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Operational Response Monitoring for Ships and the Offshore

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ABSTRACT

Hull structures and cargoes of ships and tug/barges in a seaway experience nearly continuous dynamic stress cycling. In the past several years, measures taken to ensure integrity often include installation of an operational monitoring instrumentation system. The objectives of such systems and instrumentation system designs to carry out those objectives are presented.

1. INTRODUCTION

The dynamic stress cycling experienced by ship hulls and cargoes and by tug/barge systems can lead to material yield and fatigue failures. Very large ships and tug-barges are particularly susceptible to damage because operators cannot tell when damage is occurring. Not even the most skilled sailor can determine the amount of fatigue damage done to a hull or cargo during a voyage using only his senses. Installing an instrumentation system to monitor the operational response of ships and towed offshore structures has become much more common in the past several years.

The size and complexity of ocean tows of offshore equipment such as drilling jackets, jackup platforms, and topside modules have increased dramatically, due to economic reasons. Large structures are now prefabricated far from the installation site, towed to the site, and installed for less money than it would take to ship the component parts and assemble on site. However, the tow can represent a "weak link" in the process, since the structures being transported are designed for a substantially different set of criteria than that experienced during a long ocean tow. The loss or damage of a crucial piece of equipment can mean the loss not only of the investment in the equipment itself but also the loss of revenues due to the disruption of the carefully calculated project discounted cash flow, not to mention danger to human life and to the environment. The limiting design criteria is often the loads to be experienced during transportation and installation, rather than actual operation.

Ships, particularly large ones such as oil tankers, are also subject to fatigue damage. A ship's hull structure is most affected by wave-induced dynamic forces and by static forces generated by the vessel's cargo, ballast, or hull buoyancy. Hull cracking and bottom plate damage have occurred often enough to be cause for concern. Human assessment of potential for damage is especially difficult on large ships without the aid of instruments.

With today's heightened environmental concerns, a great deal of attention is being paid to the installation of instrumentation systems to collect data for research and design purposes, and to serve as real-time advisory tools for ship operating personnel. Arctec Offshore Corporation has been involved since 1970 in field instrumentation of ships and offshore drilling rigs operating in harsh marine environments. Projects have included 15 tow monitoring systems and numerous ship performance monitors and trials instrumentation systems. This paper uses experience and results from these programs to evaluate the monitoring tools and procedures now available and present criteria that should be considered in the design and operation of any monitoring system.

One of our most sophisticated systems was that used during the tows of two of the world's largest steel jackets—Exxon's Harmony and Heritage—from Ulsan, Korea to the Santa Barbara Channel, California (1,2), which will be discussed in more detail in following sections.

In addition, Arctec Offshore Corporation was awarded a contract by the Ship Structure Committee to develop a Ship Response Monitor (SRM) that fulfills the SNAME HS-12 Panel on Hull Instrumentation requirements. This paper provides details on the SRM, the first prototype of which is now being tested on an oil tanker.

2. OBJECTIVES OF OPERATIONAL MONITORING

The ultimate objective of an operational monitoring system is, of course, to minimize risk to life, to property, and to the environment. More specifically, most monitoring systems have several specific objectives:

1. Provide ship and tug-barge motion control
2. Compile a stress history
3. Validate fatigue/stress models
4. Monitor cargo loadout and launch
5. Minimize fuel consumption and schedule maintenance.

Reduction in fatigue life of both ships and towed structures is a real concern. For example, a tow of equipment may appear to have been successful, but portions of a structure may suffer a sufficient number of stress cycles at high-enough levels to reduce the life of the structure under service conditions. Tug-barge systems are particularly susceptible to damage, because operators cannot tell when damage is occurring. This is also a concern with large ships which routinely sail routes that have severe weather patterns.

Ships, as well as offshore equipment that has been towed to a site, are subjected to rigorous, costly, and time-consuming inspections for fatique damage. Use of an operational monitoring system to collect and analyze monitoring fatigue data can greatly assist in this area and reduce inspection time. For example, Exxon had all of the fatigue analysis completed at the end of the Harmony and Heritage tows and was able to launch almost immediately (1).

