INTEGRATED SYSTEMS FOR SHIP HANDLING AND MONITORING OF HULL LOADS

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SUMMARY

Development of instruments that allow accurate measurements of ship motions, sea state and hull loads makes it possible to create advanced systems for monitoring, recording and warning of the vessel performance according to selected operational criteria. Combination of such onboard systems into one integrated system gives valuable synergies. Also, making integrated instrumentation and information systems creates a possibility for implementation of some additional functions. As samples of such additional functionalities of integrated systems, weather routing, optimization of the vessel ballast distribution and optimization of the ship motion damping system can be mentioned. This paper presents examples of innovative sensor systems, as well as examples of current and proposed integrated ship handling systems.

1. INTRODUCTION

Great improvement in the data processing, instrumentations for maritime application and sensor systems has opened new possibilities for development of advanced guidance tools for ship operation. Most of the large size vessels are presently delivered with a complex data net that connects most of the ship systems.

Many accidents with large tankers or bulk carriers, causing enormous damage to the environment, were due to failure of the hull structure due to a combination of the ship age and large sea loads. This entailed that the IMO has recommended applying hull structure monitoring systems on large bulk and tank ships. The hull structure monitoring systems are presently applied for control of the fatigue damages as well as for control of the cracks caused by overloads occurring in extreme weather conditions.

Damages on the ship bow construction and loss of valuable containers on large container vessels in hard weather conditions were reasons for the development of guidance systems for ship operation aimed to avoid such losses. The developed systems have been based either on measurement of hull loads or ship motions, or on a combination of these two methods.

Development of new ship designs, often optimized with respect to reduced structural weight as e.g. fast cargo ships was a challenge for the classification societies, which have responded by proposing regulations that included requirements of application of hull monitoring and operational guidance systems onboard.

All these factors together create a market for different products concerning the hull monitoring and operational guidance systems. Many of these systems will in fact require the same input data, sensor records, and results from pre-computation and other information. Combining and sharing out information between different systems will give new possibilities. This is the main reason for increased interest in integrated systems for ship operational guidance and monitoring of the hull loads.

2. SHIP GUIDANCE SYSTEMS

The following ship systems might be listed as samples of the components of the integrated system:

- Traditional navigation systems
- Weather routing
- Active operational guidance
- Hull monitoring systems

Traditional navigation systems will not be discussed here.

2.1 WEATHER ROUTING

Weather routing systems are used to establish the shortest time route or the most economical route from the departure point to the arrival point by applying available information of the weather condition (wave, wind, current). In addition, information of the ship speed loss due to wave, wind and ocean current must be defined (usually pre-computed). Forecast of wave and wind data are delivered for commercial application by many meteorological institutes, including the Norwegian Meteorological Institute (DNMI). Weather forecasts are computed based on the information from satellites and meteorological measurement stations on the ground. They are next used as input data to an advanced computer simulation program, which models the global weather development in the next days (at present typically for 10 days ahead). Computations of the optimal route (using different optimization criteria) are done on board by applying weather prognoses transmitted to the ship by satellite communication. Computation of the optimal route is repeated every day during the ship voyage by applying new updated weather prognoses. DNMI with co-operation of MARINTEK has developed the weather routing system that is marketed under the name "SEASTAR" (see Figure 1). A more advanced system called C-STAR, developed by C-MAP, DNMI and MARINTEK is currently released. C-STAR is integrated with the advanced electronic chart systems sold by C-map, so that the optimal route is presented directly on the electronic chart.

Figure 1: Comparison of the shortest route (Great Circle) and computed the least time route (presentation taken from the SEASTAR system).

Optimization of the ship route could be considered with respect to other criteria than the least voyage time in a seaway. There have also been carried out projects to solve the ship routing in ice, due to an increased interest to open the North East passage for commercial shipping. Among these projects there was also the EU common project called "Ice Routes" in which MARINTEK has contributed with software for ship routing in ice (the computer program "FRAM", see reference W. Kauczynski, 1998). During the "Ice Routes" project it was found that commercialization of the ship routing in ice requires improved prediction of the ice parameters read from satellite images, and to solve problems with estimation of the ice drift.
In other applications the ship routing optimization might be based other criteria like for instance passenger comfort (cruise vessels), hull loads (tankers and bulk carriers), "just in time" (container ships) or the lowest fuel consumption. The ship route optimization by applying such criteria has already been tested with successful results, and such routines can be easily adopted in any onboard system.

