ADVISORY ON STRUCTURAL HEALTH MONITORING: THE APPLICATION OF SENSOR-BASED APPROACHES

ABS

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INTRODUCTION

Increasingly, modern marine vessels and offshore units are being equipped with various tools for structural health monitoring, operational assistance, and maintenance optimization. These tools collect data through sensors and onboard instrumentation and provide status of structural health for awareness of the crew and owners and operational optimization or for carrying out repairs/modifications to prevent further deterioration or future failures.

This document focuses on the collection of data using sensors for the purpose of structural health monitoring. Specifically, it addresses the monitoring of structural loads and/or responses using sensors to infer current structural health status, predict future health states, and inform maintenance activity.

The sensor data can be used either directly in the raw format or processed to represent physical parameters, such as pressure, tensile and compressive stresses, bending moments and deformation. Trending and threshold-based alarms, in addition to the parameter monitoring, are typically an integrated function of sensor-based structural health monitoring.

This advisory provides guidance on sensor-based structural health monitoring implementation through four key sections:

Section One: Structural Health Monitoring Principles

Section Two: Sensor-Based Monitoring Plans

Section Three: Coupling Sensor Data with Analytics and Analysis

Section Four: ABS Role

SECTION 1: STRUCTURAL HEALTH MONITORING PRINCIPLES

Structural health monitoring has been widely used for decades in various industries, such as aerospace, civil and mechanical infrastructure, as well as early adoption in both the marine and offshore industries. Several industry standards and publications discuss the application of sensor-based structural health monitoring for marine and offshore assets.

IMO MSC/Circ.646 (June 1994), Recommendations for the fitting of hull stress monitoring systems requires that the hardware and software of a hull stress monitoring system be type approved by an Administration, which in practice is usually achieved via a certification of compliance issued by a recognized class society. Class societies have also published technical standards and requirements for the use of various hull monitoring systems.

The Section sets out the key principles that need to be addressed when considering implementing a sensor-based structural health monitoring program.

STRUCTURAL HEALTH MONITORING PLAN QUESTIONNAIRE

A systematic approach and careful planning will assist the various stakeholders for such systems better contextualize the monitoring purpose, set proper expectations, explore the available technologies, and ensure smooth implementation, operation, and delivery. A structural health-monitoring plan should cover sensors, data acquisition, data usage, data processing, analysis and analytics models. Below are questions to assist the stakeholder team to collect information, align expectations, and enhance common understanding.

Questions – Set 1: Define Implementation Goals

- What is the main purpose of the proposed structural health monitoring plan?
- What are the companies' current practices on structural inspection, maintenance and integrity management? Will the monitoring plan help support these aspects?
- What are the main concerns regarding the structural conditions, damages, and failure modes for the specific vessel(s) being monitored given the historical issues with the vessel or vessel class?
- What are the anticipated operation and operational environment?

Questions – Set 2: Evaluate Technology Readiness Level

- What are the measurable physical variables reflecting the structural loads, capacity, and responses relevant to the anticipated structural failure modes?
- What are the physical variable characteristics of the measured aspect of the structure, such as statics or dynamics, range, the smallest meaningful change that needs to be captured, etc.?
- Will the sensor data be used/integrated with any engineering analysis and analytics models (e.g., finite element analysis, operational modal analysis, machine learning algorithms, etc.) to derive structural health conditions and assist in detecting anomalies?
- Does the sensor data need to be transferred on shore in real-time or near real-time for monitoring and further analysis?
- Is there a need to retrieve or correlate data from other onboard systems to assist monitoring, analysis and models? What data needs to be retrieved, and at what frequency?
- What are the tradeoffs between the investment and the added value of the structural health monitoring plan? Will a techno-economic evaluation of the individual structural health monitoring plan be conducted?

Questions – Set 3: Define Sensor Type and Specification

- What sensor types are suitable for measuring the identified physical variables? Are the physical variables directly measurable?
- What are the sensor specifications required for measuring the physical variables (e.g., range, sensitivity, accuracy, response time, linearity, sensor-self noise, waterproof and environmental suitability, hazardous area suitability, power supply, etc.)?
- Where should these sensors be installed? Are these installation locations accessible and feasible for the sensor installation, inspection, and maintenance?
- How is the data transmitted and stored on board and/or on shore (wired or wireless, network topology)?

Questions – Set 4: Define Data Acquisition Device Specification

- What is the accuracy requirement for signal digitization (e.g. analog digital converter) to accurately reflecting the physical variables?
- What are the compatibility requirements for the data acquisition devices (e.g., driver, bus, interface, protocol, etc.)?
- What are the specification requirements for the data acquisition devices (e.g., electrical circuit design, noise due to various sources, system accuracy, conversion time, waterproof and environmental suitability, hazardous area suitability, power supply, and robustness)?
- How is the data from various sensors, data acquisition devices, and other data sources synchronized? What is the synchronization requirement?

Questions – Set 5: Explore Analysis and Analytics Models

- What are the data quality requirements for the data to be suitable for analysis and models?
- What condition anomalies, such as overloading, excessive deformation, stress, and fracture, can be detected directly from the data?
- What additional analysis and models are needed to extract more features and insights that cannot be derived directly from the sensor data?
- How accurate and reliable are the analysis and models?

Questions – Set 6: Define Outcomes and Deliverables

- Who are the end users? Are they physically located on board, on shore, or both?
- What is the expected deliverable format and methods (reporting, visualization, dashboard, etc.)?
- What are key insights and information required to be included in the deliverables?
- What is the expected decision-making frequency? Is real-time needed?
- Is there any training required for the end users to interpret the deliverables?

It may not be practical to answer all the above questions during the initial planning and design stage, and the answers may be refined as the project progresses. However, asking such questions up front can help stakeholders better organize and manage the project and avoid costly rework.