3. DESIGN CRITERIA

The cost and complexity of an operational monitoring system depend on the at-risk analysis. The transporting of the Exxon Harmony and Heritage jackets represented the largest trans-Pacific jacket tows ever carried out. As a result, extreme efforts were made to limit exposure and risk during the long tows, to confirm that design loading conditions would not be exceeded, and to perform a post-tow inspection. Extensive tow wind and wave criteria were developed for tows over various routes and during all seasons (2). Much of the strength and fatigue design of the jackets was dictated by tow conditions. The potential for severe weather and the need for confidence that the jackets were fit for service after the tow caused Exxon to choose a sophisticated and extensive monitoring system for both tows. More straightforward, shorter tows, however, may require a much less expensive and less complex system. A thorough cost vs. risk analysis should be completed for any project in which a monitoring system is contemplated (3).

Some of the engineering questions that must be considered include:

1. What weather conditions might be encountered?
2. How will the structure/vessel combination respond to the design conditions?
3. How effective will transport personnel be in assessing conditions and taking corrective actions?

In the case of tow monitoring systems, another question to consider is whether or not to have a technician familiar with the instrumentation system accompany the tow. Although the systems discussed here are configured and programmed to be relatively self-sufficient once started, an onboard technician provides an additional measure of reliability and reassurance. Again, this decision should be based on a careful cost/risk analysis.

4. TYPICAL MONITORING SYSTEM HARDWARE

A typical operational monitoring system is composed of sensors, signal conditioning equipment, and data acquisition, storage, transmission, and display equipment. Table 1 lists typical operational system hardware and software.

4.1 Sensors

Sensors are generally of three types: motion, stress, and environmental sensors.

4.1.1. Motion. Typically, roll/pitch displacement is measured using vertical gyros or, more recently, solid-state angular rate/displacement sensors. In tow monitoring, this information is radioed back to the tug. This data is valuable to operating personnel, as it can detect static changes as well as dynamic ones, and allows the early detection of damage that can lead to lists. The data from the angle sensors is also used to correct for the influence of gravity on the vertical accelerometers.

In most cases, structural loads are primarily dependent on accelerations and therefore most installations require accelerometers. The devices selected should be rugged, stable, and should have adequate resolution to provide statistically significant data even when sea conditions are relatively calm.

When complete definition of all motions and accelerations is important, the sensor package should include angular displacement, velocity, and acceleration sensors as well as linear accelerometers, so that motions can be calculated at any point on the structure. This is particularly important in cases where areas that experience the largest accelerations are inaccessible. Accelerometers are used because they are a means to directly measure the forces exerted on the structural members, using $F = ma$. In general, accelerations are the only variables of interest—not velocities or displacements. Of course, translational velocities and displacements can be obtained from the acceleration data by integration if desired.

Equipment portability is of critical importance, particularly in cases where a rapid installation is necessary. A typical motions measurement package is housed in a .46m × .46m × .15m (18" × 18" × 6") box and contains x, y, and z linear accelerometers and roll/pitch angle sensors. These boxes are installed at various positions throughout the structure or ship. They are levelled and the system is checked out by connecting a notebook computer, to verify that everything is functioning properly.

These motions packages are powered by 12-volt lead acid batteries. The number of batteries required depends on the length of the voyage and the power consumption of the sensors and computer. Since batteries are bulky and expensive, the ideal sensor package is, of course, one that consumes *no* power. We have used low-power CMOS microprocessors to collect and store data for over a decade. We have conducted and continue to conduct extensive research into the use of low-power computers and sensors.

Power consumption represents a real problem with gyro devices—the ability to turn these sensors on and off as needed is a necessity. We now use solid-state angular rate sensors in lieu of vertical gyros to measure roll and pitch. The angular rate is integrated to obtain short-term angle measurements. Long-term drift corrections are made using input from bubble pendulums, connected with long-time-constant circuitry. These sensors have been proven to be more reliable, less costly, and to consume considerably less power than gyros.

4.1.2. Stress sensors. Two methods can be used to determine the stresses on a structure:

1. Inferring stresses by calculating the forces using acceleration measurements and combining them with the physical (dimensional) characteristics of the structure.
2. Measuring strain and using the mechanical and physical properties of the material/structure to calculate stress.