2.2 HULL MONITORING

The hull monitoring systems are applied to monitor loads on the hull construction. This is done in order to determine the fatigue of the material as well as the impact loads. The developed systems are based on measurements of local tension in a limited number of locations. The local tension is usually measured over a length ranging from a few centimeters up to a few meters. Measurement are collected frequently by the data system and presented usually in a graphic display on the bridge. Simultaneously, results of all the performed measurements are stored in a database to be used as input data for the long-term fatigue analysis of the ship construction. In the presently installed systems the sensors for the tension measurements are almost exclusively based on strain gages. There are two main challenges with this method: The first is to transfer results of the local tension into accurate information of the global loads. The second problem is to estimate tension in the "hot spots" where it is often quite difficult to put a strain gage and to make good measurements of the strain. To solve these problems, a combination of FEM computations and data from the database are applied, but this link between the strain gage measurements and the wanted loads and local strains are a main source of uncertainty in hull monitoring systems.

In the systems applied onboard it is common practice to combine measurements of the strain with measurements of the ship motion, and with records from the pressure transducers installed on the bow (see a sample shown in Figure 2). As a result of such combination the functionality of the system is extended to monitoring slamming loads on the bow and simultaneously this system provides better documentation on the co-relation between the sea state, ship motions and sea loads.

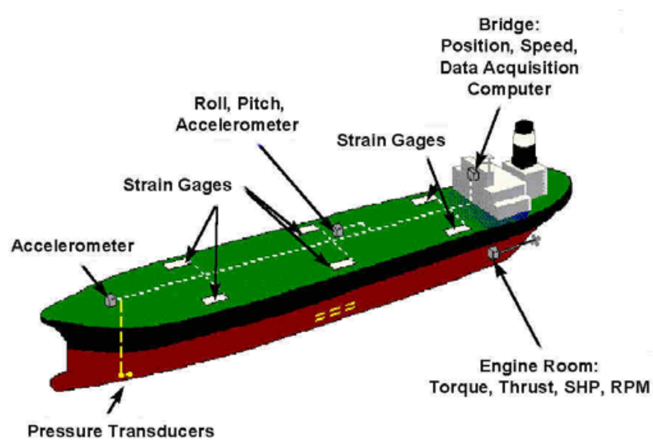

Figure 2: Sample of the hull monitoring system that includes combination of the strain gages, pressure transducers and motion sensors (Sytainstall StressAlert II).

2.3 OPERATOR GUIDANCE SYSTEMS

Operator guidance systems provide continuous guidance for the ship operator on selection of the optimal way of handling a vessel in order to assure safety of the ship, load, passengers and crew. Operator guidance system has been proposed for Norwegian coastal liners in order to assure that the vessels will operate inside of the operational limits defined in the ship operational manual. The system can also be easily used to document exceeding of the defined operational limits

Ship operational manuals are usually of large volume and they are therefore a quite awkward source, especially in an emergency situation. The main idea of the active operator guidance systems was therefore to monitor the ship motion and loads and continuously compare these responses with the operational limits, supplying the shipmaster with information of the current level of the ship responses with regard to the limiting values. In addition, the system may advice the shipmaster how to avoid exceeding the operational limits by suggesting either to slow down the ship speed or by changing the ship course.

The first prototype of the operator guidance system developed by MARINTEK was the Hard Weather Avoidance System that was ordered by A. P. Möller ship owner for its M-class container vessel. These vessels had regularly damages of the bow structure due to green water in severe weather conditions. Especially during the night it was very difficult for the crew to observe changes of the weather condition and to make correct decisions regarding the proper ship speed and heading in order to avoid hard weather damages.

This system (see sketch shown in Figure 3) was developed in 1990. It consists of one vertical accelerometer installed on the bow connected with a computer continuously recording signals. These data were sequentially transmitted to a PC installed on the bridge, which acquired data from the accelerometer, analyzed them, and presented on a screen the current status showing the probability of green water. A sample of this display is shown in Figure 4. In order to complete the database with the vessel transfer functions an extensive computation program was carried out and its results was verified by a series of model tests with a model of the actual vessel. These functions give a relation between the vertical acceleration at the bow and probability of green water. In order to calculate the probability of the green water by applying these functions the current ship speed and the wave heading must be known. Both these data have to be manually specified by an operator. Correct evaluation of the wave heading, especially in a condition of limited visibility (night, fog), is usually quite difficult. In addition, in a case when waves come from different directions, the system had no option to solve such a case. Despite of some problems with estimation of the wave direction, the system is still operating and the ship owner praises it. This system has proved that it is possible to get valuable information of the sea condition by applying one single sensor (accelerometer). In this case an entire ship was used as a wave buoy, what has already been proved to be a successful approach in many other applications.

