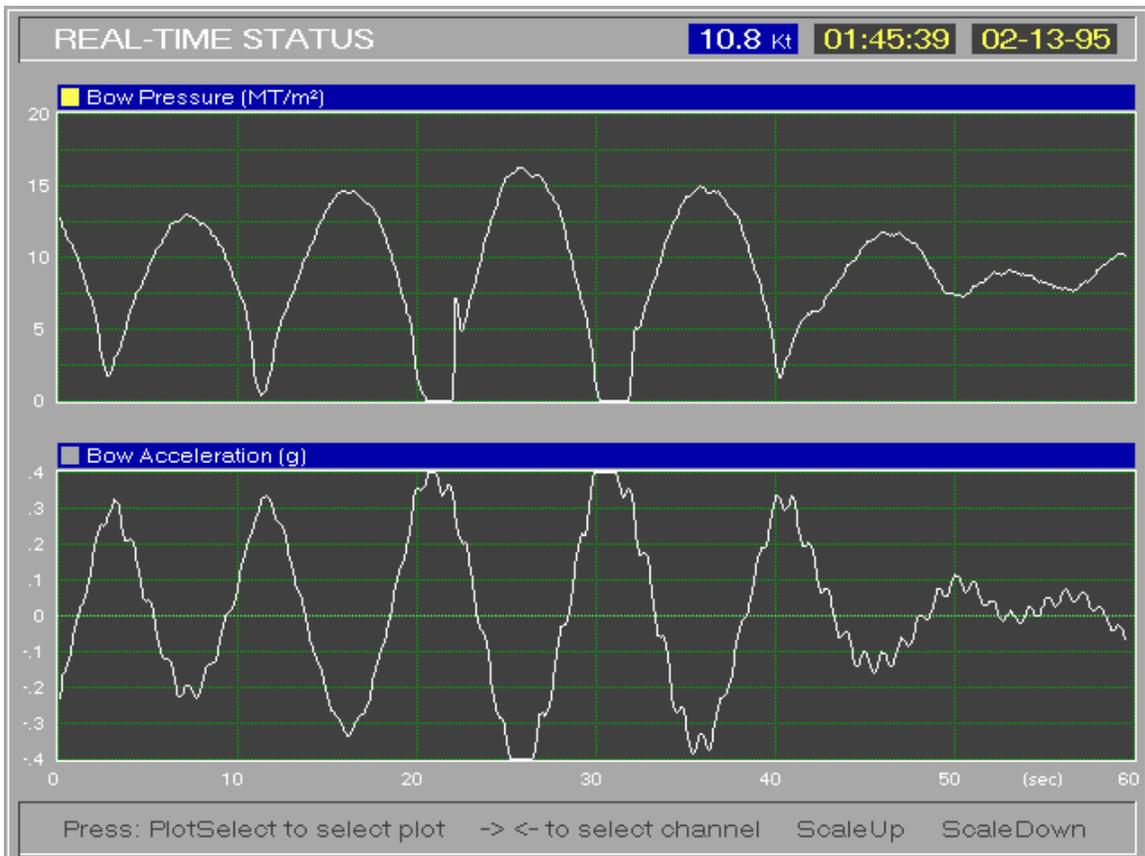
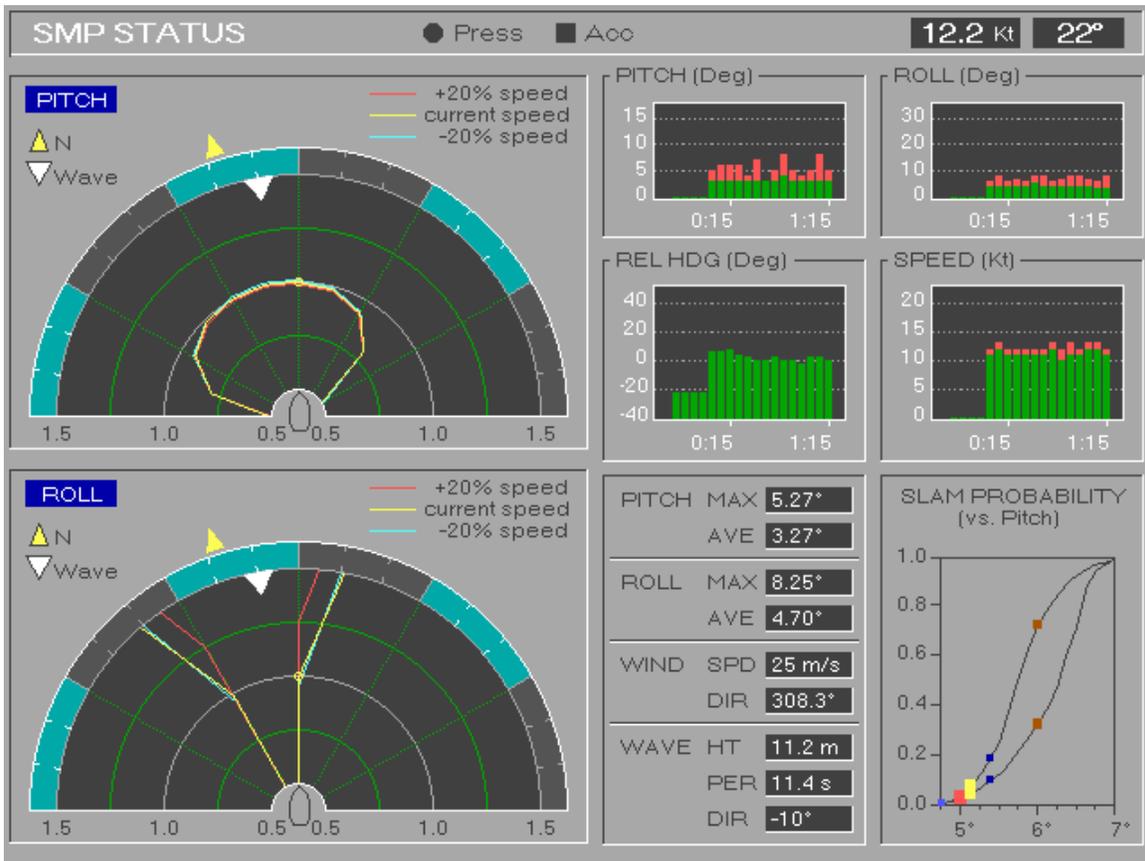
Thorn/EMI