The most exact stress measurements are obtained from strain gages. Filament-type, weld-on strain gages are best due to their (relatively) easy installation and their

TABLE I

Typical Operational Monitoring System Hardware And Software

SENSORS	Motion Sensors Stress Sensors Environmental Sensors
SIGNAL CONDITIONING	Sensor Excitation Signal Amplification Signal Filtering Signal Transmission (cable, radios, etc.)
DATA ACQUISITION, STORAGE, TRANSMISSION AND DISPLAY	Analog to Digital Converters Tape, Hard Disk, Optical Disk Drive Video Displays Modems, Faxes, Inmarsat Real Time, Multitasking Software

durability. However, strain gages are an expensive option. Their accurate placement requires a skilled technician, and each gage requires cabling, signal conditioning, filters, and an A/D converter, which adds to system costs and complexity. The decision whether to use accelerometers only or to lay strain gages must be based on a careful cost/risk analysis. Exxon chose to use strain gages on the Harmony/Heritage tows (73 on Harmony and 59 on Heritage) due to the complexity of the project and the value of the structures at risk.

The inferred method of deriving stress from the measurement of forces using accelerometers can be effective. However, in the case of tug-barge systems, the tie-downs must hold the equipment under tow solidly to the barge and must not crack. If damage occurs to the tie-downs, the model of the barge/structure as a rigid body is no longer valid. In many cases, a combination of the two methods is the best choice. Fewer strain gages (6 or so) may be used on the critical structure members, while relying on the accelerometers for the remainder of the stress information.

4.1.3. Environmental sensors. Environmental sensors are included in a monitoring system to provide real-time wind and wave data and also for research purposes, to collect metocean data for use in calibrating and refining future analysis procedures and models. Sensors include conventional anemometers and various types of wave height sensors. We typically use the R.M. Young wind sensor and find it to be reliable. However, care must be taken to protect the sensitive electronics in these units from electrostatic discharge. In particular, the order of sensor connection should be well-planned, so as not to allow a long lead to dangle unconnected from this sensor for any length of time.

We have employed both radar and laser-based noncontact wave height sensors. In both cases, data from the motions package is used to compensate the range measurement for displacement at the point of sensor location to give true wave height. Laser range finders were used with success as wave sensors on the Harmony/Heritage tows, mounted on the "bow" (mudmat end) and "stern" to detect wave slamming loads on the jackets during high sea states (1).

4.2 Signal Conditioning

Signal conditioning equipment includes sensor excitation, amplification, filtering, and transmission. Signal output from all analog sensors should be filtered, and amplified when necessary. Multichannel filter/amplifier modules can be used that provide a wide range of gains, plus low-pass and/or high pass filters, for each channel. It is essential that a cabling plan be developed beforehand, using the required sensor layout and construction drawings of the structure to be towed, so that installation problems can be anticipated and avoided.

Reliable and accurate signal conditioning is particularly important for strain gages. If strain gage bridges are to be installed, they are typically supported by commercial bridge excitation/completion panels. Highpass filtering is essential when long cable runs are necessary to reach the required strain measurement points. Filters can effectively eliminate gage outputs due to static strain or temperature effects on gages and cables, leaving only the desired dynamic strain signals. Using low-drift amplifiers following the highpass filters results in a very high static stability and allows the use of sufficient amplification to maintain good strain resolution during all seastates. On the Harmony/Heritage tows, gains as high as 20,000 were used in calm conditions, resulting in a full-scale sensitivity of only 50 microstrain and a resolution of 0.025 microstrain (1).

4.3 Data Acquisition, Storage, Transmission, and Display

A typical system employs one or more low-power data-logging computers to collect sensor data and radio it to the main computer(s) installed on the bridge. Our systems typically employ an 80386-based PC-AT which processes, stores, and displays the collected data. Motions data is usually displayed on a video system. When appropriate, color graphics are employed to aid in visual interpretation of the data.

Data can be stored on tape, hard disk, floppy disk, or optical disk drives. High capacity optical disks have been found to be a cost-effective means of data storage, as raw data can be recorded continuously.

For tow monitoring systems, reliable UHF bidirectional radio telemetry links are normally used to convey data from barge to tug. These links make use of sophisticated Xmodem file transfer protocol, ensuring the accuracy of the data received. The bidirectionality feature enables operators to configure the data collection intervals and give other commands to the data collection processor. These links can also be used to connect the barge system to the Inmarsat satellite telephone terminal on the tug.