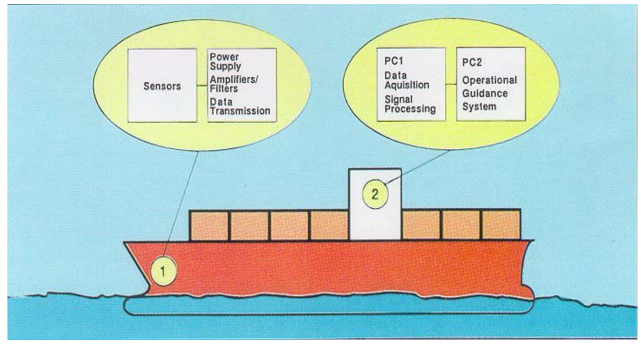

Figure 3: Sketch of the "Hard Weather Avoidance" system developed by MARINTEK

A simplified version of the Hard Weather Avoidance system has been adopted into an onboard system developed by MARINTEK and AUTRONICA (Norway) called the "Emergency management central". This system has been installed on the Norwegian costal liner m/v Polarlys.

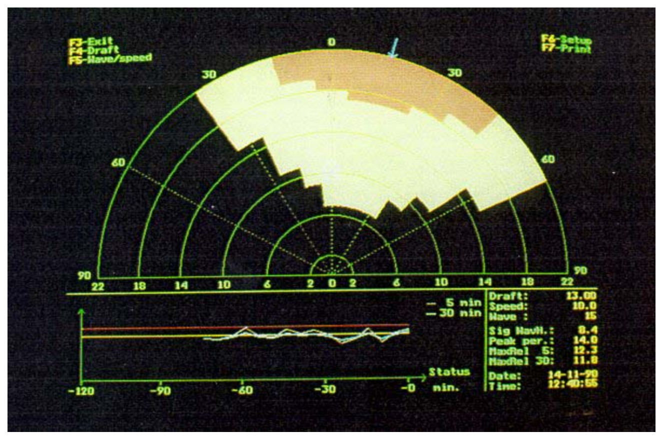

Figure 4: Sample of a display produced by the Hard Weather Avoidance system (MARINTEK 1990)

The U.S. Navy uses different types of the Operator Guidance system in its fleet, since there have been issued different limitations depending on the type of operation performed by a navy ship. Helicopter landing is a sample of such operation where it is not sufficient to have a skilled crew to assure that operational criteria will be fulfilled.

A special type of operator guidance system is the system for the hard weather warning at the Stad region (on the Norwegian West coast) developed by SINTEF (including MARINTEK) and the Norwegian Meteorological Institute (DNMI) on behalf of the Norwegian Coast Authorities. The system includes software that computes the local wave system in shallow water and in the channels between rocks and islands along the Stadlandet peninsula based on data of the wave heights, period and direction recorded in the open sea in a distance off the coast. This software applied a special theory of wave refraction developed in the pre-projects carried out by SINTEF. By applying this system small boats approaching this region can be warned of the local environmental condition that they will meet in the Stad area. The system also includes a module (developed by MARINTEK) that on the basis of information on the boat particulars allows estimating the risk of capsizing during a passage. The final conclusions issued by the system might be an advice to wait for a better weather condition or it might suggest that a passage will be safe. Information of the current environmental situation in this region is also presented on the DNMI web site (http://www.dnmi.no). A sample of wave refraction diagram presented on this site is shown in Fig. 5.

