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Application of Roll Damping Systems to Search and Rescue Vessels

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1. ABSTRACT

The newly commissioned Type 500 SAR Cutters used by the Canadian Coast Guard to patrol the western coast of Canada unexpectedly exhibited severe rolling behavior when in severe weather conditions, at cruising speeds of 13 - 16 knots, and with following or stern quartering seas. This paper describes the steps taken to determine the cause, plan remedial action, implement corrective measures, and reports the results of sea trials conducted to determine the effectiveness of the measures taken.

2. INTRODUCTION AND HISTORICAL PERSPECTIVE

The Type 500 SAR Cutters were conceived to replace a series of aging 95 foot patrol cutters to serve the needs of Canadian Coast Guard on the west coast of British Columbia. These vessels had to be capable of fulfilling a multi-role mission in this service, which included:

- Search and Rescue
- Environmental Protection
- Checking and servicing floating aids to navigation
- Enforcement of Federal laws and regulations.

Of these tasks, the primary role was Search and Rescue, however, the need to be able to operate effectively in the other duties had definite implications on the overall design.

The cutters were put into service on the Pacific Coast in 1991, and very soon displayed an extreme rolling characteristic. Although the vessels met all regulatory requirements, they had less freeboard, were wetter on the aft operating deck than intended, and had insufficient dynamic roll damping. The vessels' performance in weather has met or exceeded all expectations, however in following seas, and especially in stern quartering seas, single roll amplitudes of over 40 degrees have been reported in severe weather.

This paper describes the development, implementation, and testing of corrective actions to reduce this rolling. The vessel design is described along with its post construction characteristics. The corrective actions considered, tested, and implemented are reviewed. Roll damping features of the original design included a Flume® passive roll stabilization system and a deep box keel. Retrofit considerations included a Hyde active rudder roll stabilization system and fixed bilge keels. Extensive model and full-scale testing was conducted to evaluate the effectiveness of these systems. The results of this analysis are presented in this paper.

2.1 Ship Service Requirements

The original statement of requirements for these vessels defined the following performance objectives:

- to respond year-round to emergency calls and perform its assigned tasks in the prevailing environmental conditions of the North-East Pacific coastal waters.
- vessel to have structural integrity and stability to survive storms of a continuous wind speed of 60 knots and associated seas up to 14 metres (Sea State 8).
- capable of maintaining a continuous speed of 15 knots in Sea State 5.
- capable of maintaining full manoeuvrability in Sea State 6.
- have a minimum continuous speed of 4 knots in Sea State 0.
- be able to turn in its own length in confined waters.
- have a range of 2500 nautical miles at economical cruising speed plus a fuel reserve of 10%.

2.2 Vessel Design

In 1987, Robert Allan Ltd., Naval Architects of Vancouver, B.C. were awarded a contract as a result of a national design contract competition to undertake the design of this new class of vessel. The design consisted of four distinct phases comprising:

- concept evaluation phase
- concept design phase
- preliminary design phase
- detail design phase

Included throughout these various phases were an extensive series of analytical and model tests to verify that the performance objectives could be met. Robert Allan Ltd. (RAL) contracted with Offshore Research Ltd. of Vancouver, B.C. to undertake a test program which consisted of the following experiments:

- computer-based analysis of Ship motions and accelerations for a variety of hull forms
- evaluation of various types of static and dynamic roll stabilization systems
- preliminary model tests (1:20 scale) of the preferred hull form for:
    - flowline measurements in the vicinity of bow thruster and shaft struts
    - measurement of heave, pitch, and accelerations at FP and AP in head seas only
- final model tests (1:10 scale) for:
    - seakeeping and motions analysis
    - Flume® stabilizer tank testing
    - manoeuvreing tests

These latter tests were conducted using a 1:10 scale, self-propelled, manned model in open water in the vicinity of Vancouver. A complete description of the process of developing the design of these SAR Cutters, and the evaluation studies performed is contained in Ref. [1].

After more than 12 months of design, development, and testing, the design was completed and the Type 500 Cutters were put to public tender for construction. The final arrangement of the vessels, as designed, was as shown on Figures 1 and 2.

Principal particulars for the vessels were as follows:

Length Overall	-	49.95	Metres
Length LWL	-	46.00	Metres
Beam, moulded	-	11.00	Metres
Depth, moulded	-	6.14	Metres
Draft, mean	-	4.50	Metres

The final design calculation values for performance critical parameters were the following:

Lightship Weight	-	693	Tonnes
Load Displacement	-	897	Tonnes
Load draft, mean	-	4.403	Metres
GM in full load condition	-	1.03	Metres