Adaptive high-speed modems, facsimile machines, and commercial satellite links like Inmarsat have now made it possible to rapidly transmit data back to shore facilities. This has proven extremely valuable when decisions concerning routing or repairs need to be made mid-tow. On the Exxon Harmony and Heritage tows, statistics files and cumulative fatigue files were sent to Houston daily, as were typed reports from the barge technician. The technician could call a computer at Exxon and download files, or Exxon personnel could call directly into the barge computer to obtain upload files or leave messages (1). The reports were used by Exxon to develop a weekly fatigue hindcast and forecast. A sample daily tow log is shown in Figure 1.

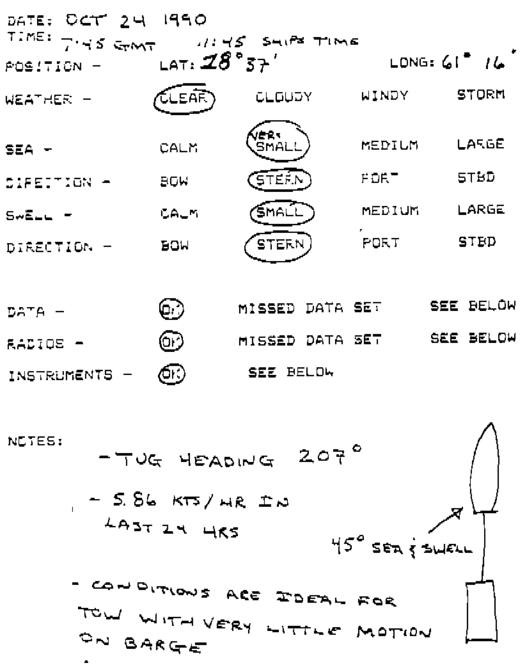

Figure 1 Sample daily tow log

5. COMPUTATIONAL PROCEDURES

Depending on the objectives, computational procedures can be extremely simple or very complex. Increases in processing power and decreases in the cost of computers have allowed more data to be analyzed and displayed in real time. Our real-time multitasking software typically handles the data acquisition and storage (when used) in the background. The data analysis and display routines run in the foreground, allowing interaction between computers and operators.

5.1 Motion

A typical motion measurement system is shown in Figure 2. Triaxial acceleration sensors (surge, sway, and heave) and roll and pitch angle sensors are typically located at the center of gravity. Biaxial acceleration sensors (sway and heave) are located at the stern (or bow). A single-axis acceleration sensor (heave) is located on the port or starboard side. A sample data display is shown in Figure 3. A sample time series analysis is shown in Figure 4.

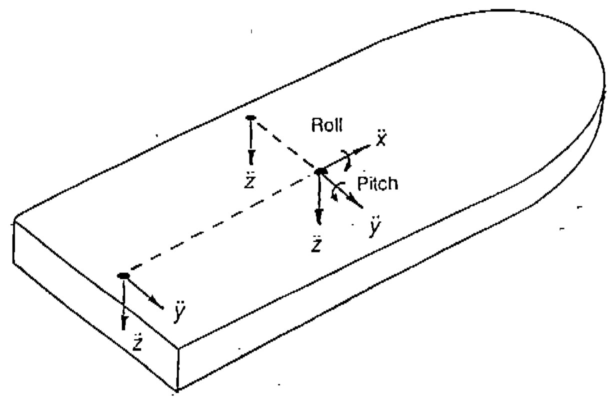

Figure 2 Motion measurement system

As mentioned earlier, accelerometers are used primarily because they allow a direct measurement of the forces exerted on mechanical components and structural members, using F = ma. The correction of the accelerations for gravity is carried out using:

Heave acc. = measured value + g[1−cos(roll)cos(pitch)]
Sway acc. = measured value − g[sin(roll)cos(pitch)]
Surge acc. = measured value + g[sin(pitch)]

Other data analysis can be incorporated into the system software, depending on the objectives. Figure 5 shows an example of the spectral density of the rolling motion of a barge. Software can continuously monitor such results to detect any changes in the GM of a barge during a voyage. Barge GM was monitored using roll motion spectral densities during a recent tow of Chevron equipment from the UAE to offshore Cabinda.

5.2 Stress and Fatigue Damage

As mentioned earlier, calculating stress and fatigue damage is one of the more important concerns of monitoring, as vessels and structures are subjected to rigorous fatigue inspections. If data is collected and analyzed during a voyage, it can shorten inspection times considerably.