SENSOR SPECIFICATION TERMINOLOGY

Sensors measure physical variations through a time-varying analog or digital signal. It is crucial to understand the terminology that defines the characteristics of sensors and measuring instruments. International standards (such as ISO/IEC GUIDE 98 series, ISO/IEC Guide 99, IEC 60050-300, IEC 62008) introduce terminology for measuring instruments in terms of the performance characteristics and the expression of the uncertainty in measurement. The following definitions are commonly referenced in sensor specifications:

- **Accuracy (of Measurement)**: a qualitative concept describing the level of agreement between the result of a measurement and the true value of the measurand, or quantity intended to be measured.
- **Accuracy Class**: the category of measuring instruments, all of which are intended to comply with a set of specifications regarding uncertainty. Accuracy class is usually denoted by a number or symbol adopted by convention. For example, accuracy classes of a thermometer are defined by IEC 60751:2008 Industrial platinum resistance thermometers and platinum temperature sensors as Class AA; Class A, Class B and Class C.
- **Error (of Measurement)**: the result of a measurement minus a true value of the measurand. Note that a true value cannot be determined, so a unique "true" value is simply an idealized concept, and in practice a Reference Quantity Value is used. ISO/IEC Guide 99:2007 may be referenced for calculating errors.
- **Uncertainty (of Measurement)**: a non-negative quantitative parameter characterizing the dispersion of the values attributed to a measurand, based on the information used. Two types of methods to evaluate uncertainty are used: Type A evaluation by the statistical analysis of a series of observations, and Type B evaluation by means other than the statistical analysis of a series of observations (for example, obtained from a calibration certificate and/or the accuracy class of a verified measuring instrument).
- **Relative Error**: the ratio of the absolute error to a comparison value. This term can be seen in some product specifications, conformity reports and verification certificates. In general, this "true value" approach concept is used with a reference quantity value and/or a conventional true value together.
- **Maximum Permissible Error (MPE)**: this represents extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system. MPE is usually given by the manufacturer in product specification. For example, MPE = 0.05 mm for a caliper gauge specified based on absolute value and MPE = 0.1% for a torque measurement based on relative error.
- **(Measurement) Repeatability**: the level of agreement among successive measurements of the same measurand, carried out under the same conditions of measurement.
- **(Measurement) Reproducibility**: the level of agreement among measurements of the same value of a quantity, when the individual measurements are made under different conditions of measurement.
- **(Measurement) Precision**: the level of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions. Precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement. Precision is used to define repeatability and reproducibility.
- **Stability (of a Measuring Instrument)**: ability to keep its performance characteristics unchanged over time when all other conditions remain the same. Stability may be quantified in several ways. For example, short-term and long-term drifts can be used to quantify stability.
- **Measurement Range (also called Measuring Range)**: a range defined by two values of the measurand, or quantity to be supplied, within which the limits of uncertainty of the measuring instrument are specified.
- **Sensitivity (of a Measuring System)**: the quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured. For example, gauge factor is the synonym of the strain gauge sensitivity.
- **Resolution**: the smallest change in a quantity being measured that can be perceived.
- **Discrimination Threshold**: the largest change in a value of a quantity being measured that causes no detectable change in the corresponding indication.
- **Step Response Time**: the duration between the instant when an input quantity value of a measuring instrument or measuring system is subjected to an abrupt change between two specified constant quantity values, and the instant when a corresponding indication settles within specified limits around its final steady value.
- **Sampling Rate**: the number of analog-to-digital conversions per unit time; it is usually expressed in samples per second.
- **Drift**: the change in the indication of a measuring instrument, generally slow, continuous, neither necessarily in the same direction and nor related to a change in the measurand.

- **Zero Offset**: the magnitude of the output signal observed from a sensor or a measuring instrument, when the input signal of the measurand is zero under a specified condition (typically in room-temperature condition).
- **Frequency Bandwidth**: the measure of a measuring instrument's ability to pass an analog signal without significant attenuation over a range of frequencies. For example, bandwidth is normally expressed in Hertz (Hz) defined by -3 dB cut-off points of the frequency response function (FRF) of signal amplitude (i.e., the lower and upper frequency points where the signal amplitude falls to –3 dB below the passband frequency). Bandwidth is an important dynamic performance characteristic of a measuring chain in order to capture the correct quantity value of a time-varying measurand.

SECTION 2: SENSOR-BASED MONITORING PLANS

Sensor packages and specifications should be developed according to the implementation goals, technology readiness, and availability considering budget limitations. For a comprehensive sensor-based structural health monitoring plan, the sensor data can be used to:

- Directly monitor the loads and structural responses, and alarm when overloading and other excessive measured parameters or events are detected.
- Serve as a data source and input into the coupled analysis and models to derive structural health condition, predict degradation and assist operational and asset integrity management decisions.
- Serve as high-fidelity data to validate and calibrate the analysis and analytics models in terms of model parameters, analysis assumptions, and outcomes.

SENSOR PACKAGES FOR TYPICAL COMMERCIAL VESSELS

For structural health monitoring, the typically measured physical variables are those relevant to the dominant loads and main structural failure modes, which vary for different vessel types due to their unique structural arrangements, operational modes and environment. Accordingly, sensor package selection is typically vessel type dependent. Table 1 summarizes some recommended sensor packages based on the measured physical variables and vessel type for common commercial ship types. Furthermore, the redundancy for selected sensor packages as discussed in Table 1 shall be assessed carefully in line with the intended purpose and data quality of the structural health monitoring system.

These sensors and their corresponding measured physical variables in Table 1 can also be applied to non-ship shape structures (e.g., Column Stabilized Unit, Self-Elevating Unit, Tension Leg Platform, Spar). For example, sensors for position, wave and wind are valid for both ship and non-ship structures. However, the direct measurand and its required instrumentation plan typically need to be developed on a case-by-case basis for a non-ship shape unit due to the diversity of its structural arrangement and configuration. Appendix B provides guidance on the selection of sensor types based on the common physical variables to be measured on marine and offshore structures.

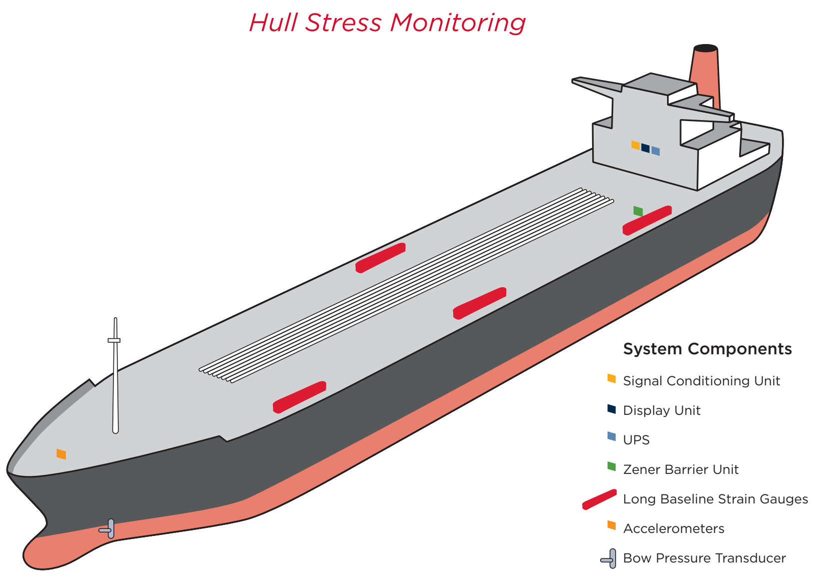


Table 1: Recommended Structural Sensor Packages for Common Commercial Vessel Types