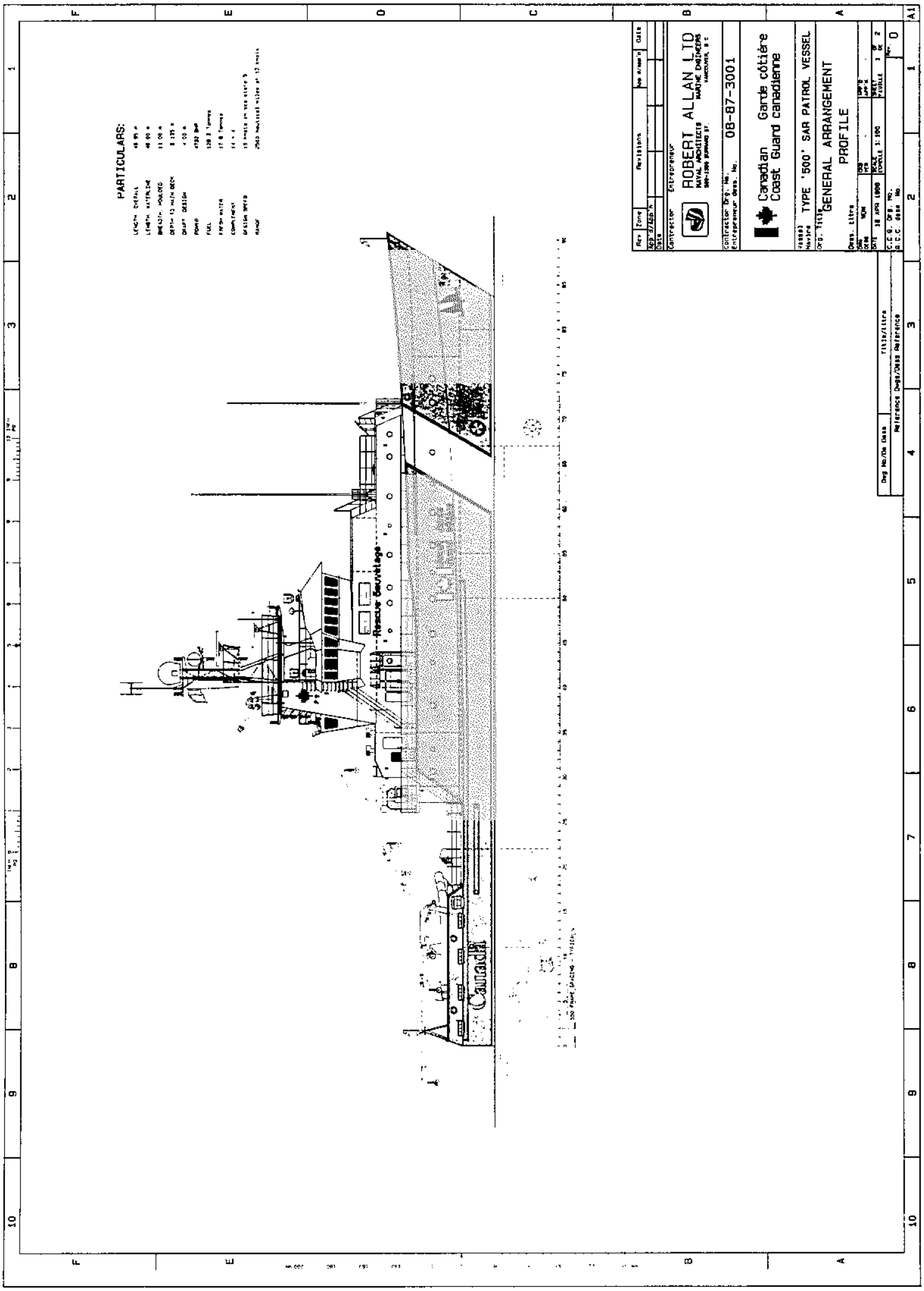


Figure 1. General Arrangement Profile of Type 500 SAR Cutter

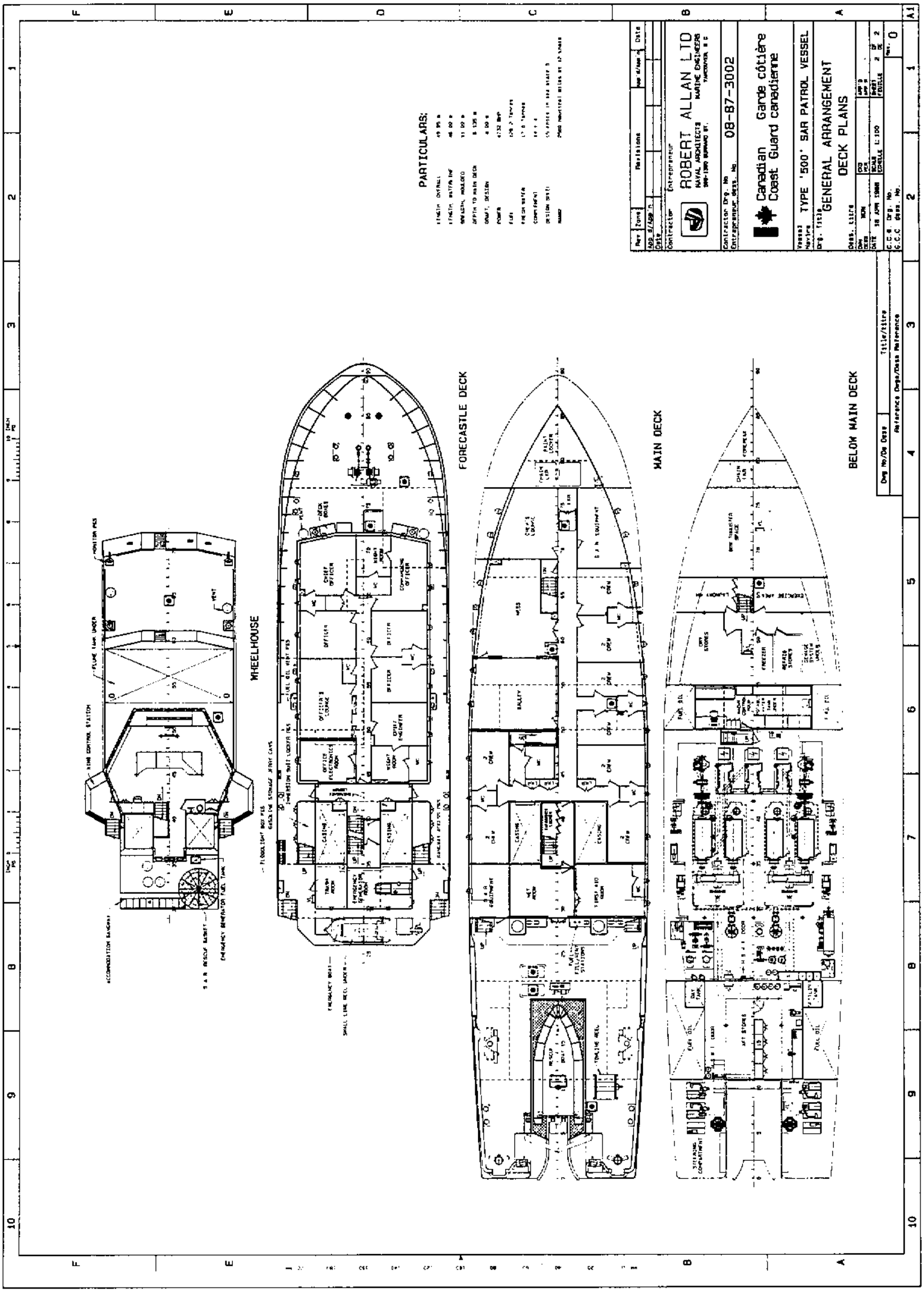


Figure 2. General Arrangement Deck Plans of Type 500 SAR Cutter

Due to an emphasis in the Statement of Requirements on vessel manoeuvrability at a wide range of speeds and conditions, the vessel was designed with large spade rudders, one behind each of two propellers. Rudder area totalled nearly four percent of lateral underwater area. The final hull form, due to the requirement for high speed in rough conditions, was one with fairly deep, but quite slack bilge sections and fairly fine waterlines.

2.3 Post-Construction Characteristics

In 1989, a contract was awarded to Versatile Pacific Shipyards Ltd. of Victoria, B.C. (VPSL) to construct two vessels to this design. Part of the contractual requirement of the shipyard under the Canadian Government's ship procurement process is to perform a "Design Check" on the tendered design documents.

As a consequence of the design check, VPSL identified the following differences in the estimated design parameters to those of the designers:

Lightship Weight	-	738	Tonnes
Load Displacement	-	896	Tonnes
GM in Full Load Condition	-	0.865	Metres

The above differences were accounted for by relatively minor differences in the estimated weights of steel and outfit, and by more significant differences in weights of machinery due to the yard proposing alternatives to the main and auxiliary machinery. The above differences having been identified, and accepted as legitimate by the Owners and the designers, inexplicably there was no alteration made to the vessels lines to accommodate the added weight nor to maintain the desired GM_T.

At delivery, the two Type 500 SAR Cutters, christened CCGS "Gordon Reid" and CCGS "John Jacobson", had the following characteristics:

Lightship Weight	-	776	Tonnes
Full Load Displacement	-	985	Tonnes
Full Load draft	-	5.00	Metres
GM in Full Load Condition	-	0.96	Metres

The reasonable GM value above was achieved only through the use of a double bottom fuel oil tank as a permanent fuel storage tank, whereas its original function was as a designated reserve fuel tank for extended missions beyond the originally specified range. Without using this tank, most operating conditions would not meet all regulatory conditions.

Some of the more significant changes to the design which occurred during the construction process to account for the substantial weight growth were the following:

- constructing the wheelhouse with fully enclosed bridge wings, instead of the open wings originally demanded by the Owner.

- constructing the entire upper funnel casings in steel instead of aluminum.
- reconfiguring the engine room air intakes to an elevated steel plenum, necessitating the further elevation of the ship's boat and its launching davit.
- changing the fire suppression systems in machinery spaces from Halon 1301 to CO_2.

2.4 Operational Characteristics

In spite of the additional weight, and the erosion of stability characteristics from those defined at the design stage, the vessels satisfied all the provisions of the Canadian Coast Guard (CCG) Statement of Operational Requirements. Their construction was in full compliance with the applicable CCG Ship Safety Regulations as well as the requirements of the American Bureau of Shipping.

During the construction phase it became necessary to make several design modifications to satisfy revised regulatory and operational requirements and these had the effect of increasing the weight of the vessels over their designed lightship weight, as discussed in Section 2.3.

Subsequent to the completion and delivery of the vessels to the Canadian Coast Guard and upon being deployed on full Search and Rescue duty, violent rolling with large heel angles at certain ship speeds and sea states was reported. The crew reported roll single amplitudes of up to 40-45 degrees in severe weather, particularly in following seas. The resulting crew discomfort and fatigue significantly impaired the ability of the crew to perform their duties during SAR missions. Obviously, it was necessary to effect corrective measures at the earliest opportunity.

2.5 Evaluation and Testing of Performance

In order to effect any remedial measures, it was essential to have an accurate assessment of the ships' behaviour in the "as built" condition to serve as baseline for evaluation of the proposed improvements. The ships' designer, Robert Allan Ltd. (RAL) and its consultant, Offshore Research Ltd. (ORL) were commissioned by the Canadian Coast Guard to conduct dedicated sea trials to measure the capability of the vessel to perform all SAR operational requirements and, at the same time, to assess the seakeeping performance of the vessel in the most severe design sea state. Measurements of roll angle and roll frequency were to be recorded during these trials.

As a result of these trials, several significant problems were identified:

- Extreme roll characteristics were displayed when operating in following seas at speeds in excess of 12 knots.

- The Flume® tank appeared to be enhancing roll in the above conditions.

- The autopilot appeared to be causing rudder induced roll in following seas.

The roll motion was severe in amplitude, but the ships did not display any lack of righting moment.

Subsequently, evaluations were performed to determine the effects on vessel stability and trim of a large number of weight reduction items, some involving "major surgery" to the vessels, and others being rather more modest in scope. Preliminary cost estimates were made for each of the options studied, and an attempt was made to establish a basis of cost-effectiveness for the implementation of each option.

Also evaluated were the possible beneficial effects of bilge keels, a bulbous bow, bilge "chines" to improve roll-damping and add buoyancy, and of tankage and ballast re-distribution. The adverse seakeeping capabilities experienced and observed during this trial as well as recommendations for corrective actions noted hereafter were included in the consultant's (ORL) report, Ref. [2].

2.6 Recommended Corrective Actions

An evaluation of the problems identified by the previously described "diagnostic" test program permitted the development of potential solutions. The following recommendations were proposed to CCG as a means by which the Type 500 Cutters could be made to fulfill their operational mandate. The principal recommendations arising from [2] were:

- Improve the righting lever characteristics of the ship by increasing GM and reducing and/or redistributing weight.

- Reduce any unnecessary top hamper to reduce wind-heel effects.

- Tuning the Flume® system to better suit the new weight and GM characteristics of the ship.

- Fit a "fast-fill" system to the Flume® tank to complement the existing "dump" system, so that the tank could be filled or dumped to better suit the operating conditions.

- Fit a rudder roll stabilization system.

- Fit roll damping appendages (e.g. binge keels) to the hull.

With the exception of certain weight reduction items and the addition of roll damping appendages, the Canadian Coast Guard has implemented all the corrective measures. The roll damping appendages in the form of bilge keels will be added at the earliest opportunity.

3. APPROACHES TO ROLL DAMPING

Vessel roll motions can be addressed in a number of ways. Some of these are inherent in the basic design characteristics of the vessel (GM_T, roll moment of inertia, etc.). Some are inherent in the form of the hull (round bilge vs. chine form, keel projection, bilge keels, etc.). Others are 'systems', either active or passive, which react to and hopefully counteract the vessels' roll motions.

As previously noted, the design of the Type 500 Cutters incorporated some of these measures, primarily a Flume® roll stabilization system. The combination of a hull form with inherent low roll damping and the passive roll stabilization tank was clearly not effective in following seas, and it was perceived that the Flume® tank was amplifying roll at long periods of encounter which were beyond the design period of the tank.

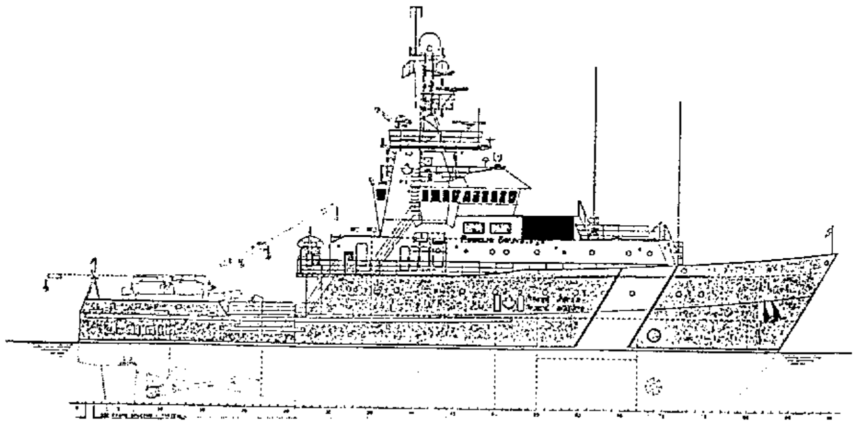
3.1 Flume® Stabilization System

The Flume® Stabilization System is a passive free surface type anti-roll or stabilizer tank. It is passive in that the movement of water in the tank is caused by the roll motion of the ship, there are no pumps or control devices. The term free surface is used to denote an open tank or channel and distinguish this type of tank stabilizer from others, such as U-tubes. The main advantage of a free surface type tank is that its response period can be changed by changing the amount of liquid in the tank.

When the ship rolls, the stabilizing tank is configured so that when filled with the proper amount of liquid, the movement of the liquid will be delayed behind the roll of the ship. It is this delay, called phase lag, that creates the stabilizing force to reduce the roll of the ship.

Since there are no moving parts in the Flume® tank, the amount of liquid in the tank is the one variable that affects the correct phase lag. The phase lag for any liquid level will change as the resonant roll period of the ship changes. The system performs at peak efficiency only when the correct phase lag is maintained. Therefore, if the natural roll period changes, the liquid level must change.