The corrected accelerations and lever arms are first used to compute:

$$\ddot{x}(t), \ddot{y}(t), \ddot{z}(t), \ddot{\theta}(t), \ddot{\phi}(t), \ddot{\psi}(t) = a_i(t)$$

For stress analysis, the stress "hot spots" to be used must be provided, obtained from analytic models devel-

Chevron Tow Monitor   Copyright 1989 1990   Arctec Offshore Corporation
System Clock: 10/17/90 16:51:09   TattleTale Clock: 10\17\90 16:52

Motion	Min	%	Max	%	Mean	Std-dev	H-Sig
Roll(deg)	-0.7	2.4	-0.7	2.4	-0.7	0.000	0.000
Pitch(deg)	-1.3	14.6	-1.1	12.6	-1.2	0.038	0.152
CGHeaveAc(ft/s^2)	0.1	1.2	0.2	2.0	0.1	0.038	0.150
CGSurgeAc(ft/s^2)	-0.1	2.3	0.0	0.8	-0.0	0.035	0.141
CGSwayAc(ft/s^2)	0.1	0.9	0.1	0.9	0.1	0.000	0.000
StnHeavAc(ft/s^2)	0.0	0.3	0.1	1.2	0.1	0.018	0.071
StnSwayAc(ft/s^2)	0.4	2.4	0.6	3.4	0.4	0.015	0.062
PrtHeavAc(ft/s^2)	0.1	1.2	0.2	2.2	0.1	0.042	0.169
Heading(deg)	194.7	38.9	194.7	38.9	194.7	0.027	0.108
BatVoltvolts	12.0	109.1	12.0	109.1	12.0	0.000	0.000
RollAcc(rd/s^2)	-0.2	95.2	0.3	133.1	0.0	0.197	0.788
PitchAcc(rd/s^2)	-0.1	177.2	0.0	11.6	-0.0	0.045	0.181
YawAcc(rd/s^2)	-0.5	1510.3	-0.3	898.7	-0.3	0.018	0.071