List of Sensor Abbreviations

ACC: Accelerometer
GNSS: Global Navigation Satellite System (e.g. GPS, GLONASS, Galileo, Beidou and other regional systems)
LBSG: Long based strain gauge
MRU: Motion Reference Unit
PT: Pressure transducer
SG: Strain gauge which can be either electrical-resistance or fiber optic type
TEMP: Temperature sensor for the structure temperature monitoring
WR: Wave radar
WS: Wind sensor for wind state monitoring, such as anemometer or automated weather station

■ Optional/Recommended ■ Typically Required

Direct Measurand	Container Carrier	Bulk Carrier	Ore Carrier	Oil Tanker	General Cargo Ship	Ro-Ro Ship	LNG Carrier	Chemical Carrier	Passenger Ship	High Speed Craft
Vertical accelerations at bow	ACC	ACC	ACC	ACC	ACC	ACC	ACC	ACC	ACC	
Vertical, transverse and longitudinal acceleration at bow										ACC
Transverse acceleration amidships	ACC	ACC	ACC		ACC	ACC			ACC	
Vertical, transverse and longitudinal acceleration at longitudinal center of gravity										ACC
Vertical, transverse and longitudinal acceleration at stern										ACC
Ship motion (at center of gravity)	MRU	MRU	MRU	MRU	MRU	MRU	MRU	MRU	MRU	
Global longitudinal stress amidships (port and starboard side)	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG
Global longitudinal stress at quarter length fore and aft of midship (port or starboard side)	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	LBSG	
Local transverse stress at transverse deck strip amidships	SG									
Global longitudinal stress below neutral axis amidships (port and starboard)	LBSG	LBSG	LBSG							
Double bottom bending stress	SG	SG	SG							
Bending/shear stress in pillar bulkheads	SG									

Direct Measurand	Container Carrier	Bulk Carrier	Ore Carrier	Oil Tanker	General Cargo Ship	Ro-Ro Ship	LNG Carrier	Chemical Carrier	Passenger Ship	High Speed Craft
Global transverse stress in wet deck between each catamaran hull										SG
Lateral loads at bowflare or bottom near forward perpendicular (slamming pressure)	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG
Lateral loads at side shell (wave pressure)	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	PT/SG	
Lateral loads at the bow door						PT/SG				
Sloshing response of liquid in tanks (sloshing pressure)				PT/SG			PT/SG	PT/SG		
Structural temperature				TEMP			TEMP	TEMP		
Position, speed and course	GNSS	GNSS	GNSS	GNSS	GNSS	GNSS	GNSS	GNSS	GNSS	GNSS
Wave condition/sea state	WR	WR	WR	WR	WR	WR	WR	WR	WR	WR
Wind condition	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS

Some of the recommended sensor packages in Table 1 have been adopted in Hull Condition Monitoring Systems on vessels. If they meet requirements of ABS Guide for Hull Condition Monitoring Systems, the vessels fitted with such sensors may be eligible for three optional class notations (i.e., **HM1** – Motion Monitoring, **HM2** – Stress Monitoring, and **HM3** – Voyage Data Monitoring). For example, a vessel fitted with one accelerometer (ACC) at the bow, one MRU, one wave radar, six LBSGs, ten strain gauges (SGs) at ten selected local critical structural areas, one GNSS device and one wind sensor (WS) in Table 1 may consider class notation **HM1** (**Slam Warning: ACS1, Ship Motion: MOT1, Sea State: ST1**), **HM2** (**Hull Girder Stress: HS6, Local Load Monitoring: LS10**), **HM3** (**Navigation, Wind: WD1**).

SENSOR SELECTION CONSIDERATIONS

The selection of sensors and/or measuring instruments is governed by the measurand, such as the measuring range and the bandwidth (also referred as frequency range) of the measurand. The following are common considerations for sensor selection:

- Environmental condition, installation location of the sensor, and protective treatment (e.g., hazardous area, ambient temperature, pressure, humidity, noise, corrosive acid, abrasive action, electromagnetic, neutron, and radiation fields, etc.).
- Space limitations that may constrain the placement and location of the sensors.
- Adequate accuracy, range, and bandwidth for the measured physical variables.
- Sensor bandwidth, which as a rule of thumb is preferably three (3) times of the measurand for slow or moderate periodic vibration and ten (10) times for impulse, shock, or sudden change measurements.
- Rise time capability, which is related to the measuring instrument's bandwidth and is an important specification parameter for transient measurement. As a rule of thumb, the system rise time is preferably three (3) times faster than the measurand's rise time.
- Wire/cable noise and resistance, and potential electromagnetic interference. Cables/wires should be installed, secured and protected properly.
- Amplification that may be applied to increase measurement resolution and improve signal-to-noise ratio.
- Signal filtering that may be applied to remove external, high-frequency noise. The anti-aliasing filter must be placed before the analog-to-digital converter

- The ground-loop effect that can be through proper design of measuring chain. A single-ended measurement device is susceptible to ground loop and differential measurement device rejects ground-loop with common-mode voltage rejection.
- Sensor, instrument, and cable/wire maintenance and re-calibration requirements.
- Life and performance degradation of the sensors and the installation method.
- Sensor location, installation, and wiring should satisfy relevant class rules, such as for water-tightness, cable penetration, trip hazards, electromagnetic interference, et al.
- Installation location and method should not have significant impact on the asset's normal operations, such as cargo loading and unloading.

CONSIDERATION FOR SELECTING SENSOR SUB-TYPES

For certain sensor types such as strain gauges and accelerometers there are various sub-types that are more suitable for certain applications than others due to their different working principles. The sub-types of commonly used structural sensors are summarized below, and Appendix D provides information on commonly available accelerometer and pressure transducers for reference.

ELECTRICAL RESISTANCE STRAIN GAUGE

Electrical resistance strain gauges convert the deformation into an electrical signal. The following should be taken into consideration for electrical resistance strain gauge selection:

- Static performance characteristics (resistance, gauge factor, transverse sensitivity, temperature coefficient of gauge factor, and thermal output).
- Long term creep and drift
- Specifications for strain measurement:
  - Frequency range/bandwidth of an electrical resistance strain gauge is typically adequate for measuring structural vibration in marine and offshore applications (such as slamming, sloshing, whipping, springing, and ice load). The bandwidth of the strain measurement is typically determined by the strain gauge instrument system rather than the strain gauges.
  - The bandwidth of strain gauge instrument system can be generally categorized as:
    - Static (slow varying): 0~200 Hz;
    - Dynamic: 0~10 kHz;
    - Super-dynamic: >200 kHz.