The Flume® System for the Type 500 SAR ships consists of a tank located above the bridge deck forward of the wheelhouse between Frames 53 and 59 (see Figure 3). As originally built, the tank was filled to the recommended level with fresh water through P/S hose connections. Liquid level readings are taken at a sounding tube located near the centerline, or by means of a liquid level monitor installed in the wheelhouse. Dump lines (P/S) are



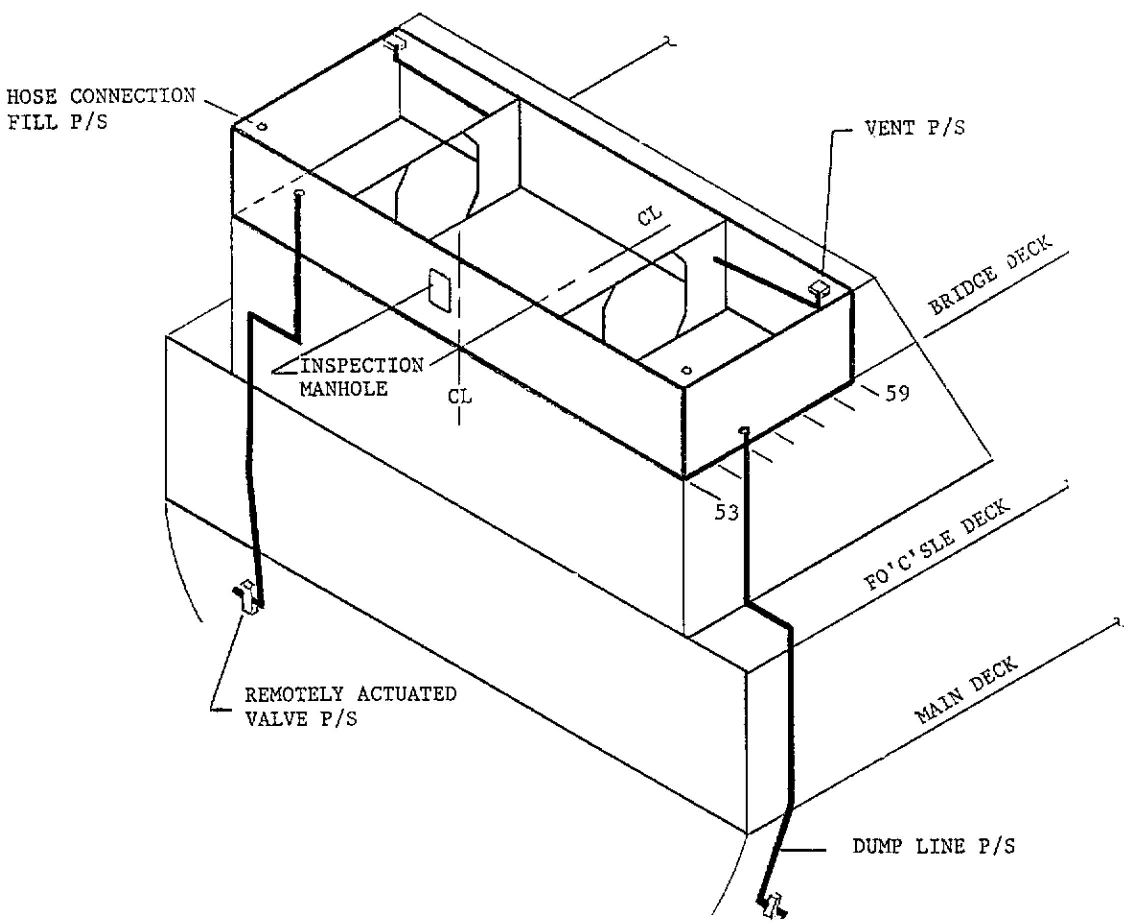


Figure 3. Flume® Tank and Piping Arrangement

installed for rapid discharge of water from the tank.

The system was designed for a specific range of loading conditions, up to 1400 tonne metres (displacement x GM). The Flume® tank design GM range was from 1.0 to 1.75 metres which corresponds to roll periods from 6 to 9 seconds and it was optimized for a range of GM's between 1.0 and 1.3 metres (roll periods between 7 and 8 seconds). The optimum tank design water level was 0.64 metres of fresh water. The current operating conditions have GM's below 1 metre; the roll periods are between 9 and 10 seconds. The longer roll period calls for a lower Flume® tank liquid level which is not possible with the installed tank design.

3.2 Hyde Rudder Roll Stabilization System

The Hyde Rudder Roll Stabilization System (Hyde RRS System) is a microcomputer based electronic control system for a ship's rudder(s). Its objective is to move the rudder in such a way that the ship's roll motions are reduced without adversely affecting the ship's course. The system includes an advanced adaptive autopilot for the purpose of accurately maintaining the vessel's course. Together, the Hyde autopilot and the Hyde RRS system work to both reduce roll and keep the vessel on course.

On most ships, movement of the rudder does not immediately affect the heading. On nearly all ships, however, movement of the rudder causes the vessel to heel or roll in the direction that the rudder was moved. In fact, a vessel can often be induced to roll by frequently moving the rudder from side to side while the ship is underway. Together, these effects can be used to reduce roll and at the same time maintain a desired course. Hyde RRS does this by precisely timing rudder commands so that the rudder moves in a manner to oppose the roll motions that are sensed by its roll sensor. The vessel is kept on course by adjusting and maintaining appropriate average rudder angles.

A more complete technical description of the system on which the Hyde RRS is based may be found in Ref. [3]. Figure 4 shows the Control Panel of the Hyde RRS System.

3.3 Weight Reduction and Redistribution

In order to increase freeboard and lower the VCG, corrective actions were recommended to reduce and redistribute weight, specifically for items located in the upper areas of the ship's structure. Such improvements both increase GM and decrease the roll period.

A number of items were identified for removal and these were categorized into three groups, namely:

- Items readily removed by crew at minimum cost

- Items which required structural modification but did not affect ship operations

- Items requiring redesign and significant cost to effect

All items and the consequence of removal or relocation were examined and the most beneficial items identified. From this activity it was estimated that a lightship weight reduction of approximately 6.1 tonnes could be accomplished.

The result of this reduction would be to increase the vessel's GM by an average of 80mm for all conditions of loading.

Computer modelling indicated that the weight reduction of 6.1 tonnes would result in an estimated roll reduction of 4% of that measured during the sea trials.

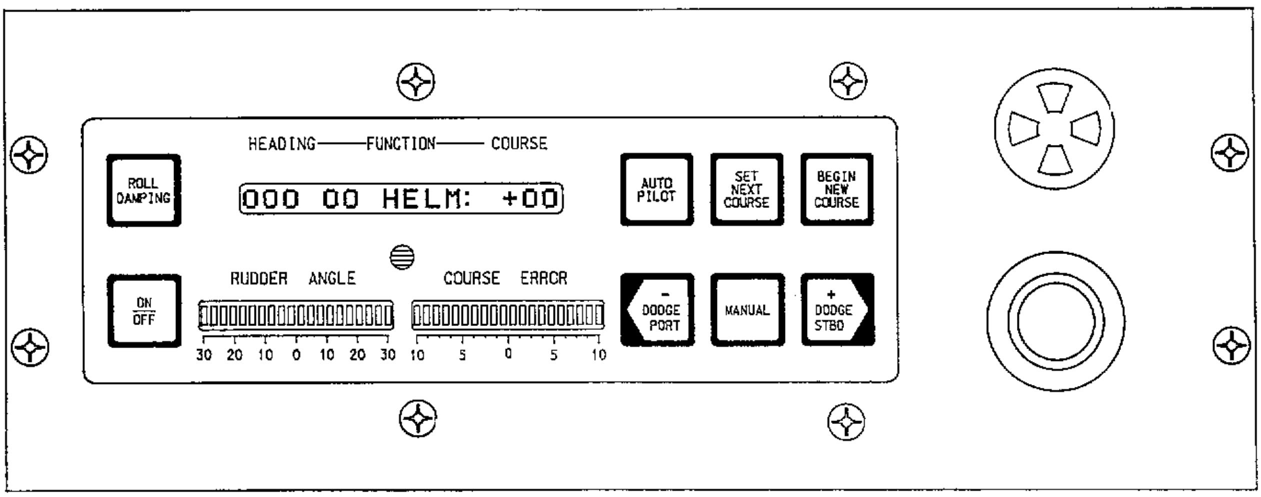


Figure 4. Hyde RRS Control Panel

3.4 Bilge Keel Evaluation

In the initial evaluation phase it was not considered that bilge keels would be particularly effective in reducing roll angles in those conditions which were proving problematic. However, in order to assess thoroughly the potential benefit of such fixed appendages, a number of bilge keel options were evaluated and tested at model scale. The options evaluated included:

- Single plate vs. double skin construction

- High aspect vs. low aspect ratios

Two alternative representative designs were tested. Somewhat surprisingly, the results indicated that roll amplitudes could be reduced by as much as 30 percent in quartering seas at 13 knots.

Roll reduction was somewhat less at higher speeds, but still substantial.

As a consequence of this study, which emphasized the significant potential benefit of bilge keels, the fitting of these was raised in the order of priority. The recommended configuration was for a double plate structure, approximately 16 metres long and 0.75 metres deep.

4. SYSTEMS IMPLEMENTED

4.1 Flume® Stabilization System

In service trials of the Flume® Stabilization System on board CCGS "Gordon Reid" were conducted in March 1992. At that time, the ships' trim and stability book limited the maximum level of fresh water in the tank to 0.40m. Although emergency valves allowed dumping of the tank to the sea, there was no practical method of adding fresh water to the tank at sea.

Rolling trials were conducted in Queen Charlotte Straits on March 19, 1992. The ship had a GM of 0.84m which corresponds to a 9.25 second roll period. Low wave conditions were encountered during the trials with swells of 1 metre during the tests.

All tests were conducted with the Flume® tank filled to a 0.40 metre liquid level with fresh water. Tests were conducted in following and beam seas. Noticeable rolling occurred in the following seas while the ship was solely under control of the existing autopilot. Rolling was observed to be correlated with rudder motions (in the order of 5 to 10 degrees double amplitude).

The Type 500 Cutters have two rudders and their observed rolling in following seas is considered to be partly due to rudder induced rolling. The coupling between rudder angle and roll in following and quartering seas is well known, particularly when the ship has relatively low stability, see Ref. [4]. This is termed a "cyclic static phenomenon" since there is no magnification factor involved. The period of encounter is relatively long in comparison to the resonant roll period of the ship. The Flume® tank has a small effect on roll in this case. Roll moments due to rudder forces are proportional to the square of the water velocity over the rudder and directly proportional to rudder angle and area.