Figure 3 Sample data display

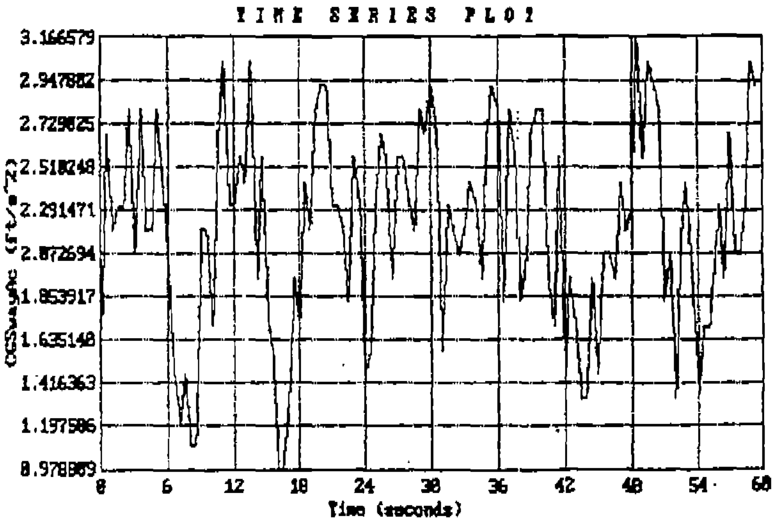

Figure 4 Onboard time series analysis

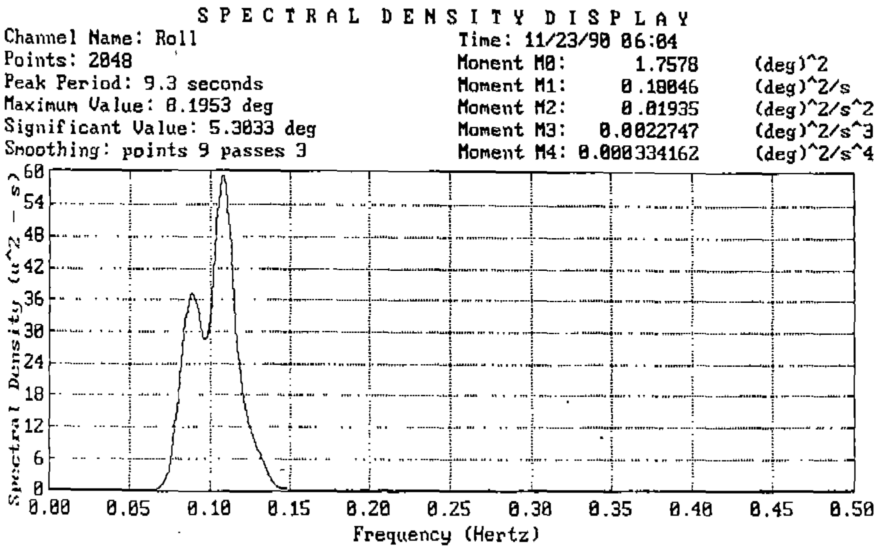

Figure 5 Spectral density display of rolling motion of barge

oped by the ship or structure designers. A "hot-spot" stress time series at each node in question is computed, using analytical model transfer functions and the measured accelerations:

$$\sigma(t) = \sum_{i=1}^{6} a_i(t) \times \mathrm{SIGMA}_i \qquad (1)$$

where SIGMA = transfer function from analytical model.

There are several alternative methods which can be used for fatigue damage analysis. In our systems, stress magnitude and frequency are determined at each zero upcrossing in the stress time series, as shown in Figure 6. Another approach used frequently is the rain-flow method of counting stress cycles (4).

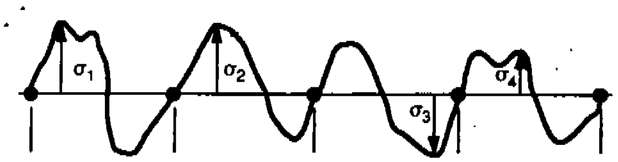

Figure 6 Determine stress magnitude and frequency at each zero upcrossing in stress time series.

Stress values are then categorized into stress "bins" to obtain the number of completely reversed stress cycles at a particular stress level. This follows accepted methods for computing fatigue life assuming an SN relationship (S = harmonic stress amplitude, N = number of cycles to failure) where N = N(S).

The cumulative damage (CD) can be expressed in a discrete form:

$$CD = n_1/N(S_1) + n_2/N(S_2) + n_3/N(S_3) + \ldots \qquad (2)$$

where n_1, n_2, n_3, ... are the number of harmonic stress cycles applied to the material at amplitudes S_1, S_2, S_3, ..., respectively. Failure occurs when the cumulative damage reaches unity, that is, CD = 1.

6. TOWED STRUCTURE MONITORING EXAMPLES

A tow monitoring system can range in complexity from relatively short tows of small jackets or "decks," to extremely elaborate tows of large jackets over thousands of miles. With the trend toward lower costs and higher power of computers, peripherals, and other hardware, it is now possible to install a useful tow monitoring system for under $40,000, although several hundreds of thousands may be spent on the more complex systems.

The monitoring system employed during the transportation of Exxon's Harmony and Heritage jackets from Korea to Santa Barbara, California represented one of the most sophisticated systems ever designed and installed by Arctec Offshore Corporation. Figure 7 shows the tug-barge configuration used during these tows. The block diagram in Figure 8 shows the tow instrumentation system components. Table 2 contains motion, stress, and environmental sensors used during the tows.

TABLE II
Harmony/Heritage Tows
Motion, Stress, and Environmental Sensors

	Harmony	Heritage
Strain gages	76	44
Wave sensors	3	0
Immersion sensor	1	1
Wind sensors	2	2
Vertical gyro	1	1
Accelerometers	6	6
Extensometers	4	4
Barometer	1	1
Compass	1	1
Barge deflection sensors	4	4