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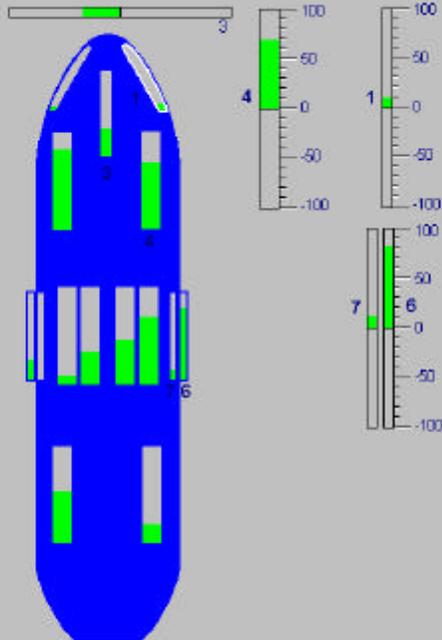
APPENDIX B - TYPICAL DISPLAY SCREENS

<u>Screen</u>	<u>Page</u>
MCA Navigation Screen (Upper Figure) This screen shows ship's position on a regional map. Ship motion amplitude can be overlaid on course plot during post-processing	B-2
MCA Operational Screen (Lower Figure) Primary real-time screen showing ship motions (visual & digital) plus navigation and stress bar charts	B-2
MCA Ship Motion Screen (Upper Figure) Screen displays ship motion statistical data, and uses SMP to predict the effect of course heading and speed change on roll and pitch	B-3
MCA Trace Screen (Lower Figure) Screen shows trace of any strain gauge (stress) or ship motion over time. This one illustrates the relationship between bow accelerometer and forefoot emergence (slam).	B-3
Safety-One Combined Stress Monitoring Screen (Upper Figure) Screen displays stress for all ship-mounted strain gauges versus position	B-4
Safety-One Stress Trend Screen (Lower Figure) Screen highlights single strain gauge where limits have been exceeded, including predicted trend.	B-4
Safety-One Fatigue Plot (Upper Figure) Fatigue accumulation based on Miner's Rule	B-5
Safety-One Stillwater Bending Moment (Lower Figure) Screen shows long-term trace of moment with respect to classification society limits	B-5
Straininstall Stress Reading Operational screen display of multiple strain gauge locations using bar graphs with adjustable operating limits.	B-6





Safety-One Hull Monitoring System



GPS Info

01.03.96 12:42:24
Position E 12°23'45"
N 52°45'19"
Course: 0
Speed: 0 knots

Show Peak

Peak Sensor

All Sensors

Sensor Statistics

Historic Trend

Report Menu

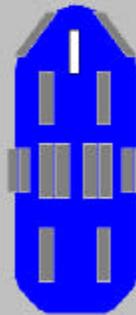
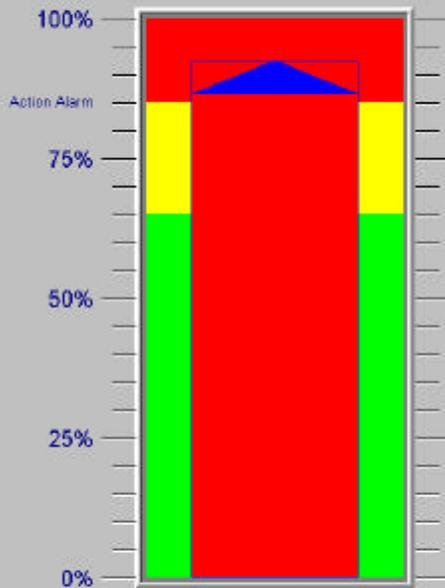
System Maint.