  For ship and offshore vibration monitoring, a dynamic strain gauge is preferred.
- Signal conditioning for strain gauges:
  - The main factors affecting strain gauge performance include bridge configuration, signal conditioning, wiring, and data acquisition device.
  - The resistance tolerance and strain induced by installation may generate initial offset voltage when no strain is applied. Offset nulling should be applied to balance the bridge so that the output voltage is zero when no strain is applied, and the bridge should be calibrated to verify the output to a known, expected value.
  - Long lead wires can add resistance to the bridge, which adds an offset error and desensitizes the output of the bridge.
  - Three Wheatstone bridge configurations are commonly used:
    - Quarter-bridge circuit is the simplest circuit and typically requires dedicated temperature compensation.
    - Half-bridge circuit is two times more sensitive than a quarter-bridge circuit and can cancel out the temperature and uniform axial strain effect.
    - Full-bridge circuit can cancel out the temperature and Poisson effect and generally offers the highest sensitivity.
- Special consideration for measuring impulse/shock response:
  - The gauge factors for static loads are valid for measuring strains caused by impulse/shock loads.
  - The strain gauge installation method may affect the gauge performance for impulse and shock induced strain measurement.
  - The gauge length selection should be suitable for application.

FIBER OPTICAL STRAIN GAUGE

For a Fiber Bragg Gratings (FBGs) strain gauge, the gauge length is the length over which the applied strain is averaged, converted and measured. This gauge length is usually not the same as the fiber Bragg grating length. Compared with the electrical resistance strain gauge, the FBG strain gauge has the following characteristics:

- Requires a light source instead of electrical excitation.
- One fiberglass cable can connect several FBG gauges, reducing wiring.
- Is inherently immune to electromagnetic interference.
- Is intrinsically safe for applications in explosive atmospheres.
- Is made of sensor material that is resistant to mechanical failure at high-level vibration loads.
- Has lighter connection leads, as fiberglass is substantially thinner than copper conductors.
- Requires temperature compensation. A dummy FBG gauge is typically used for thermal compensation.
- Requires special static-dynamic FBG measuring instruments (optical interrogators) for vibration measurement.
- Can be paired with fiber optic sensors, which are good for temperature measurement. This allows the measurement of the structure temperature and strain at the same time.

IEC 61757-1-1 provides more detailed requirements of strain sensors based on fiber Bragg gratings. There are many FBG strain gauges and interrogators available in the market. Optical interrogators are typically more expensive than the electrical ones, which may lead to the FBG solution being more costly than electrical.

ACCELEROMETERS

Various types of accelerometers are based on different physical principles and are suitable for different measuring purposes. There are 2 types of accelerometers:

- AC-response accelerometer, which can only sense changes in acceleration (but not constant acceleration).
- DC-response accelerometer, which can sense both changes in acceleration, and constant acceleration.

Force-balanced accelerometers and servo-type accelerometers can measure DC components (i.e., constant acceleration). Force-balanced accelerometers can be customized for low frequency and high sensitivity for high precision measurements.

The target measurand and the potential usage of the measurement should be considered when choosing the accelerometers to:

- Determine whether the DC-response (constant) is required for measurements
- Confirm the sensitivity, cross-axis sensitivity, and sensitivity temperature coefficient
- Confirm the measuring range
- Confirm the frequency response function / bandwidth
- Confirm the suitable temperature range

PRESSURE TRANSDUCER

Temperature and process medium of the measured fluid in contact with the sensing element must be considered carefully when selecting pressure transducers. As pressure transducers must contact the process medium directly, the mounting to the watertight members should be carefully planned and implemented. Watertight testing is recommended after the installation. Alternatively, the pressure on watertight members can be measured indirectly via strain gauges attached to the backing structures, which is a common practice for ice loading monitoring.

SECTION 3: COUPLING SENSOR DATA WITH ANALYSIS AND ANALYTICS MODELS

Engineering analyses (such as Finite Element Analysis) have been widely used in the design assessment of ships and offshore structures, and there are many recognized standards and publications providing references and requirements on such analyses (such as the ABS *Guide for SafeHull-Dynamic Loading Approach for Vessels* and the ABS *Guide for Dynamic Loading Approach for Floating Production, Storage and Offloading Installations*). These design analysis approaches and procedures provide insights into the vessel dominant loads and the corresponding structural responses and failure modes, which can be used to guide the structural sensor package selection. Table 2 summarizes the Dominant Loading Parameters (DLPs) recommended for design structural assessment of common commercial ship types.

Table 2: Dominant Load Parameters (DLPs) vs. Vessel Type

DLP \ Vessel Type	Tankers	Bulk Carrier	Container Carriers	LNG Carriers	FPSO
Vertical Bending Moment (VBM)	X	X	X	X	X
Vertical Shear Force (VSF)	X	X		X	X
Torsion Bending Moment (TM)		X	X		
Horizontal Bending Moment (HBM)			X		X
Horizontal Shear Force (HSF)					X
Vertical Acceleration (VACC)	X	X	X	X	X
Lateral Acceleration (LACC)	X			X	X
Roll (ROLL)	X	X	X	X	X

The accuracy and reliability of the analysis and analytics models reflect the uncertainties and assumptions of the model inputs (e.g. loads, environments, structural gauging, etc.) as well as the analysis and model themselves (e.g. model parameters, assumptions, approximation, etc.). Sensor-based full-scale measurements are typically treated as high-fidelity data, which not only can be used for direct load and response monitoring and parameter trending, but more importantly can be integrated with analysis and models through analysis/model calibration and validation to enhance the analysis accuracy and reliability. The integration of sensor data with analysis and models provides more accurate and reliable insights on the structural health and predicts potential damages for both global hull and local critical areas. Table 3 lists recommendations on sensor packages for the calibration and validation of global loads, analysis and model parameters. Furthermore, Appendix D provides considerations and required effects on sensor data processing corresponding to specific application scenarios.