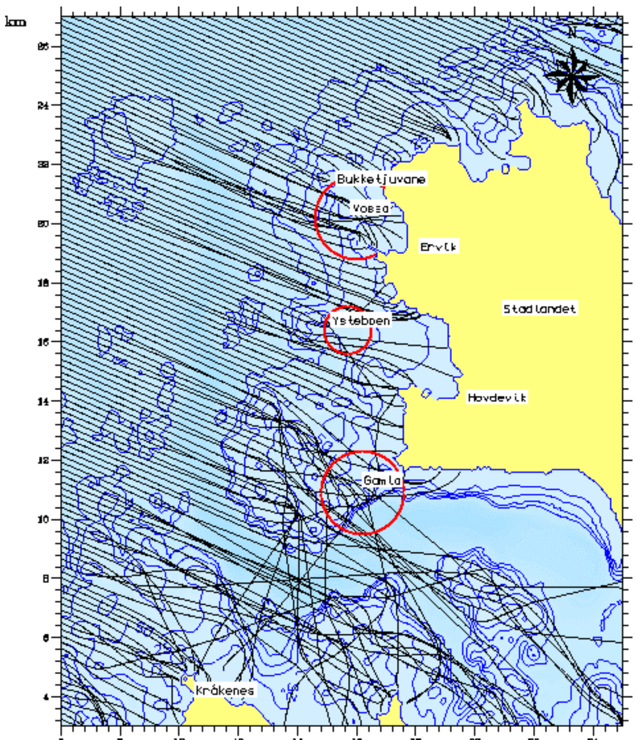

Figure 5: Sample of the wave refraction diagram obtained from the wave warning system for the Stadt area as shown on the DNMI's web site (http://www.dnmi.no)

3. NEW SENSOR SYSTEMS

3.1 MEASURMENTS OF THE HULL STRAIN BY APPYING FIBER-OPTIC CABLES

A new method to measure the local stress on the ship hull is to apply fiber optic sensors (Bragg grids). The Norwegian company SAFETY-ONE AS has developed a system that is commercialized under the name SENFIB2000 that applies fiber optic sensors for measurements of the hull stress. This system is a result of co-operation with other Norwegian companies i.e. SINTEF and TELENOR INSTALLASJON.

Application of the fiber optic sensors on board has been tested during the Norwegian Research Program called "30 years vessel" supported by the Norwegian Research Council (NFR). This project has been carried out by a group of the following Norwegian companies: Det Norske Veritas (DnV), NAVION and SAFETY-ONE.

Classification societies have already observed benefit from the use of hull monitoring systems. International Maritime Organization (IMO) has recommended using hull-monitoring systems for all tankers and bulk carriers. DnV has introduced a special class for vessels with hull stress monitoring systems (HMON-1 and HMON-2).

The Norwegian Defense Research Institute has been working a long time with development and application of fiber optic cable for stress measurement on composite constructions. Lately they have performed full scale testing of such equipment on the composite hull of the Norwegian patrol boat (MTB) "KNM Skjold".

3.2 WAVE RECORDS BY RECORDED BY MEANS OF RADAR

The Norwegian company MIROS has developed a system called WAVEX that uses ordinary ship radar for measurements of the wave height. This system measures not only the wave height but also the directional wave spectrum i.e. distribution of the wave energy as a function of the wave direction and frequency. The system analyses reflections of the radar signals caused by waves to determine the sea condition. It uses the sea clutter, which is usually filtered out of the display on the radar screen. Wave height and periods of waves are determined from the modulation of the radar signals (echoes) from water surface roughness (see Fig. 6). The system requires radar having the X-band and in addition the radar rotation speed and the applied frequencies must fulfill some requirements. In many cases it is therefore more convenient to add a dedicated radar for this system. The only additional data that must be supplied to the WAXEX system is the ship speed, which might be acquired automatically from the navigation system. A sketch showing the main components of this system is given in Figure 7

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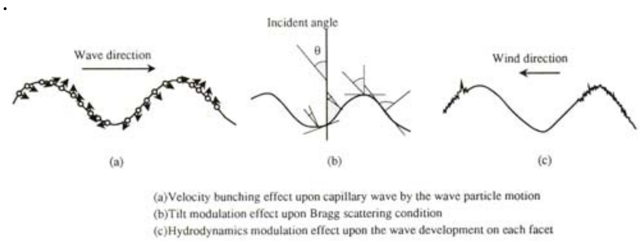

Figure 6: Principles of the method applied for determination of the wave parameters from radar echoes