12:42:24
01.03.96

ACTION ALARM

[Click here to Acknowledge Alarm](#)

Peak Sensor Indicator



Trend Indicator



Update frequency 1 minute

Trend Graph

GPS Info

01.03.96 12:39:47
Position E 12°23'45"
N 52°45'19"
Course: 0
Speed: 0 knots

Show Peak

Peak Sensor

All Sensors

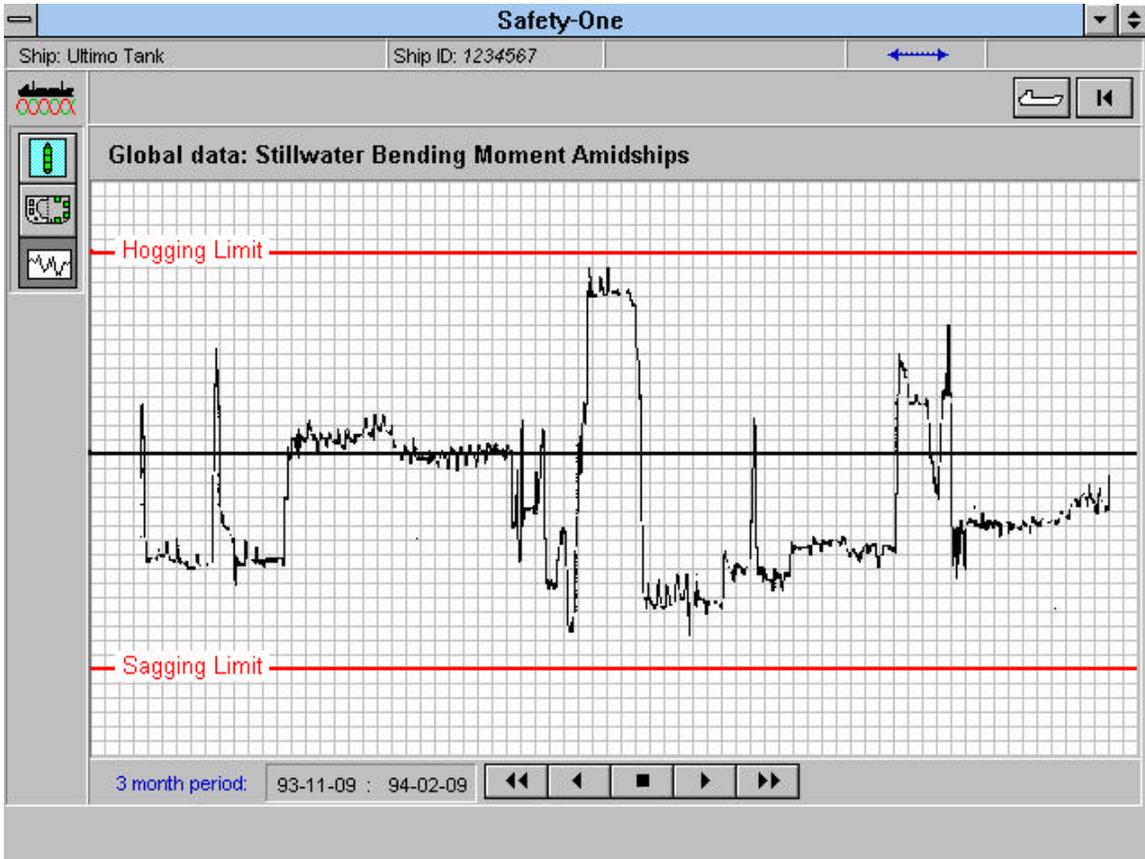
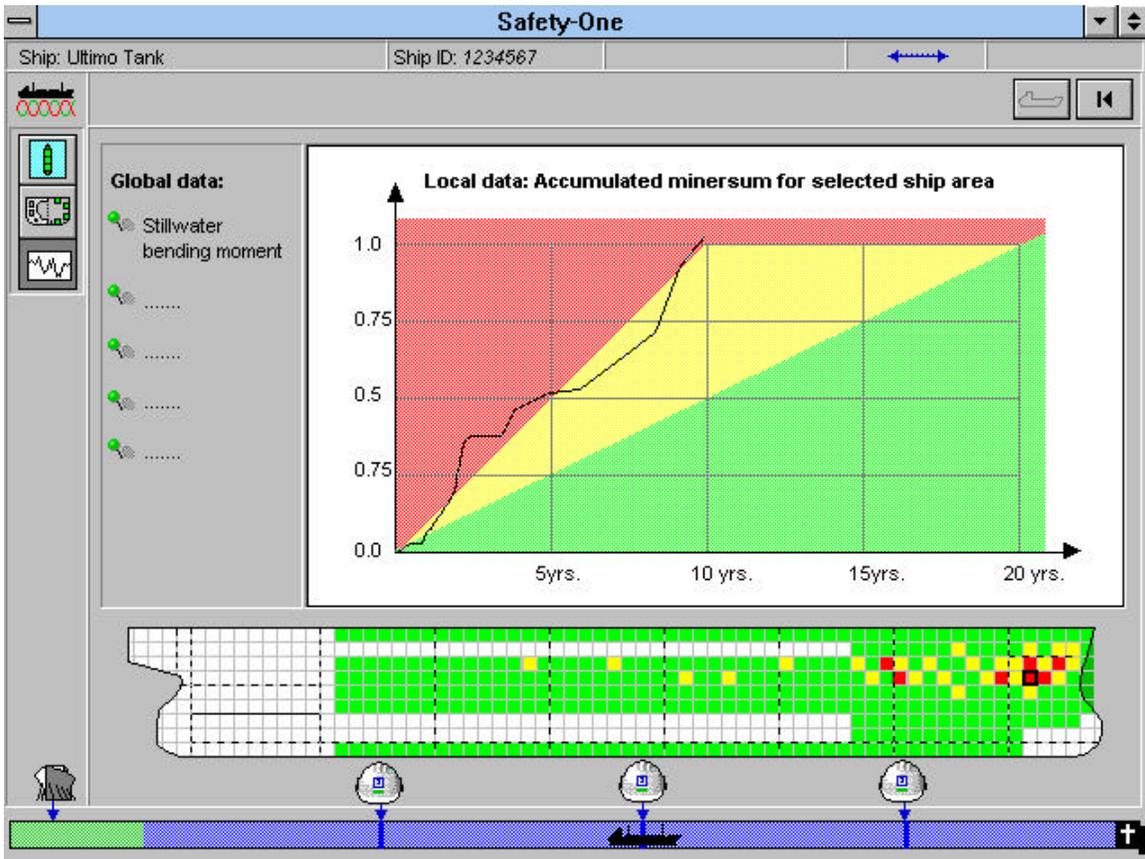