Figure 5 compares trial results in following seas at 13.4 knots and 6 knots. Roll double amplitude peak angles are sorted in descending order of magnitude and plotted versus cumulative cycles (see Section 5.1 for further discussion of the analysis). The observed roll periods in both tests were similar and ranged from 10 to 16 seconds. The ship was operating with the EMRI autopilot; two rudders were active during the tests. Comparison of significant roll double amplitude indicated that the 7.8 knot reduction in

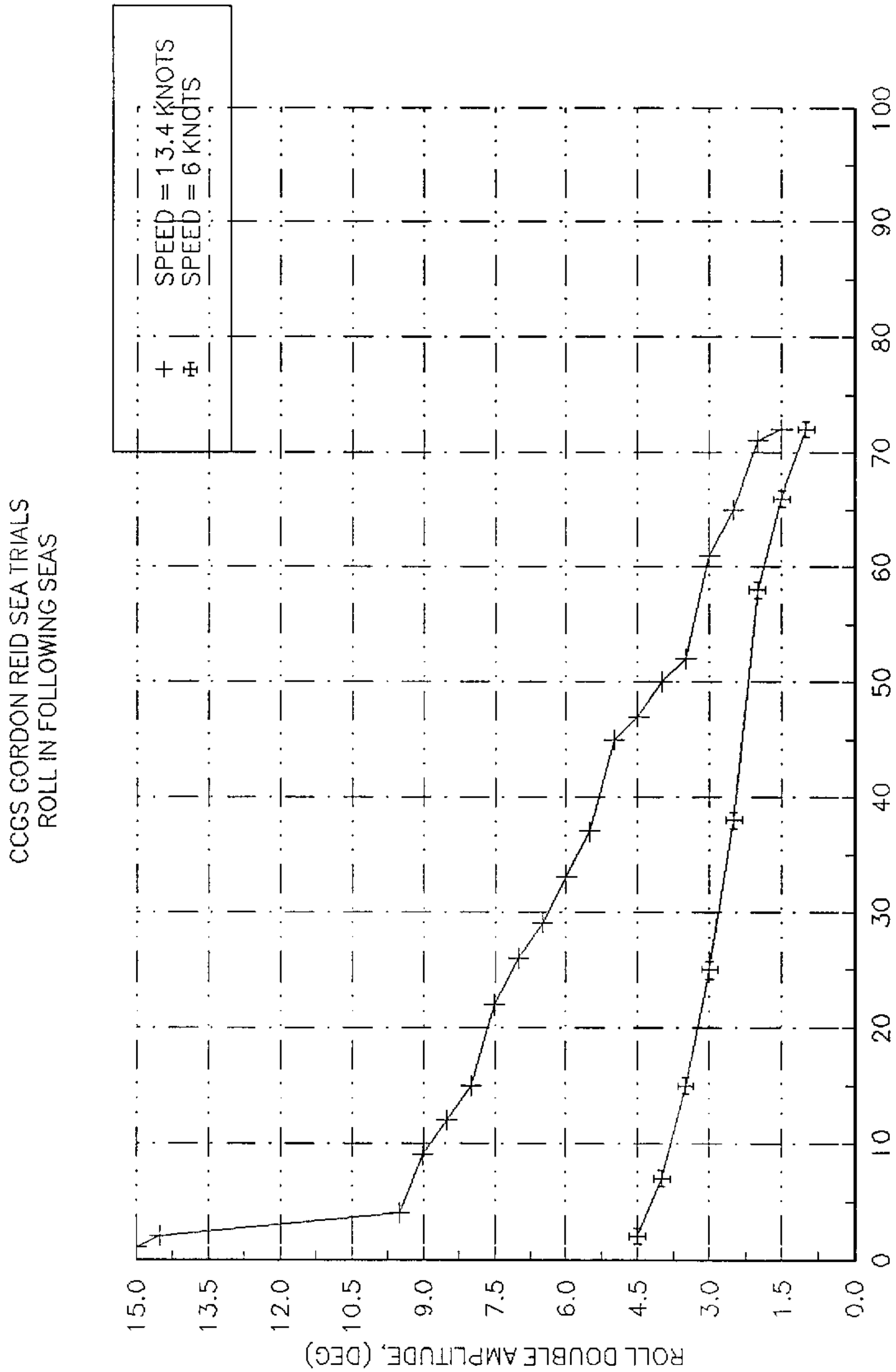


Figure 5. Roll in Following Seas (0.4m fresh water in tank)

speed (55%) resulted in a 60% reduction in roll.

It is well known that roll damping is reduced when speed is reduced and tests for roll due to waves show increased roll when speed is reduced. Ship speed also affects the period of wave encounter and in following and stern quartering seas the encounter wave period is longer than the actual wave period. For example, at 13.4 knots in following seas a 9 second wave period in encountered as a 17.65 second wave while at 6 knots it is encountered with an 11 second period. This effect moves wave encounter periods away from roll resonance as speed is increased over 6 knots and therefore leads to higher wave induced roll at lower speeds. Accordingly, these results indicate that roll-yaw coupling fed back through the autopilot was contributing to the observed roll.

4.2 Stabilizer Tank Piping Modifications

The original design intent was that the Type 500 Cutters would operate with the Flume® stabilization tanks at their optimum operating level of approximately 0.5 metre in all conditions and at all headings. This proved impossible for the reasons enumerated and it was recommended to the Owners that the use of the Flume® tank be limited to those conditions where it would be beneficial. In other circumstances, such as prolonged heading into weather or in following seas, the tank could be "dumped" and the subsequently "stiffer" ship would perform better in those attitudes where roll reduction was not necessary (head seas) or where roll reduction was better addressed by alternate means (following seas). In order to accomplish this capability, a 'fast-fill' piping system complete with level monitoring devices was installed. This enabled the stabilizer tank to be filled from the ship's fire main system.

4.3 Hyde RRS System

A Hyde RRS System (HRRSS) was installed on the CCGS "Gordon Reid", first as a rental for evaluation only in October 1992, and later as a permanent installation in February 1993. Installation of a second system on the CCGS "John Jacobson" followed in April 1993.

The evaluation trials, done aboard the CCGS "Gordon Reid" in October 1992, involved thorough performance testing of the RRSS algorithm. Tuning of the autopilot was not of concern in these tests and thus peak performance from the autopilot was not sought. It was later revealed that autopilot performance, particularly adaptive gain adjustment, has a substantial impact on the RRSS performance of the system. Fortunately, the RRSS algorithm showed substantial roll damping capability in the service for which the system was targeted; namely, duty in heavy stern quartering seas where roll periods can become elongated to more than 13 seconds.

Due to the success of the initial trials with the RRSS, CCG decided to install these systems permanently on both ships. It was decided that the most economical, and least disruptive, approach for this installation would be to interface the Hyde RRS System to the EMRI steering system as simply another source of rudder command signals.

The permanent installation on the CCGS "Gordon Reid" incorporated the Hyde RRS into the central steering console as one of the helm control sources selectable by a button. In this configuration, control can be switched away from either autopilot (EMRI or Hyde) at any time by pressing a button near the helm lever at the central console or either bridge wing console. The Hyde RRS computer and roll sensor are mounted in the 'tween decks equipment space immediately beneath the ship's bridge.

Installation on the CCGS "John Jacobson" proceeded in a similar fashion with system tuning and commissioning sea trials immediately following the installation. Installation was arranged to coincide with a normally scheduled crew change at the Canadian Coast Guard Station in Victoria, B.C. Calm water tuning and adjustments for each ship were completed in the sheltered waters near Esquimalt Harbor. On both occasions, sea conditions suitable to stimulate lively ship motions were readily available after only a short run up the west coast of Vancouver Island.

5. RESULTS FROM SEA TRIALS

5.1 Original Performance of Flume® System

The Flume® system was originally tested during the first set of sea trials of the CCGS "John Jacobson" in November 1990 as the vessel entered the Strait of Juan de Fuca. The predominant wave at the test location was a swell of about 1.5 metres height, 46 metres length, and approximately 5.5 seconds period entering the strait. There were also some wind waves from the opposite direction which were short and choppy, containing little energy.

The stabilization tests were conducted on a heading of 190 degrees, crossing the strait with the swell on the starboard beam. The speed was 16 knots. The first test conducted was with the tank empty (unstabilized). For the second test, the tank was filled to a level between 0.4 - 0.5m and the tests were repeated on the same course. The duration of each test was 15 minutes, long enough to obtain a reliable statistical sample.

During both tests the roll motions of the ship were measured with a gyroscope and recorded on a pen recorder. A roll period of about 9 to 10 seconds was obtained from the data without the Flume® tank which corresponds to a GM of 0.80m. Analysis of the test results are shown in Figure 6. Analysis of the tests included reading peak to peak roll angles from the charts and sorting them

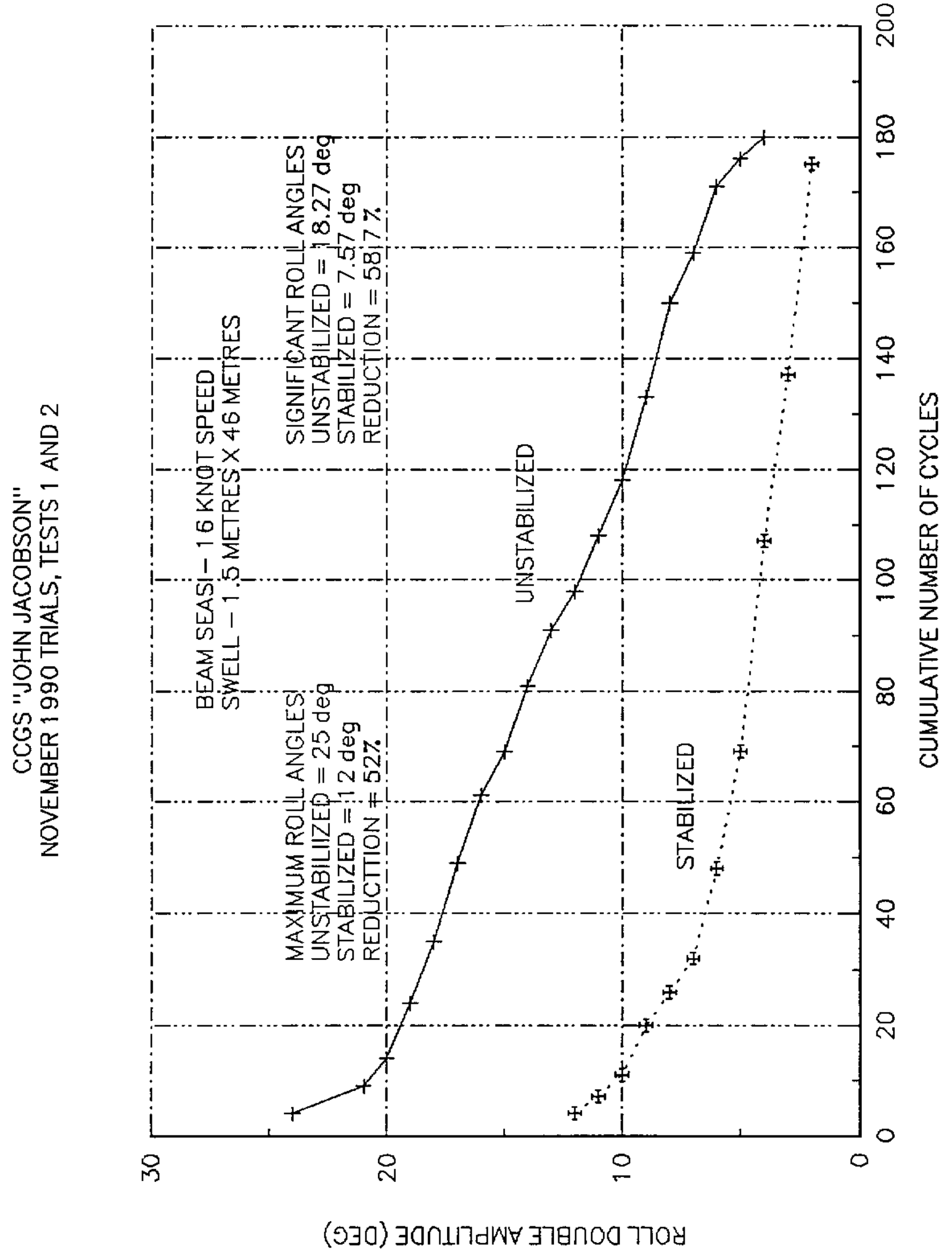


Figure 6. Test of Flume® Tank Roll Reduction

in descending order of magnitude. Approximately 180 points were obtained from each test. The maximum value and the average value of the one-third highest rolls (defined as the significant roll angle) were obtained from the data for the two runs.