Table 3: Sensor Package for Analysis and Model Calibration

Description of Symbol and Legend

XXX: Most Preferred
XX: Moderately Preferred
X: Less Preferred

- Basic level of data processing is required as defined in Table 9
- Medium level of data processing is required as defined in Table 9
- Advanced level of data processing is required as defined in Table 9

	Data Source / Quantity of Interest	Motion Reference Unit (MRU)	Long Based Strain Gauge (LBSG)	Strain Gauge (SG)	Accelerometer (ACC)	Pressure Transducer (PT)
Dominant Load Parameter	Vertical accelerations at bow		XX	XX	X	
	Vertical Shear Force (VSF)		XX	XX	X	
	Torsion Bending Moment (TM)		XX	XX	X	
	Horizontal Bending Moment (HBM)		XX	XX	X	
	Horizontal Shear Force (HSF)		XX	XX	X	
	Vertical Acceleration (VACC)	XXX			XX	
	Lateral Acceleration (LACC)	XXX			XX	
	Roll (ROLL)	XXX			XX	
Loading	Ice Pressure			XXX		
	Sloshing Pressure			XXX		XX
	Slamming Pressure			XXX		XX
Finite Element Model	Natural Frequency	XX	XXX	XXX	XXX	
	Modal Damping Ratio	XX	XXX	XXX	XXX	
	Displacement Mode Shape			XXX	XXX	
	Strain Mode Shape		XXX	XXX		
Stress	Stress at Sensor Location		XXX	XXX		
	Stress at Any Location		XXX	XXX	XXX	
Miscellaneous	Still Water Bending Moment		XX	XX	X	
	Vibration Dose Value	XXX			XXX	
	Motion Sickness Dose Value	XXX			XXX	

Note: Arrangement of sensors refers to both number and mounting position of sensors.

SECTION 4: ABS ROLE

As a classification society, ABS has established technical requirements published in Rules and Guides for vessel design, construction and survey. ABS conducts independent verification and validation through engineering review and onboard/onsite survey to promote the asset's safe operation. Sensor-based structural health monitoring requires the installation of hardware and software on board the asset and may also involve integration and interconnection with existing onboard systems that may impact the vessel's safe and normal operation. In addition, the monitoring system provides structural health awareness and condition anomalies, which can potentially impact ABS inspection and survey decisions. Therefore, the safety, quality, accuracy and reliability of the sensor-based structural health monitoring are of significant interest to classification societies.

ABS has offered optional class notations to recognize that the structural health monitoring system is in compliance with ABS standards and requirements. The ABS *Guide for Hull Condition Monitoring Systems* presents the need for fitting sensor-based hull condition monitoring systems and lists safety and performance specifications for various types of systems, such as slamming warning, hull girder stress monitoring, and green seas warning. Optional class notations **HM1**, **HM2**, or **HM3** can be awarded for monitoring systems that satisfy the Guide's requirements. With the advent of data analytics capabilities and the coupling of operational data and sensor measurements with analytics and analytics models, structural health monitoring is evolving into the concept of the structural digital twin. The ABS *Guide for Smart Functions for Marine Vessels and Offshore Units* offers the optional class notation **SMART (SHM)** to vessels with structural health monitoring capabilities based on the coupling of sensor-based monitoring with analysis and analytics models for structural health condition diagnostics and prognostics.

For sensor-based structural monitoring, ABS can provide not only the requirements and independent verification and validation on system capability, safety and integrity, but also give functional and implementation recommendations to assist stakeholders to obtain more value out of the implementation. With the proven accuracy and reliability of the structural monitoring system, informed, targeted, condition and risk-based alternative means of crediting class survey requirements can be implemented to enhance the asset safety with less intrusiveness and reduced cost.

APPENDIX A: ABBREVIATIONS AND ACRONYMS

AC: Alternating Current

ASTM: American Society for Testing and Materials

DC: Direct Current

DGPS: Differential Global Positioning System

DLP: Dominant Load Parameters

DSP: Digital Signal Processing

EMA: Experimental Modal Analysis

FBG: Fiber Bragg Grating

FRF: Frequency Response Function

GPS: Global Positioning System

GNSS: Global Navigation Satellite System

IEC: International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers

ISO: International Organization for Standardization

IEPE: Internal Electronic Piezoelectric

LBSG: Long Base Strain Gauge

LVDT: Linear Variable Differential Transformer

MEMS: Micro-Electro-Mechanical Systems

MRU: Motion Reference Unit

MSDV: Motion Sickness Dose Value

OMA: Operational Modal Analysis

PE: Piezoelectric

SHM: Structural Health Monitoring

VDV: Vibration Dose Value

VDR: Voyage Data Recorder

APPENDIX B: COMMONLY USED SENSOR TYPES

Table 4 lists common physical variables for marine and offshore assets and the commonly used sensor types to measure or derive them.

Table 4: Common Physical Variables and Sensor Types

Physical Variable	Physical Variable Measurement	Recommended Sensor Types
Hull bending moment (vertical, horizontal and torsional in longitudinal direction)	Indirect	Long based strain gauges (LBSGs)
Sectional force (vertical and horizontal shear force)	Indirect	Long based strain gauges (LBSGs)
		Strain gauges (either electrical resistance or fiber optic type)
Slamming event detection	Direct	Accelerometer (vertical direction)
		Pressure transducer
Pressure (slamming, sloshing, wave, etc.)	Indirect	Strain gauges (either electrical resistance or fiber optic type)
	Direct	Pressure transducer
Gyro heading/orientation	Direct	GNSS or from VDR
Rigid body motion (6 degrees of freedom)	Direct	Motion Reference Unit (MRU)
Vibration - low frequency	Direct	Inertia accelerometer, i.e., forced balanced type
		Accelerometer (ACC), e.g., piezo type, fiber optical, or Micro-electro-mechanical systems (MEMs)
Vibration - high frequency	Direct	Accelerometer, e.g., piezo type, fiber optical, or Micro-electro-mechanical systems (MEMs)
Tension	Direct	Load cell - tension
Structural displacement at a certain degree of freedom	Direct	Linear variable differential transformer (LVDT)
		High resolution differential global positioning system (DGPS)
	Indirect	Integral based on accelerometer signal with DC component
Structural deflection	Indirect	Accelerometers
		Strain gauges
		Fiber optic sensors
Structural temperature	Direct	Temperature sensor e.g., thermal couple, fiber optic sensor)
Local strain/stress	Direct	Electrical strain gauge / rosette
		Fiber optic strain gauge
Structural modal shapes and natural frequency	Indirect	Strain gauges
		Accelerometers
Foundation fixities (dynamic)	Indirect	Accelerometers
Inclination (heel, list, trim)	Direct	Inclinometer or inertia accelerometers/gyros or loading computer data link
Position	Direct	Global Navigation Satellite System (GNSS) or from Voyage data recorder (VDR)
Speed	Direct	GNSS or from VDR
Course	Direct	GNSS or from VDR
Gyro heading/orientation	Direct	GNSS or from VDR
Crack initiation and propagation	Direct	Acoustic emission sensor, Electrochemical fatigue crack sensor