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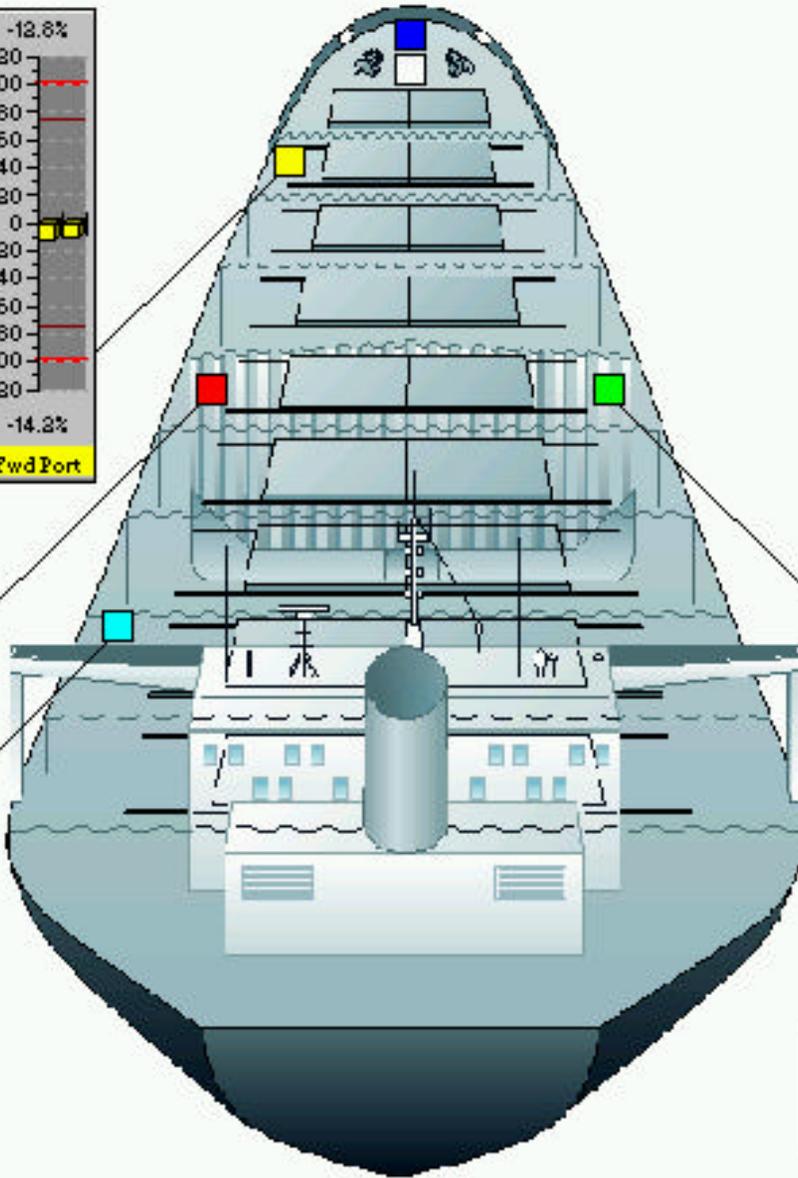
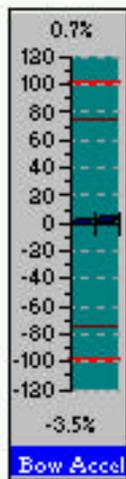
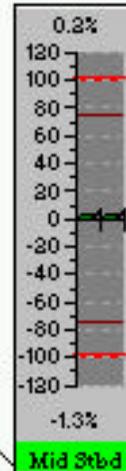
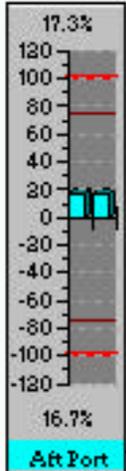
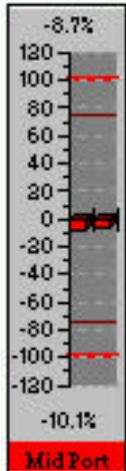
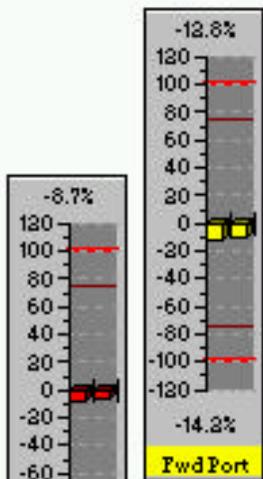
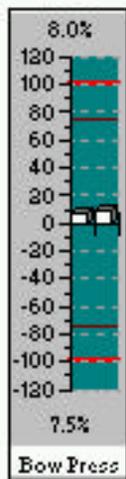
Historic Trend