Figure 6 shows roll double amplitude versus cumulative number of occurrences for tests with and without stabilization. For example, roll greater than or equal to 12 degrees peak to peak occurred 90 times when the Flume® tank was empty and only 4 times when it was operational. Over 50% roll reduction was achieved, which met the design objectives despite the lower stability and longer roll period.

5.2 Description of Sea Trial Procedure

In April 1993, instrumentation was installed on the bridge of the CCGS "John Jacobson" to monitor lateral acceleration, rudder and roll angle. The data was recorded on magnetic tape and printed as a time series trace during the trials.

After the Hyde RRS system was installed on the vessel, calm water roll-up and roll decay trials were conducted at several speeds in the protected waters off Esquimalt Harbour to determine the optimum RRS control parameters. Commissioning trials were then conducted the next day in the vicinity of the La Pérouse wave buoy located at 48° 50' north 126° 00' west off Barclay Sound. The trials area is shown in the chart -- West Coast, Vancouver Island, reproduced as Figure 7.

During the trials, the wind speed and wave height were obtained from the hourly marine weather forecast. At the completion of the trials, the statistical weather data and the wave spectra were obtained from the Marine Environmental Data Service (MEDS) in Ottawa. The wave spectra for the trials period is shown in Figure 8. From this it can be seen that the significant wave height was approximately 4m at a peak wave period of 11.1 to 13.5 seconds. These wave conditions correspond to the lower boundary of sea state 6 and are at the upper limit of specified ship service requirements described in Section 2.1 for maintaining speed and manoeuvrability.

5.3 Presentation of Data Obtained

Two series of trials were conducted in beam and stern quartering seas, at discrete speeds of 10, 13, and 16 knots. The first series with the stabilization tank filled with 0.38m of salt water, the second with it empty. For each series, the first set of data was acquired with the vessel controlled by the EMRI autopilot (EMRI). Control was then switched to the Hyde autopilot (H PILOT) and another set of data acquired after sufficient time had elapsed for it to be in its adaptive mode. Control was then switched to the Hyde RRSS (H RRSS) and a third set of data acquired. The

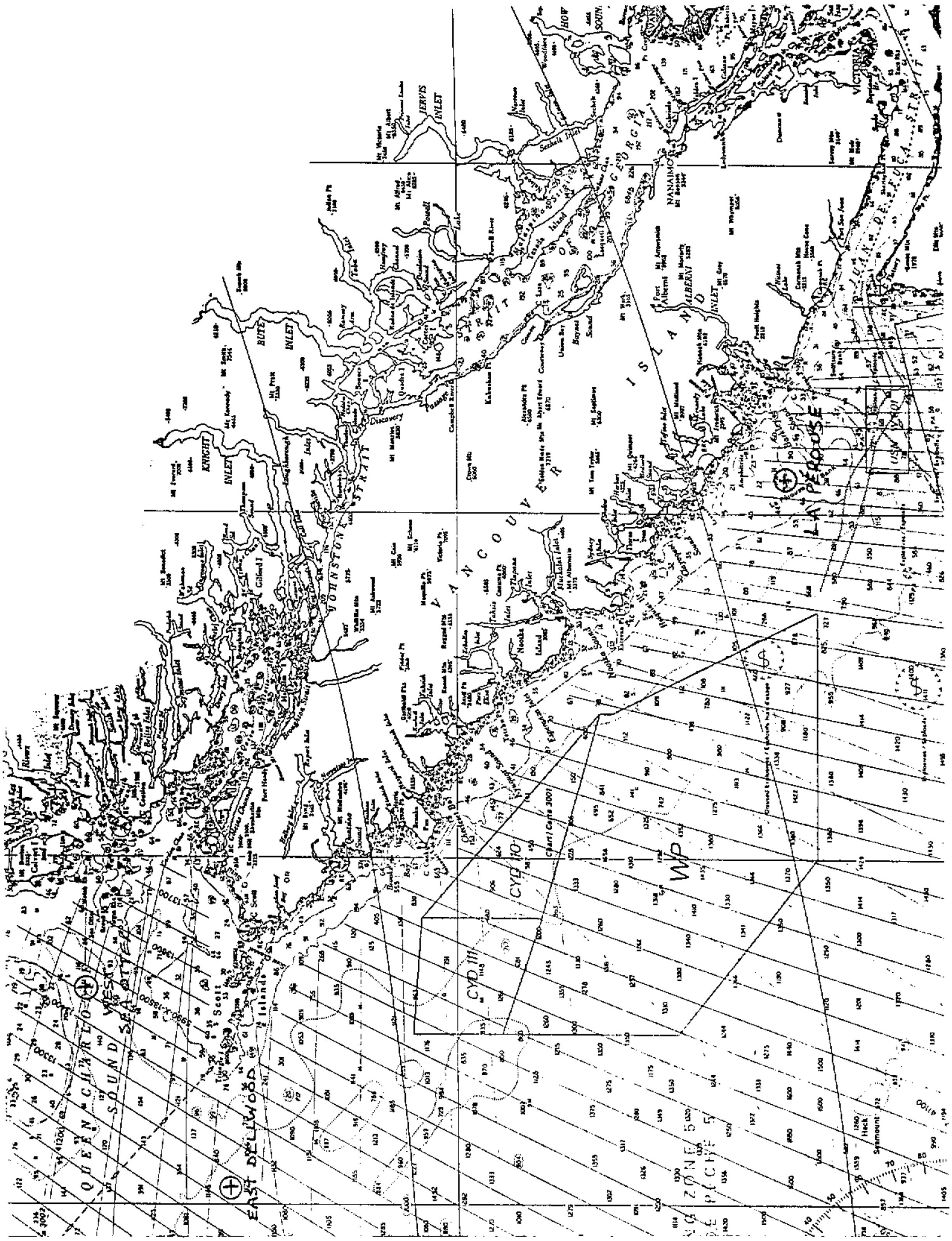


Figure 7. Chart of the West Coast of Vancouver Island

Station C46206 . La Perouse Bank

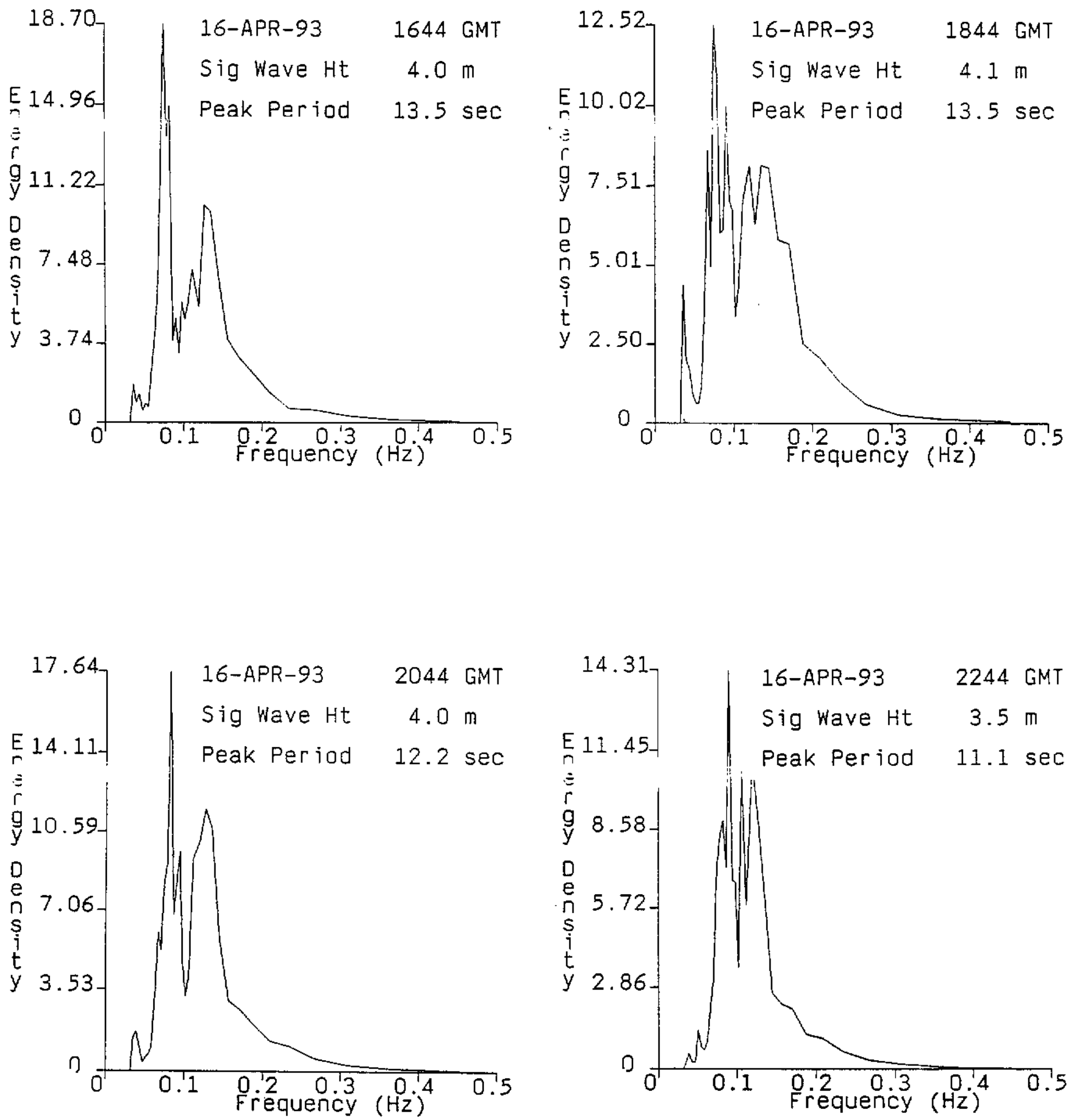


Figure 8. Wave Spectra at time of Trials

summary of results is presented in Table 1. Figure 9 shows the first 150 seconds of the time series data obtained during Runs 1, 2, and 3 when the Flume® tank was filled to 0.38m with sea water. Figure 10 shows Runs 29, 30, and 31 where the Flume® tank is empty.