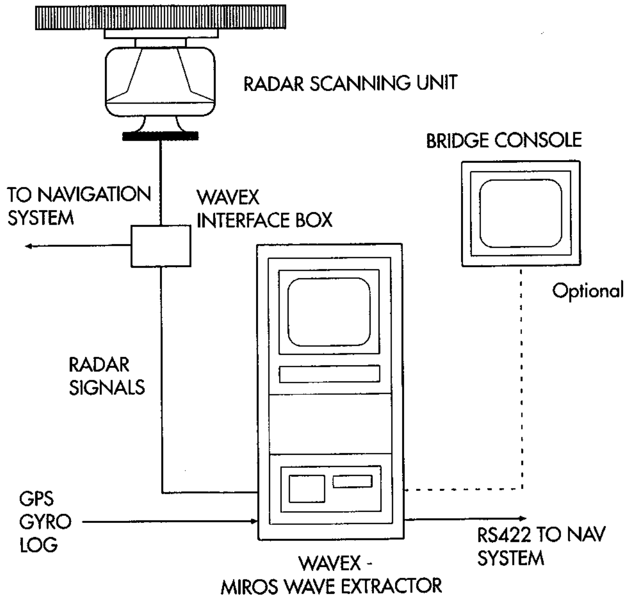

Figure 7: Main components of the WAVEX system

Development of the WAVEX system has been initiated in the year 1989. For a long time period the system has been used on a stationary offshore platform where a conventional wave radar was applied to measure waves. Later, as a result of cooperation with DnV and Stena shipping company a commercial system for ships has been developed. This system is presently used onboard of the large ferry m/v STENA EXPLORER.

The possibility of continuous and accurate determination of the wave parameters has large impact on the development and potential of operator guidance and hull monitoring systems. There are also other suppliers of wave radars for application on merchant ships.

3.3 MEASUREMENTS OF VESSEL POSITION AND WAVE INDUCED MOTIONS

Development of equipment for measurements of the ship motion based on accelerometers or gyroscope, which might be combined in one unit called Inertial Motion Unit (IMU), has contributed to an improvement of onboard operational guidance and hull monitoring systems. Such equipment provides high accuracy, and simple installation and integration with other instruments, compared to conventional accelerometers and gyros. An example of a commercially available, well-proven IMU is the MRU, manufactured by the Norwegian company SEATEX (see description of this product on the web site: http://www.seatex.no). The MRU contains a collection of high-precision accelerometers and inclinometers, which in combination with on-line computations performed by the integrated circuitry of the MRU, provides accurate measurement of acceleration and motion in six degrees of freedom. Assuming that the ship moves as a rigid body (which is not too far from the truth) the motion or acceleration on any point on the ship can be found by means of this small unit, placed for instance on the bridge. This means that costly and complex cabling of accelerometers placed around the ship is no longer necessary.

Measurements of the ship position and speed over ground are presently based on the GPS-technique. Three classes of the GPS systems are available:

- GPS - tolerance of the vessel location in a range of 1-20 m
- DGPS - tolerance of the vessel location in a range of 1 m
- CDGPS - tolerance of the vessel location in a range of 1 cm

Modern GPS receivers allow to determine the location and speed of ships in surge, sway and heave with a quite high accuracy. By applying special GPS systems it is also possible to determine the ship rotations in roll, pitch and yaw. This requires however installation of two or more antennas on the hull, with a distance of minimum 3-5 m. In this way, the GPS can to a certain extent replace an IMU.

It is also possible to integrate the GPS system with an IMU unit. By combining these two elements a complete inertial navigation system will be achieved (TNS system). This combination requires however to adopt software, which combines measurements from these two systems by using for instance Kalman filtering to solve a set of 50 differential equations.
Such systems are presently available on the market. They are manufactured by several companies, among them also the Norwegian company SEATEX (a system called SeaPath).

4. INTEGRATED SYSTEMS FOR SHIP HANDLING

Systems that have been described in this review are quite different with regard to the performed operations as well as with regards to methods of action. But all of them have a common feature and that is that they have been developed to provide guidance for safer ship handling. All of these systems require in general the same input data, and in many cases a great benefit might be achieved when the computed results are shared between different systems. Integration of different onboard systems is expected therefore to provide many benefits. The tendency towards integration of onboard systems has been observed for a long time, especially in the hull monitoring systems, which are designed to achieve high functionality. As shown in a sample in Figure2, it is today a common practice to combine usage of the pressure transducers, motion sensors and strain gages in order to provide more complete information of the hull load, as well as to make possible an estimation of the current environmental situation.