Report Menu

System Maint.

12:39:47
01.03.96





02/02/94 22:15 

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APPENDIX C: SUMMARY OF SECONDARY RESEARCH ON ICE LOADS

	<u>Page</u>
Table C-1 - Ice Breaker Hull Stress Measurements - Local Response Characteristics	C-2
Table C-2: Icebreaker Hull Stress Measurements - Global Response Characteristics	C-3
Table C-3 - Summary of Strain rates Measured in Ships	C-4

Table C-1 - Icebreaker Hull Stress Measurements - Local Response Characteristics

Vessel Name	CAC Class	Ice Type	Location	Test Date	Data Rate (Hz)	Typical Response Characteristics - Local Loads/Responses			
						Nat. Freq. (Hz)	Duration (sec.)	Max. Stress (MPa)	Location on Hull
USCGC Polar Sea	CAC 2	First Year Ridges	Beaufort Sea Alaska	October 1985	100	NA	0.4 - 1.0	42	Bow Ctrline Stem Bar
USCGC Polar Sea	CAC 2	Multi-Year	North Chukchi Sea	1982	32	NA	0.5 - 1.0	~ 345	Bow
MV Arctic	CAC 4	Multi-Year	Strait Belle Isle	June, 1984	NA	NA	0.3 - 2.0	256	Bow
MV Arctic	CAC 4	First Year	Eastern Arctic	Nov./Dec 1986	100	NA	0.3 - 2.0	51	Stern Frame 34
MV Arctic	CAC 4	Old Ice	Eastern Arctic	Nov./Dec 1986	100	NA	0.3 - 2.0	153	Stern Frame 40
MV Arctic	CAC 4	Open Water Slamming	North Atlantic	Nov./Dec 1986	100	NA	NA	34	Stern Frame 30
MV Kigoriak	CAC 4	Weak 1st & 2nd Year	Beaufort Sea NWT	1981 (August)	100	NA	0.15 - 0.50	32	Bow
NB Palmer	CAC 4	Thick First Year	Antarctic	August 1992	50	NA	0.15 - 0.5	~138	Bow
Oden	CAC 4	Decaying Multi-Year	Arctic	Aug-Sep 1991	50	NA	0.3 - 0.5	~ 350	Bow
CCGS Louis S.St.Laurent	CAC 4	Multi-Year	Arctic	August 1994	100	NA	0.5 - 2.0	~ 235	Side Shell Stern