From the time series data it can be seen that the adaptive autopilot (H PILOT) generally used less rudder angle than the non-adaptive autopilot (EMRI); this was to be expected, especially for longer roll periods. As a consequence, less roll and lateral acceleration was experienced. Although the H RRSS used more rudder than the EMRI or H PILOT, the roll angle and lateral acceleration were reduced. The time series data were analyzed to determine the average roll period, significant double amplitude roll angle, and the percentage roll reduction when controlled by the H RRSS compared to either the EMRI or H PILOT. These calculated results are summarized in Table 1. From this it can be seen that at all speeds, a substantial roll reduction was achieved with the H RRSS. The percentage roll reduction was calculated as:

$$\text{Reduction (\%)} = 1 - \frac{\text{significant roll with H RRSS}}{\text{significant roll without H RRSS}} \times 100$$

Note that the unstabilized roll, or "significant roll without H RRSS", acquired using the adaptive autopilot (H PILOT) is usually smaller than the unstabilized roll acquired using the non-adaptive autopilot and is thus likely to be more representative of the true unstabilized roll situation. This is reflected in the smaller percentage roll reduction values reported for the RRSS when the adaptive autopilot is used to acquire the unstabilized roll estimates.

5.4 Trial Conditions

Although it has been noted that the trials were conducted in beam and stern quartering seas, the trial data indicate that a more complex situation was encountered. Roll motion is quite sensitive to wave direction, especially when the ship is underway. Provided the encounter and natural roll frequencies are the same, unidirectional beam seas always produce the largest resonant rolling. It should be noted that resonant roll at this heading decreases when speed increases due to increased roll damping with speed.

Large amplitude roll can also occur in stern quartering seas for high speed ships, especially when coupled with low GM. As noted previously, the Type 500 Cutters were especially susceptible to this problem, which was also exacerbated by the relatively large rudders and their effect on ship motions. Rudder induced roll generally will not be a problem in bow and head seas since the period of encounter is short and autopilots don't respond to these higher frequency wave excitations.

Keeping this sensitivity of roll to wave heading in mind, the double peaks in the wave spectra measured during the trials (see

SEAKEEPING TRIALS WITH EMRI, HYDE AUTOPILOT & RRSS ON APRIL 16, 93.

RUN NO	HEADING DEGREES	WAVE DIRECTION	STEER PUMP	AUTO PILOT	FLUME TANK	SPEED KNOTS	SIG ROLL ANGLE	RRSS EMRI	% REDUCT	RRSS H PILOT	% REDUCT	ROLL PERIOD
					m							sec
1	316	SS QUAR	4	EMRI	0.38	13	25.6	0.67	33			9.5
2	316	SS QUAR	4	H PILOT	0.38	13	23.1			0.74	26	10.9
3	316	SS QUAR	4	H RRSS	0.38	13	17.1					9.6
4	30	S BEAM	4	EMRI	0.38	13	43.4	0.34	66			12.4
5	30	S BEAM	4	H PILOT	0.38	13	24.3			0.60	40	10.6
6	30	S BEAM	4	H RRSS	0.38	13	14.7					9.4
7	30	S BEAM	4	EMRI	0.38	10	30.1	0.53	47			10.7
8	30	S BEAM	4	H PILOT	0.38	10	16.6			0.97	3	8.6
9	30	S BEAM	4	H RRSS	0.38	10	16.1					8.9
10	275	PS QUAR	4	EMRI	0.38	10	20.1	0.54	46			9.5
11	275	PS QUAR	4	H PILOT	0.38	10	19.7			0.55	45	9.1
12	275	PS QUAR	4	H RRSS	0.38	10	10.9					8.2
13	275	PS QUAR	4	EMRI	0.38	13	27.5					10.3
16	275	PS QUAR	4	EMRI	0.38	13	24.5	0.56	44			9.1
17	275	PS QUAR	4	H PILOT	0.38	13	25.6			0.54	46	10.1
18	275	PS QUAR	4	H RRSS	0.38	13	13.7					9.5
20	275	PS QUAR	4	EMRI	0.38	16	33.4	0.63	37			11.2
21	275	PS QUAR	4	H PILOT	0.38	16	26.6			0.80	20	9.9
22	275	PS QUAR	4	H RRSS	0.38	16	21.2					9.9
23	50	S BEAM	4	EMRI	0.38	16	23.8	0.66	34			9.9
24	50	S BEAM	4	H PILOT	0.38	16	25.8			0.60	40	11.1
25	50	S BEAM	4	H RRSS	0.38	16	15.6					9.3
26	250	PS QUAR	4	EMRI	0	10	26.7	0.48	52			8.3
27	250	PS QUAR	4	H PILOT	0	10	19.7			0.65	35	8.9
28	250	PS QUAR	4	H RRSS	0	10	12.8					8.7
29	250	PS QUAR	4	EMRI	0	13	34.1	0.50	50			8.8
30	250	PS QUAR	4	H PILOT	0	13	25.3			0.67	33	8.6
31	250	PS QUAR	4	H RRSS	0	13	16.9					8.5
32	250	PS QUAR	4	EMRI	0	16	44.4	0.51	49			9.7
33	250	PS QUAR	4	H PILOT	0	16	29.8			0.76	24	9.1
34	250	PS QUAR	4	H RRSS	0	16	22.6					9.52
35	30	S BEAM	4	EMRI	0	16	32.3	0.67	33			9.04
36	30	S BEAM	4	H PILOT	0	16	RUN ABORTED					
37	30	S BEAM	4	H RRSS	0	16	21.7					8.9
38	30	S BEAM	4	EMRI	0	12	33.7	0.61	39			9.7
39	30	S BEAM	4	H PILOT	0	12	29.7			0.69	31	10.1
40	30	S BEAM	4	H RRSS	0	12	20.4					8.3
41	30	S BEAM	4	EMRI	0	10	21.5	0.94	6			8.6
42	30	S BEAM	4	H PILOT	0	10	21.1			0.96	4	9.2
43	30	S BEAM	4	H RRSS	0	10	20.2					9.3