4.1 ACTIVE OPERATOR GUIDANCE SYSTEM

The ship motion measurements and operator guidance applied in the “Hard weather Avoidance” system (as described in chapter 2.3) might be listed as a good example of combination of the onboard systems that provides significant synergy effects. The main problem with the existing “Hard weather Avoidance” system is a shortage of data regarding the wave direction and wave period. This system is also not able to analyze multipeak wave spectra. Systems that include a wave radar have a significant advantage since it provides direct information on the current sea condition and from this one can evaluate the vessel responses and probability of exceedance of the operational criteria. Two years ago a group of the Norwegian companies (MIROS, MARINTEK, DnV, HITEC and SEATEX) has initiated a research program supported by the Norwegian Research Council (NFR) dedicated to develop the Active Operator Guidance system based on the abovementioned principles. It was assumed that this system should result in a prototype of the system that would later be commercialized. Besides the WAVEX wave radar, the system also includes the MRU-5 motion sensor produced by SEATEX. HITEC has contributed to this project with an integrated bridge system, while DnV has shared their knowledge of such systems from their previous work on introduction of the ship classes with the hull monitoring systems.

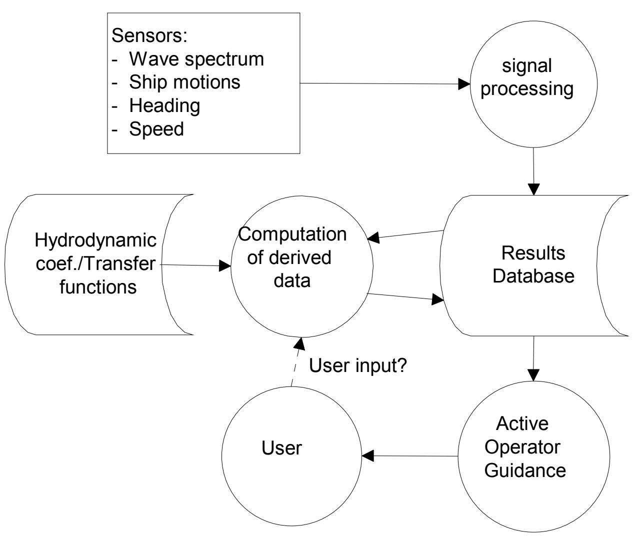

Figure 8: Sample of the data flow in the Active Operator Guidance system

A sample of the data flows in the Active Operator Guidance system in shown in Figure 8. Computations of the ship motions and accelerations are usually done by means of the computer program based on the linear strip theory. Basic principles of this theory were published by Salvensen, Tuck and Faltinsen in 1970. Since that time many computer programs for computations of the seakeeping characteristics have been developed by applying this theory and by adding many additional modifications. Linear strip theory has proved to give results that match very good the experimental results, including also high sea conditions where the ship motions definitely include nonlinear effects. Strip theory allows computing the ship motions, accelerations, relative motions, as well as the global loads on a hull.

Measurements of the ship motions provide a kind of redundancy to the system. In a case when the measured wave data and computations of the ship motions are correct, measurements of the ship motions are unnecessary since all the ship responses can be computed based on the wave data, hull geometry, vessel speed and hull mass distribution. However the long time experiences show that the wave measurements and the ship response computations will never provide results that are 100% consistent. In this context, direct measurements of the ship motion is therefore assumed to be the most accurate and these results can be used for modification of the transfer functions of the ship responses or for correction of the wave data (following the method applied in the Hard Weather Avoidance system, see section 2.3). By comparison of the measured and computed ship response at the current ship speed and wave heading, a correction factor is defined. It is assumed that the same correction factor can be used to modify the particular ship response at other speeds and headings. In this way the “corrected” ship responses at the different conditions are obtained and they are presented as output from the operator guidance system by applying a presentation scheme similar to the display used in the Hard Weather Avoidance system (see section 2.3).

Data for the “Operator guidance” computed by comparison of the measured (or computed) amplitudes of the particular ship response e.g. amplitude of the vertical acceleration at a particular location of interest, for instance the passenger area dining room, with the level specified in the operational criterion concerning this response (e.g. the passenger comfort criterion). A ratio of these two values can be called the operability factor that can be computed as:

$$C_{operability} = \frac{Measured\ /\ computed\ \ response}{Limiting\ \ response\ \ value}$$

When the operability factor $C_{operability}$ is larger than 1.0 this means that the criterion is exceeded. The operability factor $C_{operability}$ can be computed for a set of the different ship courses and speeds that will allow an operator to select an optimal ship course and speed at that the criterion will not be exceeded and simultaneously without dismissing other navigation requirements. In the case when several operational criteria must be fulfilled simultaneously, the operability factor $C_{operability}$ is computed by superposing results from all the considered criteria and the maximum computed value for each combination of the considered ship speed and course is presented as the final value for guidance. A list over the operational criteria that could be considered in the guidance system may include the accelerations and roll amplitude that is crucial for the passenger comfort or for a sensitive load, relative motion at the bow that are crucial for probability of the bow slamming and the green water etc.