Physical Variable	Physical Variable Measurement	Recommended Sensor Types
Crack	Direct	Guided wave sensor
Wind	Direct	Anemometer or Automated weather station
Wave/sea state	Direct	Wave radar
Current	Direct	Acoustic doppler current profiler (ADCP)
		Acoustic current meter
Water temperature	Direct	Conductivity-temperature-depth system (CTD) or Thermosalinographs
Salinity	Direct	CTD or Thermosalinographs
Ice concentration	Direct	Camera or Satellite image
Ice thickness	Direct	Camera via calibration
Air temperature	Direct	Thermometer or automated weather station
Air pressure	Direct	Barometer or Automated weather station
Water depth	Direct	Water depth sensor
Plate thickness	Direct	Point thickness sensor
Still water bending moment (SWBM)	Indirect	LBSGs or from loading computer
Power output and revolutions of propulsor(s)	Direct	Shaft torque meter, Shaft revolution counter

APPENDIX C: COMMENTARY ON ACCELEROMETER AND PRESSURE TRANSDUCERS

There are various types of cost-effective accelerometers suitable for marine and offshore applications on the market. In addition to the traditional inertia or piezo types, an emerging technology called Micro-Electro-Mechanical Systems (MEMS) allows for producing inexpensive accelerometers in volume. Smart sensors, which integrate microcontrollers (MCUs), digital signal processors (DSPs), application-specific integrated circuits (ASICs), or field programmable gate arrays (FPGAs), are also commercially available. Table 5 compares the commonly available accelerometer types and their potential applications for reference.

Table 6 provides an overview and comparison of the different pressure transducer types in terms of different sensing technology and design philosophy. Low and/or medium range strain gauge type pressure transducers (either electrical or FBG strain gauge type) or variable capacitance transducers are recommended when measuring pressure from sea/waves (such as slamming) and liquid pressure (such as sloshing in tanks). Variable reluctance transducers may be considered when extreme overpressure may be experienced and high degrees of accuracy and critical stability over extended periods are required.

Table 5: Commonly Available Accelerometer Types [9, 20]

Sensing Technology	Response	Pros	Cons	Application
Capacitive Micro-Electro-Mechanical Systems (MEMS)	DC	Inexpensive, small size and easy to integrate into electrical systems; Often come as surface-mount devices that can be directly mounted to printed circuit boards	Poor signal to noise ratio, limited bandwidth, and mostly restricted to small acceleration levels (less than 200 g)	Mobile and electronic devices for motion tracking and disk drive protection (for example, detecting drops); Applicable to estimate displacement and velocity through integration over time.
Piezoresistive (PR)	DC	Wide frequency bandwidth; Measures down to zero hertz so can be used for accurately calculating velocity or displacement	Typically, low sensitivity; Temperature compensation is required (some commercial products have compensation internally integrated); More expensive than the capacitive MEMS accelerometers	Generally, not for lower frequency and amplitude testing; Suitable for impulse/impact measurements which have large frequency range and high amplitude (for example, commonly used in automotive safety testing, weapons testing, and higher shock range measurements); Applicable to estimate displacement and velocity through integral over time.
Charge mode piezoelectric (PE)	AC	Wide frequency bandwidth; Good sensitivity; Easy installation; Low noise levels; Durable in hostile environments.	Not suitable for measuring static accelerations and low frequency vibrations; Need special cabling to shield from noise; Requires a charge amplifier	Widely used for test and measurement; Could be the first choice for most vibration measurements; Could be applied to extreme temperature conditions (for example, -200°C to +640°C and beyond), such as turbine engine monitoring; Improper to estimate displacement and velocity through integral over time.
Voltage mode Internal Electronic Piezoelectric (IEPE) (Charge mode PE with build-in charge amplifier)	AC	Wide frequency bandwidth; Good sensitivity; Easy installation; Low noise levels; Requires no special cabling; Easily integrated with other systems.	Build-in microelectronic circuit limits the ability to tolerate hostile environments when compared to PE accelerometers	Widely used for tests and measurements and could be the first choice for most vibration measurements; Large operating temperature range (for example, -40° to +125°C); Commonly used type for structural health monitoring purposes (for example, high-rise buildings, long-span bridges, and marine and offshore structures); Unable to estimate displacement and velocity through integral over time.

Table 6: Pressure Transducer Comparison and Overview [7]

Design Category	Sensing Element	Sensing Element Configuration	Remarks on Application
Electrical Pressure Transducers	Linear Variable Differential Transformers (LVDT) Transducer	Most commonly bellows, capsules, or Bourdon tubes	For very low- or high-pressure measurements, overpressure exposure, or high levels of vibration. For measuring differential pressure of process media having high dielectric constants, especially liquid media. Accuracy and frequency response depend on mechanical linkage and seal.
	Potentiometric Transducer	A bellows or Bourdon tube is commonly used as the sensing element	For very low-pressure measurements, overpressure exposure, high levels of vibration, stability and repeatability over extended periods of time, or extremely high-resolution requirements. Frequency response depends on mechanical linkage.
	Variable Capacitance Transducer	Diaphragm	Appropriate for measuring differential pressure of process media having high dielectric constants, especially liquid media.
	Variable Reluctance Transducer	Diaphragm	Well suited for measuring most process media, especially if the core coil sensors are isolated from the process media. Well suitable for applications that include high shock or vibration levels, extreme overpressure, high degrees of accuracy, or critical stability over extended periods. All reluctance devices are affected by strong magnetic fields.
	Piezoelectric Transducer	Piezoelectric crystals made of quartz, tourmaline, or ceramic material	Very effective in measuring changes in pressure. The piezoelectric crystals only produce an output when they experience a change in load. With adequate signal conditioners, they can also be used to perform static measurements.
Fiber-Optic Pressure Transducers	Fabry-Perot interferometers (FPI)	Two mirrors with one stator	Suitable for almost all applications. Extremely sensitive and fit for high resolution measurements. Recommended for environments where electromagnetic interference may be a concern. Is intrinsically safe and acceptable in hazardous environments.
	Bragg Grating Interferometer	Diaphragm with FBG	
	Quartz Resonators	A pair of quartz resonators (one vibrated due to pressure and the other due to transducer internal temperature)	
	Micromachined Membrane/Diaphragm Deflection	Membrane/Diaphragm	

APPENDIX D: COMMENTARY ON COUPLING SENSOR DATA WITH ANALYSIS AND ANALYTICS MODELS

Vibration-based modal analysis approaches based on accelerometer measurements are well understood and have been applied in various scenarios [8, 19]. In addition to the vibration-based approach, strain-based modal analysis approaches based on strain gauge measurements have been investigated extensively [18, 21]. In strain-based modal analysis, the mass-normalization of the displacement mode shapes and the strain mode shapes cannot be performed with the purely strain-based Experimental Modal Analysis (EMA). The normalization (scaling) problem for strain mode shapes can be addressed by employing an accelerometer in addition to the strain gauges. In contrast to the vibration-based modal analysis, the strain-based modal analysis methodology has advantages in sensing local damages with a high signal-to-noise due to the smaller sensor size and the working principles of strain gauges. Strain-based modal analysis can be an alternative to vibration-based modal analysis in identifying modal parameters (e.g., natural frequency, damping, and mode shape). Combining strain and vibration data is a common practice for modal analysis [22].