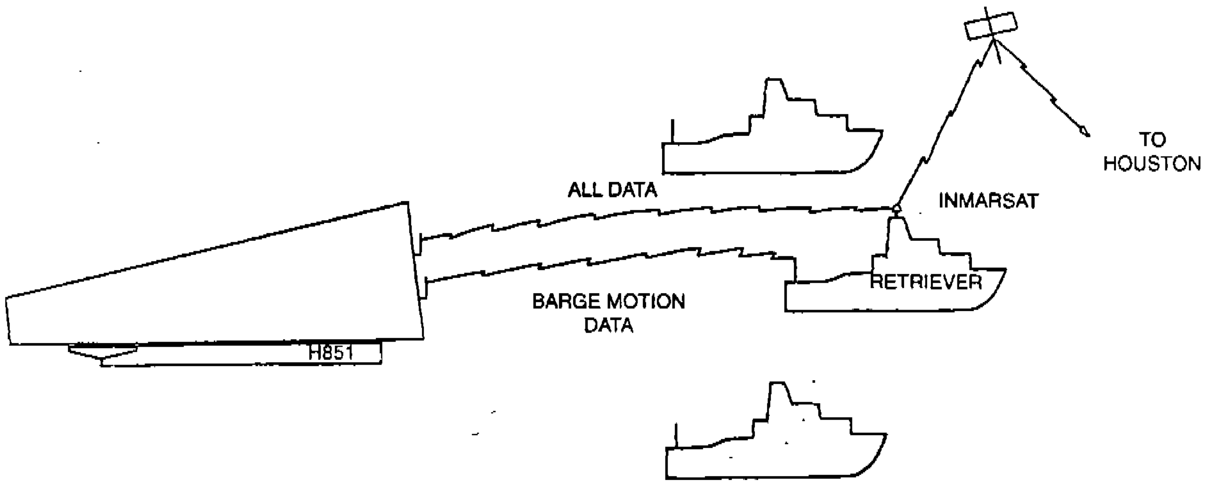

Figure 7 Large Jacket Transportation—the Harmony/Heritage Tows

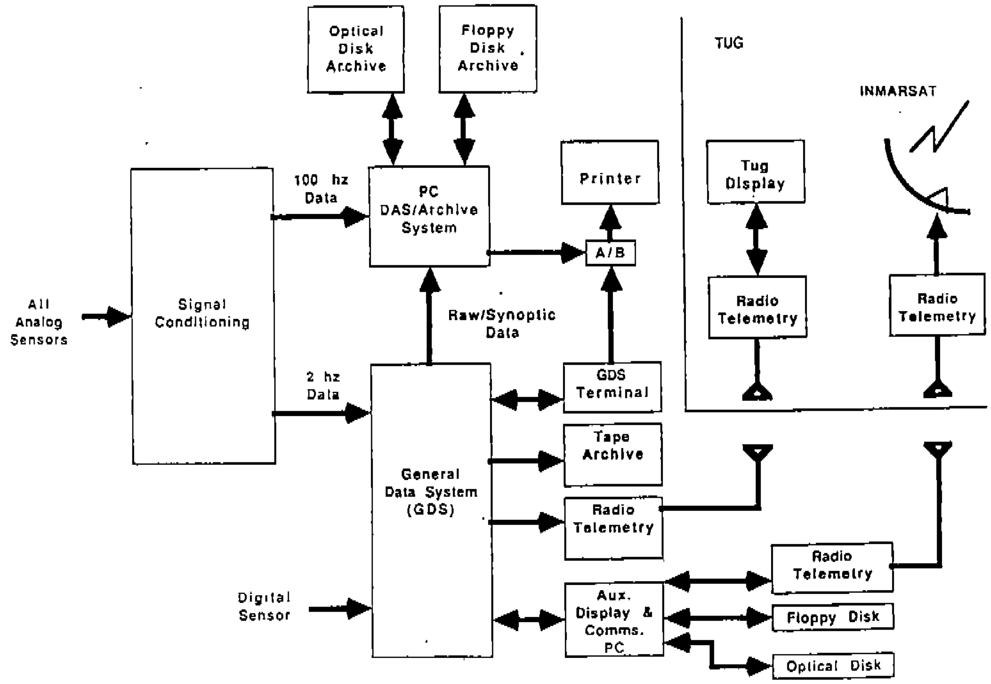

Figure 8 Tow instrumentation components

7. SHIP OPERATIONAL MONITORING EXAMPLES

Figure 9 depicts a typical ship operational monitoring system. With these systems, the objectives are typically threefold:

1. improve ship safety
2. reduce heavy weather damage
3. improve operational efficiency.

Potential benefits are measured in terms of loss of life, environmental damage, and damage to or loss of material property. Arctec Offshore Corporation is currently involved with several tanker monitoring projects for major oil companies. The ultimate purpose of most of these projects is to provide tanker masters with real-time information regarding the structural behavior of their vessels during all phases of operations. However, initially many of the systems are being used to collect performance data that will be analyzed to determine structural limit criteria.