Table 1. Table of Results from Trials

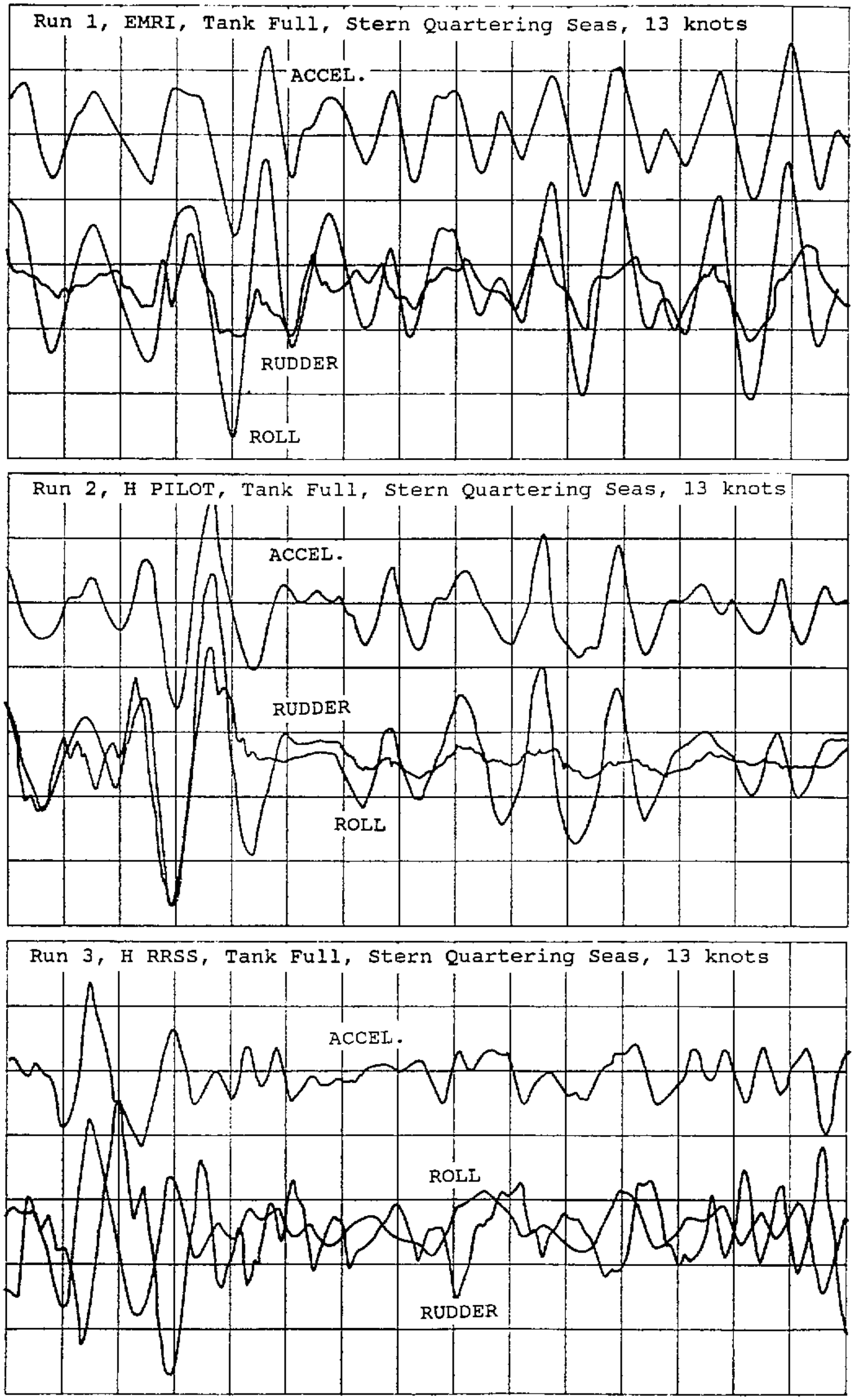


Figure 9. Time Series Data for Runs 1, 2, and 3

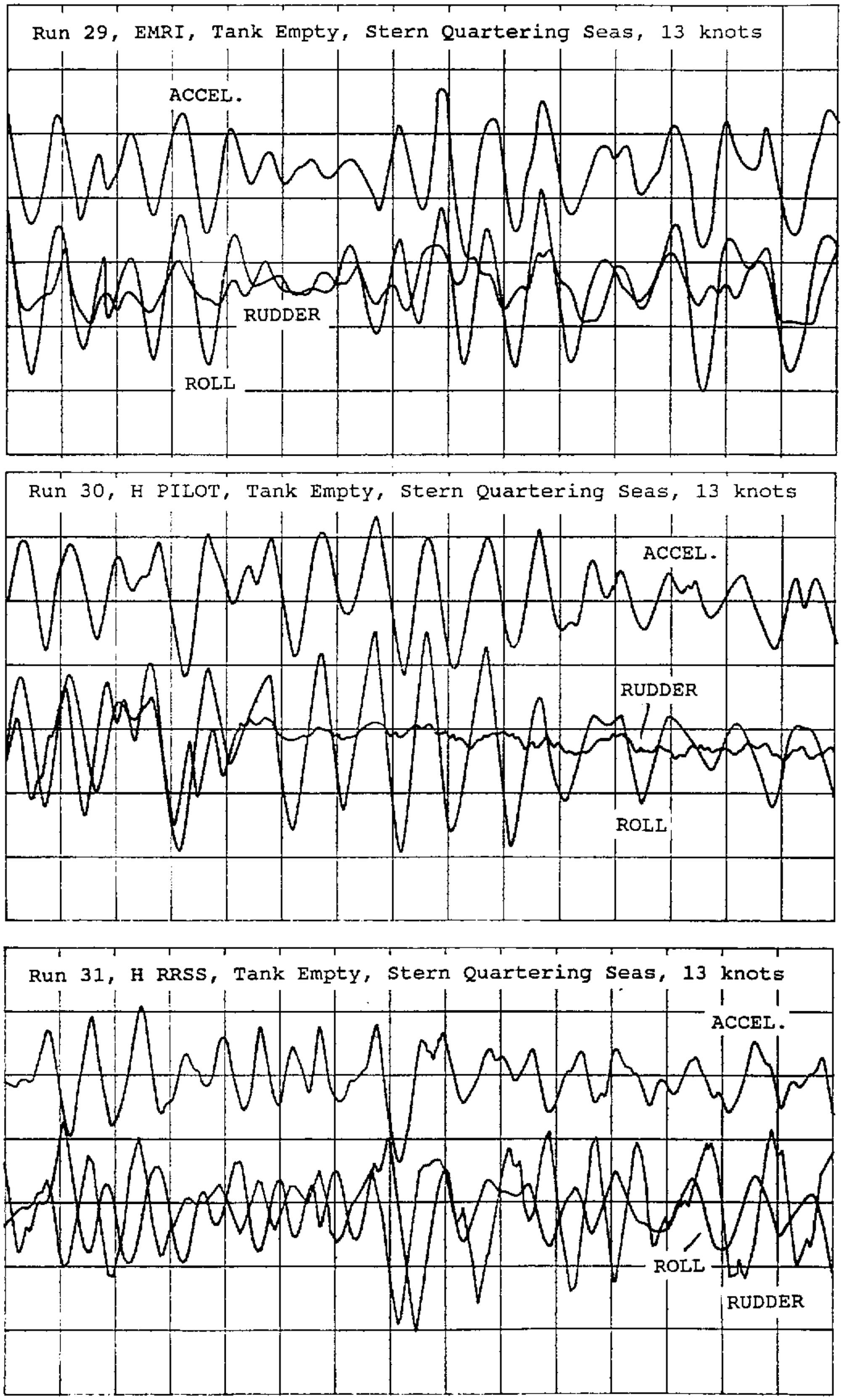


Figure 10. Time Series Data for Runs 29, 30, and 31

Figure 8) indicates that a combination of swell and wind waves coming from different directions was encountered. The 12 to 13 second spectral peak observed in Figure 8 is probably due to swell with the secondary 7 and 8 second spectral peak present being due to local wind waves. Visual observations of wave direction, included with the test data, tend to represent the wind waves since they are easier to see than swells.

Analysis of ship and wave direction data in Table 1 indicates that the observed true wave direction varied between 110° and 140° which follows the coast from the Strait of Juan de Fuca to the wave buoy at La Pérouse. Data for swells in the trials area indicate that they came from the southwest. Recorded wind speed and direction at the La Pérouse wave buoy show that the wind encountered by the ship came from directions between 117° to 130° which is similar to the encountered wave direction. The wind speed varied between 23 and 26 knots (12 to 13.5 m/s). Based on this information, Figure 11 shows probable wave encounter patterns for the trials.

Referring to Figure 11, trials in starboard beam seas encountered an additional longer period swell on the port stern quarter. Because of this, some rudder induced roll is likely in these trials, especially those with a non-adaptive autopilot active. The Runs affected include numbers 3 to 9, 23 to 25, and 34 to 43.

For trials in port stern quartering seas, swell is encountered as head to bow seas and will have a negligible effect on roll. The Runs conducted at this heading include numbers 10 to 22 and 26 to 34.

5.5 Expected System Performance

In order to assist in evaluation of trial results, the expected design and system performance of the EMRI autopilot, the Hyde autopilot, the Hyde Rudder Roll Stabilization system, and the Flume® Stabilization System are summarized in the following sections:

5.5.1 EMRI Autopilot

The EMRI main steering and autopilot system installed during construction is a 2 rudder, 4 pump control system. The autopilot is interfaced to the gyro compass and is not adaptive. During autopilot control, its rudder order is simultaneously transmitted to both rudders to ensure synchronization.

Operational experience with the system indicated that, due to its non-adaptive nature, relatively large rudder angles were ordered in following and stern quartering seas. As a result, rudder induced roll has been experienced. Initially, some of the observed difficulty in following and stern quartering seas was due to improper initial settings.

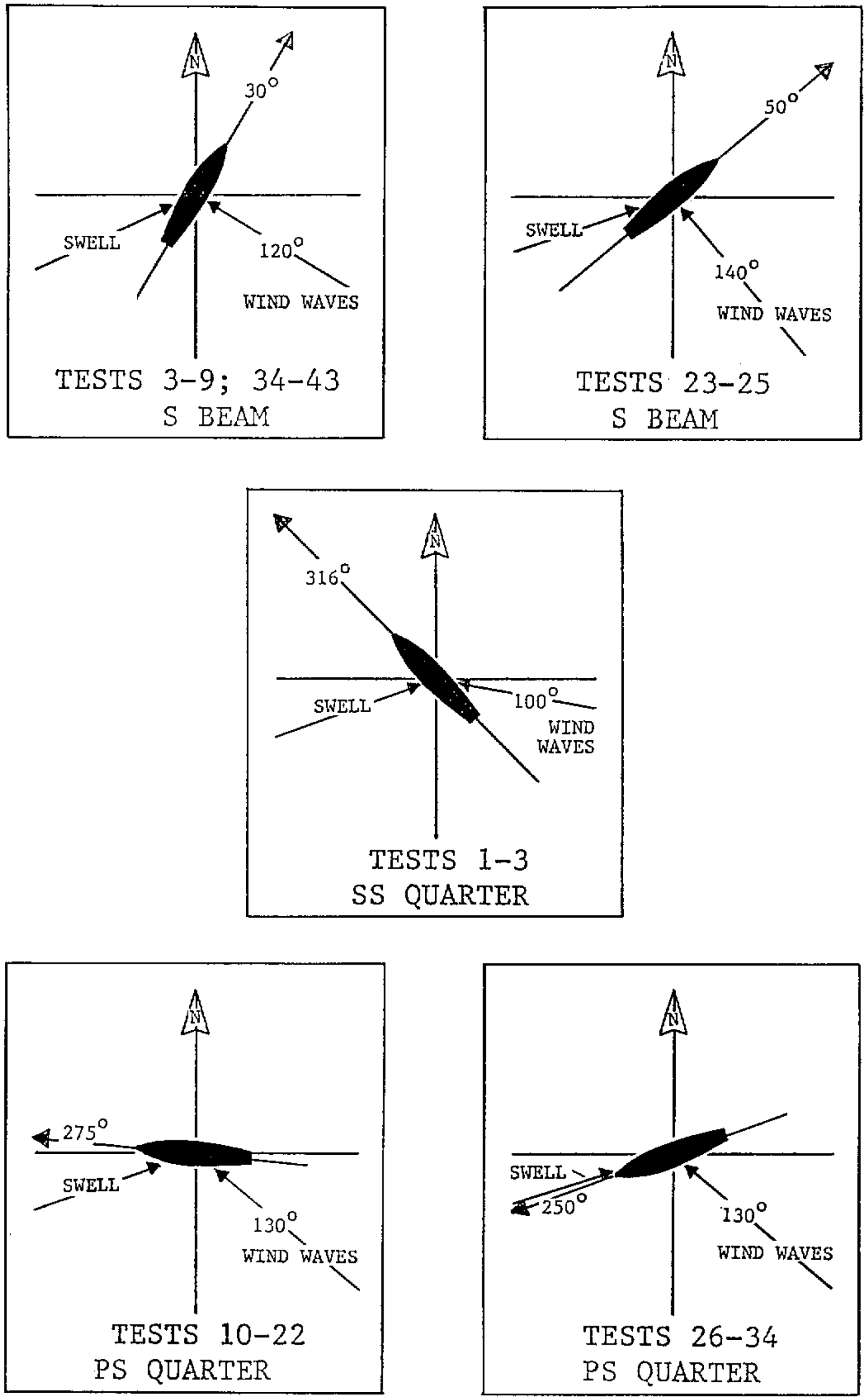


Figure 11. Wave Encounter Patterns for Trials

5.5.2 Hyde Autopilot

The Hyde autopilot is an adaptive autopilot which has a "learning" capability that allows a reduced rudder angle to be used to maintain heading in waves. Considering the large rudder area provided, only small rudder angles are required to maintain the course constant.

5.5.3 Hyde Rudder Roll Stabilization System (RRSS)

The Hyde RRSS senses the roll motion of the ship and generates a corrective signal for the rudder to counteract wave roll excitations without affecting course or speed. The center frequency of the roll sensing filter for the RRSS in these trials was 10 seconds. The system corrects for longer or shorter roll periods adaptively, but is optimized for roll periods centered about 10 seconds.

It should be noted that the RRSS stabilizing moment is proportional both to rudder angle and to the square of the ship speed. The RRSS control system has a ±20 degree rudder oscillation limit and is optimized for a 13 knot cruising speed.

5.5.4 Flume® Stabilization System

The operating principles of the Flume® Stabilization System are described in Section 3.1. At the 0.4 metre water level used during the trials, it is tuned to a ship resonant roll period of 9 seconds and has been demonstrated to reduce rolling by 50% in beam seas. When the ship rolls with a 11 second or higher period, such as occurs during rudder induced rolling in stern quartering seas, the tank water moves with the ship and does not provide a stabilizing moment. It acts as any other tank with a static free surface and increases the static heel angle. The free surface moment of the tank is 140 metre tons with a correction equal to about 18% of the GM, increasing the "static" heel angle by the same amount.

5.6 Observed Performance

Overall performance characteristics of the systems observed during the trials are discussed in the following sections:

5.6.1 EMRI Autopilot

Trial results in beam seas with the original, non-adaptive autopilot active show a definite correlation between rudder angle and roll angle. For example, examination of the time trace for Run 7 in Figure 12 (starboard beam seas at 10 knot speed) shows the rudder angle in phase with roll angle and thus contributing to the roll. As noted in Section 5.3, swell from the port stern quarter was present in addition to beam wind waves. This condition causes excessive rudder action.