Table 7 lists applicable sensors with popular vibration-based monitoring techniques and potential analysis and models coupling. Table 8 lists the time series of vessel responses that can be obtained from structural sensors and monitoring systems. Table 9 summarizes the application scenarios of the time series sensor data and the corresponding required level of effort for signal processing.

Table 7: Sensor Recommendations and Potential Applications

<table>
<tr><th>Sensor Package Option</th><th>Application</th><th>Response Type</th><th>Example Use Case/Coupled Analysis and Model</th></tr>
<tr><td rowspan="10">Strain gauge (electrical or FBG) with proper dynamic strain instrument</td><td>Fatigue</td><td>AC</td><td>Fatigue damage direct calculation, ignoring mean stress effect</td></tr>
<tr><td rowspan="4">Structural Vibration (Cyclic)</td><td rowspan="4">AC</td><td>Operational Modal Analysis (OMA) of wave induced global vibration, and model updating and modal parameter tracking</td></tr>
<tr><td>Natural frequency, damping ratio, and (unscaled) strain mode shapes [#1]</td></tr>
<tr><td>Slamming/sloshing identification and load estimation</td></tr>
<tr><td>Whipping/springing identification</td></tr>
<tr><td rowspan="4">Strength (Static/ Quasi-static)</td><td rowspan="4">DC & AC</td><td>Global load estimation through algorithms to interpret filtered sensor data within wave frequency</td></tr>
<tr><td>Ice loading estimation</td></tr>
<tr><td>Slamming/sloshing identification and load estimation to interpret filtered sensor data within loading frequency.</td></tr>
<tr><td>Whipping/springing identification to interpret filtered sensor data within wave frequency of concern</td></tr>
<tr><td rowspan="3">Motion Reference Unit (MRU)</td><td rowspan="3">Rigid Body Motion/Attitude</td><td rowspan="3">DC & AC</td><td>Human comfort evaluation, such as motion sickness dose value (MSDVZ) and/or vibration dose value (VDV) based on filtered translational accelerations</td></tr>
<tr><td>Foundation fixity tuning that is based on OMA results of filtered translational accelerations</td></tr>
<tr><td>Natural frequency, damping ratio, and (unscaled) displacement mode shapes [#1]</td></tr>
</table>

Sensor Package Option	Application	Response Type	Example Use Case/Coupled Analysis and Model
Array of force-balanced accelerometer or servo-type accelerometer [#3]	Rigid Body Motion	DC & AC	Use algorithm to calculate the real-time 6 degree of freedom motion based on kinetics principle and linear algebra
	Tilt Estimation	DC & AC	Tilt estimation (approximate)
	Structural Vibration (Cyclic)	DC & AC	OMA of filtered accelerations (such as wave induced global vibration) and model updating and modal parameter tracking
			Natural frequency, damping ratio, and (unscaled) displacement mode shapes
			Slamming/sloshing/whipping/springing identification to interpret filtered sensor data within frequency of interest, that can correlate with strain gauge measurement data to reduce inaccuracy
			Human comfort evaluation, such as motion sickness dose value (MSDVZ) and/or VDV based on filtered translational accelerations
			Estimates vibratory displacement/deformation of structure due to wave load by double integral of acceleration and filtering out the drift caused by integral of low frequency and constant acceleration components, then conducts OMA of filtered vibratory displacement/deformation (such as wave induced global response) and model updating and modal parameter tracking Output natural frequency, damping ratio, and (unscaled) displacement mode shapes [#2]
Array of MEMS Voltage mode IEPE accelerometers [#4]	Structural Vibration (Cyclic)	AC	Same as "Array of force-balanced accelerometer or servo-type accelerometer" IEPE has relatively high eco-technical advantage compared to force-balanced accelerometer or servo-type accelerometer

Notes:

[#1] Both displacement mode shapes and strain mode shapes are related to structural vibration natural frequencies. Using a modal decomposition and a modal expansion technique, it is possible to obtain the time series of dynamic displacement and stress based on identified mode shapes respectively. The total displacement and stress should consist of both static and dynamic parts, which can be found by adding the static part to the inferred dynamic part as an offset properly. Such total displacement and stress can be used for strength and buckling check or extreme value analysis.

[#2] Some finite element software can only output displacement mode shapes. If that is a case, the strain can be obtained by imposing displacement on to the finite element model.

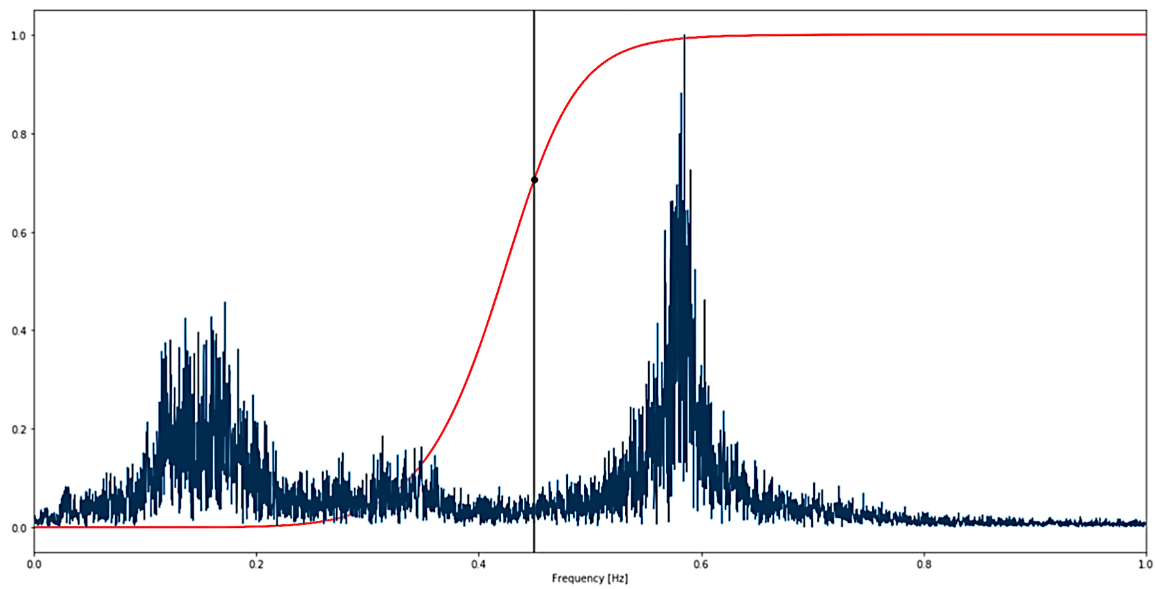
[#3] MEMS Capacitive Accelerometers and MEMS Piezoresistive Accelerometers are economic alternatives of force-balanced accelerometers or servo-type accelerometers, when large numbers of sensors are required.