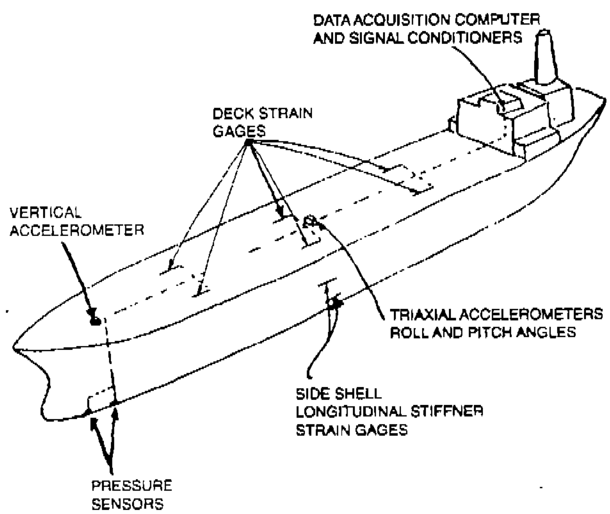

Figure 9 Typical Ship Operational Monitoring System

Various organizations in the U.S., Europe, and Japan have been investigating for many years the use of shipboard instrumentation systems to aid mariners in making decisions related to safe and efficient operation of their ships. However, the concept has not yet been commercialized to the point where standardized equipment is available and in-use on a number of ships.

Researchers, owners, and operators who participated in research efforts all agree that some form of monitoring is required, but have had difficulty agreeing on details, such as the number and type of sensors required and the manner in which information should be displayed. An important SNAME paper in 1980 by Chazal et al. (5) and resulting discussions led to a consensus of what was needed:

"...a simple system consisting of no more than two or three sensing devices which can be installed on different ships with indicators having a common element of presentation."

The SNAME HS-12 Panel on Hull Instrumentation was tasked with reviewing all prior work and providing performance requirements for such a system, to be called the Ship Performance Monitor (SRM). SNAME HS-12 made the following recommendations:

- The system should be configured as a navigational console comprised of a display unit, function controls, keypad, microcomputer, signal conditioning, sensors and cables.
- It should have the capacity to support monitoring and alert functions with analysis or output from STAN-

DARD and OPTIONAL sensors with standard formatted displays, user information, system status, sensor calibrations and diagnostics.

- It should be expandable so capacity can be added later to support guidance and predictive functions as well as monitoring and alert functions.

Bow vertical acceleration was specified as a standard measurement, since bottom slamming, flare immersion impact, damage due to shipping water, and damage due to longitudinal bending can all be related to vertical accelerations at the bow. In addition, pilot house lateral accelerations were specified as a standard measurement to be made, since cargo shifting and fluid sloshing damage are in most cases caused by lateral accelerations due to heavy rolling, and can be related to lateral accelerations in the pilot house.

Arctec Offshore Corporation was awarded a contract by the Ship Structure Committee to translate SNAME HS-12 Panel performance requirements into cost-effective hardware and software. In the first phase of the project, a number of designs, sensor types, cable systems, packaging concepts, and user interfaces were evaluated. Over 25 commercial research and experimental monitoring projects from the period between 1961 to the late 1980s were examined. These projects incorporated monitoring systems aimed at aiding operators in assessing the potential for damage to their ship and/or its ability to safely complete its mission. A wide variety of vessels, operating environments, sensors, data acquisition units, and displays were employed. The following types of measurements were made:

- bow vertical accelerations
- midship biaxial accelerations
- midship deck stresses (longitudinal and shear)
- longitudinal bending moment stresses
- shaft torque, thrust and RPM
- ship speed and heading
- roll and pitch (period and angle)

Several types of damage were reported, including:

- bottom slamming
- flare immersion impact (bow slamming)
- damage due to shipping water
- cargo shifting
- damage due to fluid sloshing
- damage due to hull girder bending (infrequent)

Findings from these efforts led to the formulation of design specifications for a relatively low-cost, generalized, computer-controlled instrumentation system (6).

During the second phase of the project, a prototype Ship Response Monitor (SRM) was designed and constructed. It consists of standard industrial measurement and control hardware operating under control of software written in the C language, for ease of portability. The SRM incorporates an accelerometer package at the bow and other optional sensor arrays, depending on the type of ship the system is installed on. The prototype SRM was installed on an Exxon tanker in August 1991 for several months of field testing. At the end of that time, the effectiveness of the system will be evaluated.

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