Table C-2: Icebreaker Hull Stress Measurements - Global Response Characteristics

Vessel Name	CAC Class (Estimated)	Ice Type	Location	Test Date	Data Acquisition Rate (Hz)	Typical Response Characteristics - Global Loads/Responses			
						Nat. Freq. (Hz)	Duration (sec)	Max.Stress (MPa)	Location on Hull
USCGC Polar Sea	CAC 2	First Year Ridges	Beaufort Sea Alaska	October 1985	100	3.0	0.6 - 1.0	42	01 Deck
MV Arctic	CAC 4	First Year	Baffin Bay Arctic	Nov./Dec 1986	100	0.9	0.8 - 1.0	47	Main Deck Midships
MV Arctic	CAC 4	Old Ice	Baffin Bay Arctic	Nov./Dec 1986	100	0.9	0.8 - 1.0	57	Main Deck Midships
MV Arctic	CAC 4	Open Water Slamming	North Atlantic	Nov./Dec 1986	100	0.9	0.8 - 1.0	182	Main Deck Midships
MV Kigoriak	CAC 4	First Year Ridges	Beaufort Sea NWT	1983 July	100	2.9	0.15 - 1.45	101	Main Deck
MV Kigoriak	CAC 4	Multi-Year Ridges	Beaufort Sea NWT	1983 October	100	2.9	0.15 - 1.80	NA	Main Deck
MV Robert Lemeur	CAC 4	First Year Ridges	Beaufort Sea NWT	1983 July	100	2.2	0.15 - 1.45	128	Main Deck

Notes:

1. Local load can be quoted in pressure (i.e., pressure gauge or by interpretation of strain-gauges). However, the associated area in which the pressure is applied must be specified. Local panel pressure increases with decreasing area.
2. Local Loads: Bow, Side, Bottom, Stern
3. Impact duration increases with increasing ramming speed.
4. The “rise time” is generally 30% - 50% of the impact duration time.

Table C-3
Summary of Strain rates Measured in Ships
 (from Malik, L., Tomin, M. [26])

Vessel Name Type	Location and Condition	Strain Rate (sec⁻¹)	Comments
Sealand McLean SL-7 (Container)	Midships (50' Seas, whipping)	1.1×10^{-3}	3.2×10^{-3} strain rate if yield strain reached in 1/4 cycle of whipping
Fotini L Ocean (Bulk Carrier)	Midships (Whipping)	9.0×10^{-4}	
Stewart J. Cort (Great Lake Ore Carrier)	Midships (Springing)	5.1×10^{-4}	
Model Tests	-	3.2×10^{-2}	Model Testing of Collisions
Container Ship (Unknown)	-	6.0×10^{-3}	Analytical estimates based on collapse time of 0.18 sec. in a collision
I.B Sisu (Baltic Icebreaker)	Bow	6.0×10^{-2} 0.1 to 0.14 0.1	- Measured during ice impact - Based upon extreme estimates - suggested to be used in analysis
MV Arctic (OBO)	Deck Bow Plate Bow Frame	7.3×10^{-4} 5.0×10^{-3} 2.5×10^{-3}	Maximum Measured During Ramming Ice
Kigoriak (Icebreaker)	Deck Bow Plate Bow Frame	2.0×10^{-3} 3.2×10^{-3} 1.3×10^{-3}	Maximum Measured During Ramming Ice
MS Attis	Bow	8.8×10^{-3}	Sea Slamming

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APPENDIX D: MANUFACTURER & OPERATOR SURVEYS

	<u>Page</u>
Hull Response Monitoring System (HRMS) Survey for Manufactures	D-2
Hull Response Monitoring System (HRMS) Questionnaire for Ship's Officers/Operators	D-7

**HULL RESPONSE MONITORING SYSTEM (HRMS)
SURVEY FOR MANUFACTURERS**

1. Please indicate your objectives for the HRMS:

	<u>Very Important</u>	<u>Desirable</u>		<u>Not Important</u>
To minimize slamming or to reduce ship motions				
To monitor hull structure stresses due to wave or ice conditions				
Optimize routing to avoid weather, save fuel, or control arrival time				
Keep records for engineering studies, help future ship design, etc.				
To meet classification society (ABS, Lloyd's, etc.) designation				
Other _____				

2. What sensors do you currently offer?

	<u>Yes</u>	<u>Range / Accuracy</u>
Navigation (GPS or other)		_____
Ship motions (roll / pitch)		_____
Ship accelerations (G-loads)		_____
Pressure:		
In-Tank		_____
Side / Flare / Bow		_____
Bottom		_____
Hull stress / strain gauges:		
Deck		_____
Ice zones (bow, etc.)		_____
In-tank		_____
Bottom shell		_____
Slam detection		_____
Weather prediction & routing		_____
Environmental:		
Wave		_____
Wind		_____
Ice		_____
Ship Performance:		
Speed		_____
Shaft RPM		_____
Horsepower / Fuel		_____
Other _____		