[#4] When harsh operational environments are to be encountered, MEMS Charge mode piezoelectric (PE) accelerometers are substituted for MEMS Voltage mode Internal Electronic Piezoelectric (IEPE) accelerometers. A combination of IEPE or charge mode PE accelerometers with a few force-balanced accelerometers or servo-type accelerometers could offer more flexibility and a high quality of required time series that consists of both static and dynamic parts, when a proper algorithm (sensor fusion) is adopted. This may benefit the hull monitoring system design.

Table 8: Time Series of Vessel Responses after Digital Signal Processing (DSP)

Signal Type	Applicable Direct/ Indirect Basic Measurand	Filter Applied	Pass-Band Frequency	Stop-Band Frequency	Remarks
Vibration	Strain/stress/ Motion/Translational acceleration due to wave	No filtering			Including all static and vibration components
		Low-pass filtering	0.3 Hz	0.4 Hz	Including static, temperature variation, and wave-induced components
		Dynamic high-pass filtering	0.01 Hz		Wave-induced vibration and hull global vibration components
		High-pass filtering	0.4 Hz	0.3 Hz	Hull global vibration components
Shock	Sea pressure due to slamming	Low -pass filtering	5 Hz		
	Translational acceleration due to slamming	Low -pass filtering	5 Hz		As slamming indicator, acceleration > 5 Hz is not due to wave induced response or wave induced global vibration
	Liquid pressure due to sloshing	Low -pass filtering	30 Hz		

Note: the pass-band and stop-band frequency are for typical ship applications, and are for reference purpose only.



High-pass Filter

Table 9: Required Effort Level for Sensor Data Processing

Effort Level	Feature Extraction	Feature Description
Basic	1. Statistics of time series data i. No filtering ii. Low-pass filtering iii. Dynamic high-pass filtering iv. High-pass filtering	Maximum value
		Minimum value
		Mean value
		Standard deviation
		Skewedness
		Kurtosis
		Mean zero crossing period (or mean crossing up count)
		Maximum peak to peak value
		Number of observations used to calculate statistical parameters
		Histogram of all the peaks
		Histogram of all the troughs
	2. Features for transient signal (such as slamming, sloshing, impact)	Integrated energy of each event
		Rise time of each event
		Number of events during time interval
	3. Probability distribution and threshold value	
	4. Threshold values and alarms for each channel	Alarms triggered when the measured value exceeds the threshold (or a given percentage of the threshold).
Medium	5. Fatigue damage estimation from strain sensors	Rain flow counting of successive stress time series interval without overlap.
	6. Parametric roll	Can be done by MRU directly, for roll and pitch specifically.
	7. Trend predictions for each channel	Calculations for each time interval of each sensor are adopted for trend prediction.
	8. Hull strain/stress	
	i. Raw strain	Option 1: raw strain (all components, no filtering).
	ii. Dynamic strain	Option 2: dynamic strain after high-pass filter in order to remove low cycle temperature effects (only dynamic).
	iii. Compounded strain by filtered dynamic strain and loading computer	Option 3: compounded strain by adding a strain offset corresponding to the static strain retrieved from the loading computer at sensor location to the filtered strain without low cycle temperature effects via a high-pass filter.
	iv. Compounded strain by filtered dynamic and static strain	Option 4: compounded strain by summing dynamic strain (only dynamic) and the mean of the low pass filtered measured strain (only static; where the mean is taken over a day to remove the temperature effects).
Advanced	9. Modal analysis	Recommended 20-30 min time series with sampling rate 20 Hz.
	i. Natural frequency of global vibration modes - displacement based	Array of individual accelerometers.
	ii. Damping of global vibration modes- displacement based	Array of individual accelerometers.
	iii. Mode shape of global vibration modes - displacement based	Array of individual accelerometers.
	iv. Natural frequency of global vibration modes - strain based	Array of individual strain gauges (i.e. LBSG).
	v. Damping of global vibration modes- strain based	Array of individual strain gauges (i.e. LBSG).
	vi. Mode shape of global vibration modes - strain based	Array of individual strain gauges (i.e. LBSG).
	10. Loads due to transient sea pressure (slamming)	Event data trigger by predefined threshold as time series A slamming warning level is to consider the whipping effect (without wave-induced response) from the global deck sensors located amidships. The warning level based on whipping from global strain sensors in deck amidships is based on the critical situation where slamming occurs on one side of the bow in bow quartering seas. This would be equivalent to a whipping response that is twice as high in head seas at the same slamming magnitude when slamming occurs on both sides simultaneously. In head seas the warning level should therefore be regarded as an early warning.
	11. Global sectional forces	Recommended 20-30 min time series with sampling rate 20 Hz.
	i. Still water bending moment (SWBM)	Refer to hull strain/stress Option 1 of Table 9 and Option 4 of Table 9 to estimate the bending moment whose proper estimate could be the mean value of the time series. The SWBM's estimates can be assembled according to loading conditions, and the statistics of same loading condition may be computed.
	ii. Dynamic sectional forces (moment and forces)	Refer to hull strain / stress Option 1, Option 3 and Option 4 which can be used to define the DLPs (based on extreme value) for ships.
	12. Loads due to liquid motions in tanks (sloshing)	Event data trigger by predefined threshold as time series.
	13. Response due to operation in ice	Event data trigger by predefined threshold as time series.
	14. Comfort measurements by motion sickness dose value (MSDVZ) and/or Vibration dose value (VDV)	Calculated from translational accelerations from tri-axial accelerometer or high spec MRU.

APPENDIX E: REFERENCES

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