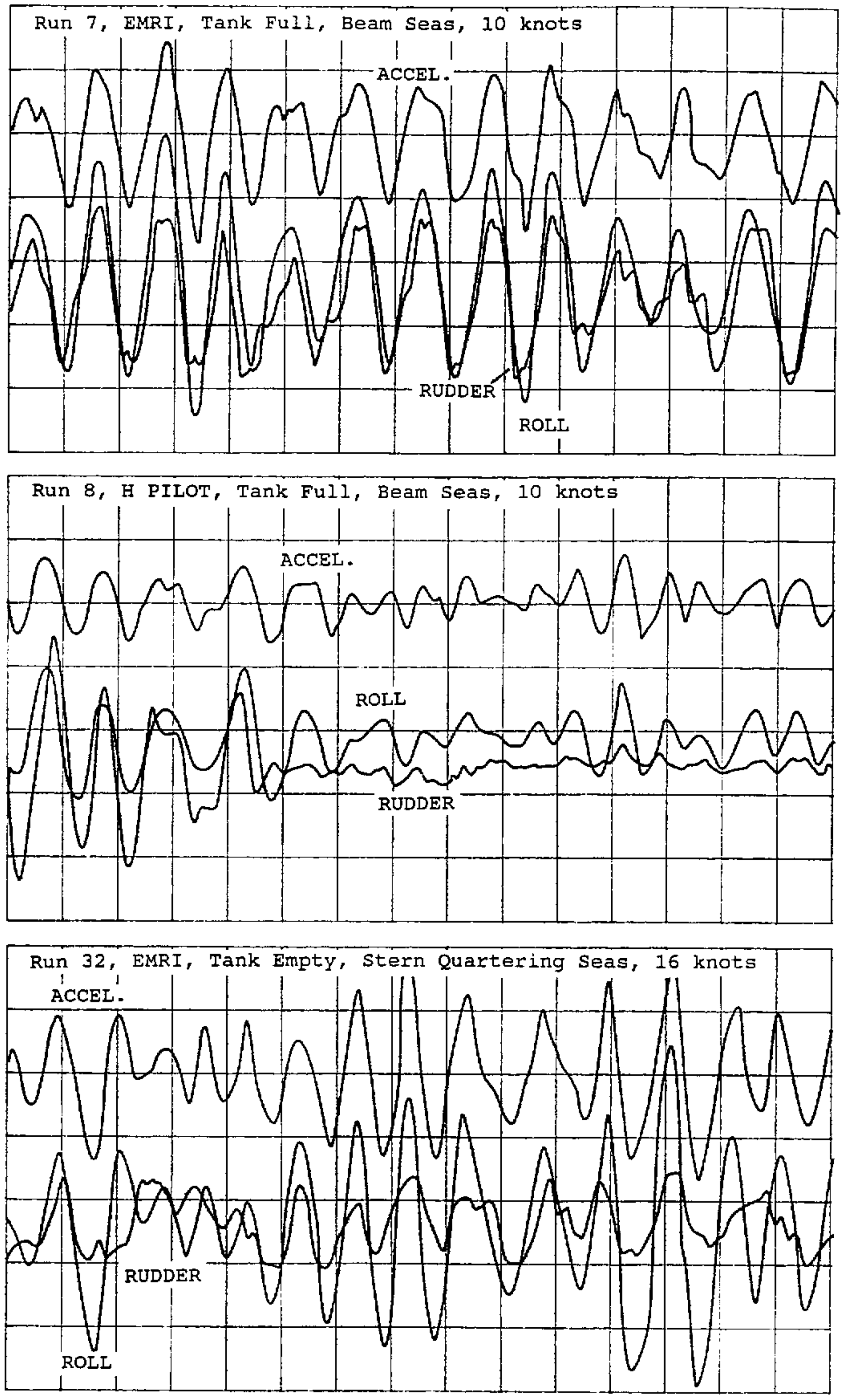


Figure 12. Time Series Data for Runs 7, 8, and 32

The largest roll angle measured during the trials, 44.4 degrees double amplitude, occurred in Run 32 at a speed of 16 knots in stern quartering seas using the non-adaptive autopilot. Again, the time traces in Figure 12 for Run 32 shows the rudder angle to be in phase with the roll angle.

5.6.2 Hyde Autopilot

Examination of time traces for runs in beam seas using the retrofitted adaptive autopilot shows a considerably reduced rudder activity compared to the original, non-adaptive autopilot. For example, comparing Run 8 in Figure 12 (Hyde autopilot in beam seas) with Run 7 in Figure 12 (EMRI autopilot in beam seas) shows much lower rudder and roll angles with the adaptive autopilot.

Many of the test sequences were such that runs with one autopilot were accomplished immediately after runs with the other. This close proximity means similar wave conditions were encountered and comparison of results can be used to estimate the amount of roll induced by roll-yaw coupling to the rudder via the autopilot.

For trials in starboard beam seas, comparison of Runs 4 and 5 at 13 knots, and Runs 7 and 8 at 10 knots indicate that rudder induced rolling accounts for 44 percent of the total. In addition, the roll period with the adaptive autopilot active is about 2 seconds shorter than roll period with the non-adaptive autopilot active. This clearly demonstrates that forced rolling at a period influenced by the steering gear characteristics has been occurring on these vessels.

5.6.3 Hyde Rudder Roll Stabilization System

It is considered appropriate to evaluate RRS performance based on comparisons with the Hyde autopilot since this data is more representative of the natural roll of the ship. Considering results in stern quartering seas at 13 knots, the speed for which the RRS System was tuned, roll reductions of 40 to 46 percent were achieved in tests with the Flume® tank operational. Roll reductions of approximately 30 percent were achieved in tests with the Flume® tank empty under the same conditions.

5.6.4 Flume® Stabilization System

The trials program was conducted with the Flume® tank filled to a 0.38 metre level at the start of the trials. Runs number 1 through 25 at various speeds, headings, and system configurations were accomplished and the tank was then emptied. Runs 26 through 43 were similar runs with the tank empty. This trial procedure means that comparable runs with the Flume® tank filled and empty took place with a considerable time delay between them. It is noted from Figure 8 that the waves may have been lower at the end of the test which would act to reduce the apparent roll reduction due to the Flume® stabilization system.

Two of the nine pairs of runs operating with the non-adaptive autopilot showed higher roll with the Flume® filled to 0.38m in comparison to runs with an empty tank (run pairs 7 and 31 at 10 knots and run pairs 4 and 38 at 13 knots). Refering to Figure 11, the vessel was encountering wind waves on the starboard beam and swell on the port stern quarter. Examination of the chart records for these runs shows that rudder motion was in phase with roll.

The observed roll periods for runs with water in the tank were 12.4 seconds for run 4 and 10.7 for run 7. Lower roll periods were observed when the tank was empty, 9.7 seconds for run 38 and 8.6 seconds for run 41. As noted in Section 5.5.4, when the ship rolls with an 11 second or longer period the Flume® tank acts as any other tank with a static free surface. It has a free surface correction to the GM of 18 percent which can increase the resonant roll period from 9 seconds to 10 seconds. This moves the roll resonant period closer to the forcing period of the steering system and can contribute to the higher roll observed. In addition, since the GM is less than design, static heel angles will also increase in proportion to the reduction in GM.

Considering tests in beam seas with the Hyde RRSS active, roll with the Flume® tank filled to 0.38 metres was approximately 20 percent lower than comparable tests with the tank empty contributing to an overall roll reduction of 60 percent in one instance. As noted previously, the tank is not effective for forced roll at periods at or above 11 seconds and will do little to reduce such rudder induced roll when the EMRI autopilot is active.

6. CONCLUSIONS AND FUTURE PLANS

The Type 500 SAR Cutters failed to perform to expectation when placed into service in 1990/1991. The fundamental problem was one of extreme rolling motions which occurred in following seas. Contributing to this problem were the following:

- Excessive weight built into the ship
- Reduced GM below design objectives, and below that for which the Flume® stabilizing system had been designed
- Rudder induced rolling (roll-yaw coupling through the autopilot)

An extensive program of full scale testing and analysis was conducted on behalf of the Canadian Coast Guard, which indicated that the desired performance characteristics of these new ships could be regained through a combination of corrective measures which would: (1) reduce weight, (2) increase stability, and (3) eliminate rudder induced rolling.

Trial results show that the adaptive gain Hyde autopilot has reduced rudder induced rolling; that is, rolling caused by the effect of waves on vessel yaw motions coupled through the autopilot to the rudder. Compared to use of the non-adaptive autopilot, roll reductions of 20 to 40 percent in beam and stern quartering seas were observed.

Operation of the Hyde Rudder Roll Stabilization System under similar conditions reduced roll by 30 percent compared to use of the adaptive autopilot only with the Flume® tank empty. With the Flume® tank at 0.38m, the Hyde RRS System reduced roll by as much as 46 percent under the same conditions. Thus, the Flume® and Hyde systems are shown to operate cooperatively in their roll reduction effects. Note that the roll periods observed during the combined runs ranged from 8.2 to 9.9 seconds. At longer roll periods their combined effects have been observed to diverge.

Referring to the ship service requirements outlined in Section 2.1, it is apparent that the corrective measures evaluated have made substantial progress toward the design objectives. It is expected that the combination of corrective measures including installation of the Hyde Rudder Roll Stabilization System, Flume® System modification, weight reduction, and the addition of bilge keels will significantly improve the seakeeping characteristics of the vessel. This result will provide a sea-kindly platform to allow the crew of these vessels to perform their duties during SAR missions in the worst design sea state without undue discomfort or fatigue.

The Canadian Coast Guard will continue to implement all the recommended corrective actions when vessel mission priorities permit.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the collaborative efforts of Offshore Research Ltd., Vancouver, B.C. Canada, which conducted the April 1993 trials and provided the analyzed data.

8. REFERENCES

[1] Robert G. Allan, P.Eng. "Concept Design Studies for the Canadian Coast Guard 'Type 500' Search and Rescue Cutter", presented to the Society of Naval Architects and Marine Engineers, Pacific Northwest Section, September 1989.

[2] "Type 500 Instrumented Seakeeping Trials", prepared by Offshore Research Ltd., Vancouver, B.C., Canada, April 1992.

[3] C. G. Källström, W. L. Schultz, "An Integrated Rudder Control System for Roll Damping and Course Maintenance", 9th Ship Control Systems Symposium, Bathesda, Maryland, U.S.A., 1990, Proceedings Vol 3, pp 278-296.

[4] R. Taggart, "Anomalous Behaviour of Merchant Ship Steering Systems", Marine Technology, Vol 7, No. 2, April 1970.