SURVEY (Page 3)

10. What kind of Displays are available?

- Real Time Display for:
 - All sensors
 - Some sensors
 - Readings for last 60 seconds or less
 - Readings for 1 - 60 minutes
 - Readings for more than 1 hour
- Historical Display
 - Average for most recent values (last 5 minutes, etc.)
 - Statistical average (e.g., 24 hours)
- Replay last 2 hours or less
- Replay last 2 hours or more
- Replay selected extreme events

11. How many screens displays are available in your HRMS?

- 1 to 4
 - 5 to 10
 - More than 10
 - Other types of display _____
-

12. Does the system provide warnings after exceeding limits?

_____ Slam	Visual	Audible
_____ Hull Stress	Visual	Audible
_____ Pitch Acceleration	Visual	Audible
_____ Other _____	Visual	Audible

13. Does the system predict events or weather?

- Eminent slam
- Ship motion amplitudes if course / speed is changed
- Ship response through weather forecast
- Arrival time
- Other _____

14. Do you have the ability to upload or download data by satellite at regular intervals?

- Upload data from HRMS
- Download weather / ice information
- Download weather / ice predictions
- Other _____

SURVEY (Page 4)

15. What types of logistics support do you normally provide?

- Training
 - Onboard the ship during operations
 - At your facility or other location ashore
 - Operating Manual
 - Hard copy
 - CD-ROM, VCR, or similar
 - Maintenance / Repair Manual
 - Hard copy
 - CD-ROM, VCR, or similar
 - Computer on-line help or expert systems
 - Satellite link for trouble shooting
 - Data analysis and reporting
 - Real time or near-real time
 - Post processing after a voyage or period of time
 - Other _____
-

16. How many systems have you installed on the following types of ships?

- _____ Tanker / Liquid Products Carrier
- _____ Military - Combatant / Supply
- _____ Container Ship
- _____ Bulk Carrier
- _____ RO-RO / Ferry
- _____ Offshore Drill / Pipelaying / Work vessel
- _____ Other _____
- _____ **Total Sales to date**

17. What is included in your basic or standard HRMS system?

- Sensors: _____
- _____
- _____
- _____
- Computer: _____
- _____
- _____
- CPU/Sensor Data Link:
- Conventional hard-wire
 - Radio link
 - Other _____

SURVEY (Page 5)

18. Has your basic system been classed by ABS or Lloyd's?

Yes: Designation is _____

No

Currently under review

19. What is the price for this basic system, not including installation?

Less than \$ 50,000

\$ 50,000 to \$100,000

\$100,000 to \$250,000

More than \$250,000

20. Is there a sales or technical person we can contact if we have additional questions?

Name _____

Phone _____

FAX _____

21. Thank you for your time in completing this survey. The survey was developed in response to Ship Structural Committee Project SR1373, administered by the US Coast Guard. The results will be used to generate a report documenting the current state of the art in Hull Response Monitoring Systems, including an ASTM specification. Your support in answering this survey will help define the technology and economic feasibility of Hull Response Monitoring Systems available to the industry.

We would greatly appreciate it if you could enclose any sales or technical brochures and return the survey to:

MCA Engineers
2960 Airway Avenue, # A-103
Costa Mesa, CA 92626
(714) 662-0500 / 668-0300 FAX

1. Please indicate your objectives for using an HRMS:

Very Useful Sometimes Helpful Not Helpful

- To minimize slamming or to reduce ship ship motions
- To monitor hull structure stresses due to wave or ice conditions
- Optimize routing to avoid weather, save fuel, or control arrival time
- Keep records for engineering studies, help future ship design, etc.
- To meet classification society (ABS, Lloyd's, etc.) designation
- Other _____

2. What type of ship do you serve on or support?

- Tanker Military - Combatant
- Products Carrier: type ____ Military - Supply
- Container Ship Offshore Platform
- Bulk Carrier RO-RO / Ferry
- Other _____

3. How many ships in your fleet are equipped with HRMS? _____

4. What is your billet or position (Master, Port Engineer, etc.)? _____

5. How many years have you been at sea? _____

6. What are your main trade routes? (Check all that apply)

- North Sea or Baltic Sea
- Mediterranean
- Atlantic Ocean: _____ Northern _____ Tropical _____ Southern
- Pacific Ocean: _____ Northern _____ Tropical _____ Southern _____ TAPS
- Gulf of Mexico / Caribbean
- US Great Lakes
- Arctic / Antarctic
- Indian: _____ East _____ West
- Other _____

SURVEY (Page 2)

7. Does your current ship have sensors for measuring the following items? Please check all that apply.

Yes No Don't Know

Navigation (GPS - other)

Ship motions (roll / pitch)

Ship accelerations (G-loads)

Pressure:

In-Tank

Side / Flare / Bow

Bottom

Hull stress / strain gauges:

Deck

Ice zones (bow, etc.)