The considered Active Operator Guidance system will provide reliable data regarding the ship motions and the current sea condition. However, further improved reliability and ease of use could be obtained by integration with the onboard loading computer, which will provide correct and updated data of the ship load condition and the corresponding GM to the system.

When active motion damping devices (tanks, fins) are installed on a ship it may be beneficial to share information available from the active operator guidance system. In this case data regarding the ship motions and sea state can be used to tune the damping system at the selected load condition and the specified sea state. Data available from the operator guidance system regarding the sea state and ship motions can be used to optimize the ballast distribution and water level in the roll damping tanks.

But the most promising extension of the operator guidance system is probably integration with a weather routing program. Guidance provided from the present version of the Hard Weather Avoidance system to the operator does not include an advice whether to change the course or to change the speed. It is obvious that an optimal solution will depend on the location of the destination point, any restrictions in the area and the required arrival time to the next harbor. As a result of the combination of the Active Operator Guidance system with weather routing a guidance given to an operator will consider how to fulfill the short-term requirement of the ship operability and simultaneously to select the ship course and speed with regards to the most optimal route. It might be assumed that in such integrated system a selection of the optimal route could be based on the different criteria and not only on the least voyage time. By applying the same criteria for the route selection as these considered in the Active Operator Guidance system, the integrated system will give advice of the route selection that will give a reduced probability of exceeding of the operational limits.

This is also possible to extend the guidance system by including the route selection in the sea regions characterized by the specific wave system as e.g. the Stadt region on the Norwegian coast. In this case the wave prognoses in the considered sea area must be computed by applying the computer program based on the wave refraction theory instead of determining the wave parameters from the wave radar. Using the pre-computed wave conditions the expected ship responses on the pre-defined ship route will be calculated. This will allow estimating whether the proposed route through the passage in the forecasted weather condition is safe or not.

Combination of the weather routing and Active Operator Guidance systems may also be applied to evaluate the hull load on the designed route and to provide guidance on how to avoid hull overloading and unnecessary large fatigue loads. In this application the integrated system will in fact act as the hull monitoring system. The main problem with such an application is that the nonlinear effects have a much stronger influence on the induced global loads than on the ship motions. Since a probability of the hull overload is much higher in severe sea conditions, an accuracy of the computed global loads might not be satisfactory. In order to increase the accuracy of evaluation of the hull stress additional information from sensors (i.e. from strain gages or pressure transducers) must be provided.

It should be noted that all the required hardware and infrastructure required for such an integrated system is usually already present. Also, the methodologies required in the system are well known. Standards for communications between maritime information systems have also been evolved to an advanced stage, but incompatible communication standards might still be an obstacle.

4.2 “HULL STRESS MANAGEMENT” RESEARCH PROJECT

The Hull Stress Management system could be listed as an example of the integrated onboard system. In this system information obtained from sensors, from measurement of the ship motions and wave parameters, and from the numerically determined ship responses and loads are combined in one data system that collects data and provides warning and guidance regarding the ship response as well as the hull loads. The considered system will have the same possibilities for an extension of other functionalities as the Active Operator Guidance system, but the hull monitoring module is already added as an additional option. It is also planned in the considered system to supply computations of the hull load with results from the onboard load calculator. This combination is not so crucial for the system applying the ship motions and accelerations, but it is actually very important for the hull monitoring system.

5. CONCLUSIONS

A fast development of sensors and data communication has contributed to creation of new possibilities for creation of advanced systems for ship handling. An integration of the different sensors and systems with numerical routines for computations of ship responses and sea loads gives a possibility to provide documentation on the ship loads for the ship owners and classification institute, as well as a guidance for the ship operator in severe weather conditions. Such an integrated onboard system can be realized by combining measurements of the wave parameters, ship motions and hull stresses. In many cases, all the components required for an integrated system is already present, only the integration is lacking.

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