In-tank

Bottom shell

Slam detection

Weather prediction & routing

Environmental:

Wave

Wind

Ice

Ship Performance:

Speed

Shaft RPM

Horsepower / Fuel

Other _____

8. How are the sensors connected to the central computer / display console?

Conventional hard wiring

Optic fiber

Radio Link

Other _____

9. What kind of computer is provided with your HRMS:

Apple / Macintosh _____

IBM compatible (486, Pentium, etc.) _____

Workstation (Sun, DEC, etc.) _____

Proprietary / Other _____

SURVEY (Page 3)

10. What operating software is provided on the computer:

Apple / Macintosh

Microsoft DOS

Microsoft Windows / NT

UNIX

Other _____

11. What is your data storage capacity?

Less than 1 MB

1 MB to 100 MB

100 MB to 1 GB

More than 1 GB

12. What is the data (sensor) sampling rate?

Less than 1 per second (< 1 Hz)

1 to 5 Hz

6 to 10 Hz

10 to 50 Hz

50 to 100 Hz

More than 100 Hz

13. What kind of Displays are available?

Real Time Display for:

All sensors

Some sensors

Readings for last 60 seconds or less

Readings for 1 - 60 minutes

Readings for more than 1 hour

Historical Display

Average for most recent values (last 5 minutes, etc.)

Statistical average (e.g., 24 hours)

Replay last 2 hours or less

Replay last 2 hours or more

Replay selected extreme events

14. How many screen displays are available in your HRMS?

1 to 4

5 to 10

More than 10

Other types of display _____

SURVEY (Page 4)

- 15. Does the system provide warnings after readings exceed limits?**
_____ Slam Visual Audible
_____ Hull Stress Visual Audible
_____ Pitch Acceleration Visual Audible
_____ Other _____
- 16. Does the system predict events or weather?**
Eminent slam
Ship motion amplitudes if course / speed is changed
Ship response through weather forecast
Arrival time
Other _____
- 17. Is your system intrinsically safe in explosive atmospheres?**
Yes
No
- 18. Do you have the ability to upload or download data by satellite at regular intervals?**
Upload data from HRMS
Download weather / ice information
Download weather / ice predictions
Other _____
- 19. Have you been trained how to use the system?**
Vendor training
Training from other officers / company personnel
Self-taught
- 20. Do you think the system is “User Friendly?”**
Yes
No
- 21. When and how often do you use the Hull Response Monitoring System:**
Seldom
or Never Sometimes Often
During storm seas **at night:**
 in daylight:
During moderate seas **at night:**
 in daylight:
During mild conditions **at night:**
 in daylight:

SURVEY (Page 5)

22. Do you process the stored data regularly?

- Yes
- No

23. What do you like most about your system? _____

24. What do you like the least? _____

25. What sensors or abilities would you like to add? _____

26. What kind of screen display would you like to add? _____

27. How long do the components in the Hull Response Monitoring System last?

Less than	More than	Not	
<u>1 Year</u>	<u>1 - 5 Years</u>	<u>5 Years</u>	<u>Installed</u>

Stress / Strain gauges

Pressure sensors

Motion sensors (roll, etc.)

Central computer

Data storage device(s)

Display

Power supply

Satellite link

Software

What do you have the most trouble with? _____

28. Do you know whether your HRMS meets Classification Society requirements?

Yes

ABS designation _____

Lloyd's designation _____

No

SURVEY (Page 6)

29. Please rank the following vendor support services for effectiveness:

None or Poor or Good or
Useless Marginal Excellent

- Vendor-supplied training
- Operating Instructions / Manual
- Repair Instructions / Manual
- Availability of spare parts
- Answers questions promptly
- Provides service promptly

30. What additions to the Operating Manual / Instructions would help you most?

31. What additions to the Repair / Maintenance Manual would help you most?

32. What additions to the training would help you most?

OPTIONAL

33. Who manufactured your system?

Name: _____

Address: _____

34. Do you know the system cost, including installation?

- Less than \$ 50,000
- \$ 50,000 to \$100,000
- \$100,000 to \$250,000
- More than \$250,000

35. Do you think the system benefits justify the cost?

- Yes
- No

Thank You! Please return to: MCA Engineers

2960 Airway Avenue, # A-103
Costa Mesa, CA 92626
(714) 662-0500 / 668-0300 FAX

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