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Interim Report to the Office of Naval Research: "Comparison of SWATH and Monohull Vessel Motion for Regional Class Research Vessels"

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I. Objective

The attitude characteristics of a monohull and SWATH vessels are being compared using measurements of their motion. This is being done with two "Regional" vessels based in Moss Landing, California, the *R/V Pt. Sur* and the *R/V Western Flyer*.

II. Vessels

The two vessels are shown in figure 1. The *R/V Western Flyer* is a SWATH vessel which is owned and operated by the Monterey Bay Aquarium Research Institute and *R/V Point Sur* is a monohull vessel owned by the National Science Foundation and operated by Moss Landing Research Laboratories. The *R/V Western Flyer* is principally used with a remotely operated vehicle (ROV) although science and engineering cruises are carried out on occasion which do not require the use of a ROV. The *R/V Point Sur* is a UNOLS vessel and carries out a broad spectrum of ocean research activities in any given year. Some characteristics of the vessels are given in Table I.

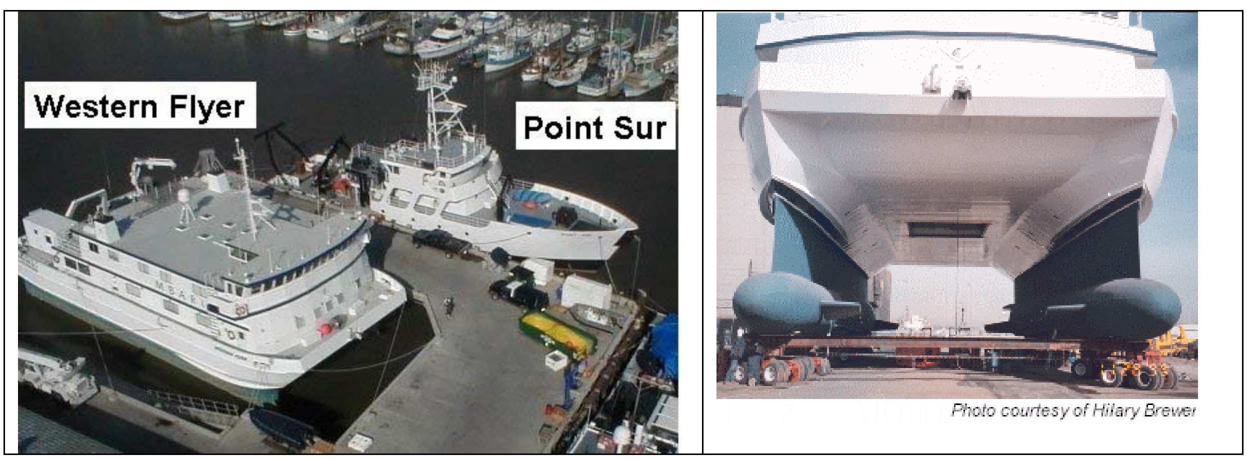

Figure 1. (left) R/V Western Flyer and R/V Point Sur alongside the MBARI Pier in Moss Landing, CA. (right) R/V Western Flyer in shipyard.

Table 1: Vessel characteristics.

Vessel	*PT SUR*	*WESTERN FLYER*
Length	135 ft	117 ft
Width	32 ft	53 ft
Displacement, Long Tons	539 tons[1]	419 tons[2]
Daily Cost	$9,415	$23,860[3]

III. Instrumentation

Two attitude measurement systems were deployed on these vessels. An inexpensive two axis precision tilt meter built by Applied Geomechanics[4] was used on all cruises. This measures roll and pitch at a 4 Hz rate. In all but the first cruise on the *Western Flyer,* a six degrees of freedom inertial system built by Crossbow Inc.[5] was used. The inertial system measures three accelerations and three angle rates and an internal computer estimates roll and pitch using a Kalman filter. The output from the inertial system can be as high as 110 Hz. On one of the cruises on each ship, the Crossbow was run at maximum rate. On later deployments it was run at 10 Hz.

Information on sea and swell was provided by the ship's officers. Ship's course and speed was recorded from the ship's navigation system and did not vary significantly during the period of time that ship motion was measured. Estimates of wind speed and direction were provided by the ship's officers on the *Western Flyer* and by an underway data system on *Point Sur.*

IV. Deployments

The data included in this report was taken on two cruises on each vessel. The *Western Flyer* was instrumented for a cruise from the Gulf of California to Monterey in May 2003. This cruise had only the AGM unit. In addition the *Western Flyer* was instrumented in July 2003 for a Central California hydrography cruise; the Crossbow was also used on this cruise, sampling at its maximum rate of 110 Hz.

There were also two cruises on the *Pt. Sur*. In July 2003, a Central California hydrography cruise encountered similar sea conditions to those observed during the *Western Flyer* July cruise. Data were also collected on a hydrography cruise in October 2003 during which sea conditions forced the *Pt. Sur* to zigzag between stations to avoid heavy rolling. Both *Pt. Sur* cruises used both the AGM tiltmeter and the Crossbow inertial unit. On the first cruise, the Crossbow was run at maximum rate; on the second, it was run at 10 Hz.

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[1] A sister ship, *R/V Cape Hatteras,* has a displacement tonnage of 640 long tons.
[2] Design water line.
[3] Includes ROV and pilots.
[4] Applied Geomechanics (AGM) Model MD900-T
[5] Crossbow DMU-VGX solid sate vertical gyro

Measurements were made by recording data with both instruments at the same time for about 15 minutes. Each of these 15 minute records was treated one as a data sample for purposes of determining the characteristics of the attitude variation on the ship. The number of samples for each cruise is shown in Table II.

Table II. Data Samples

	AGM	Inertial	Stations	Underway
Western Flyer May 2003	27	0	13	14
Western Flyer July 2003	9	10	2	8
Pt Sur July 2003	45	41	15	30
Pt Sur October 2003	23	22	4	19

V. Time Domain Analysis

As the first step in the analysis, the time series of roll and pitch from the two instruments was compared. The data records were similar. The two units agreed to within 0.2 degrees at any given time.

The second step was to find the rms of the roll and pitch over each 15 minute sample. The results are plotted, by vessel, in figures 2 and 3.

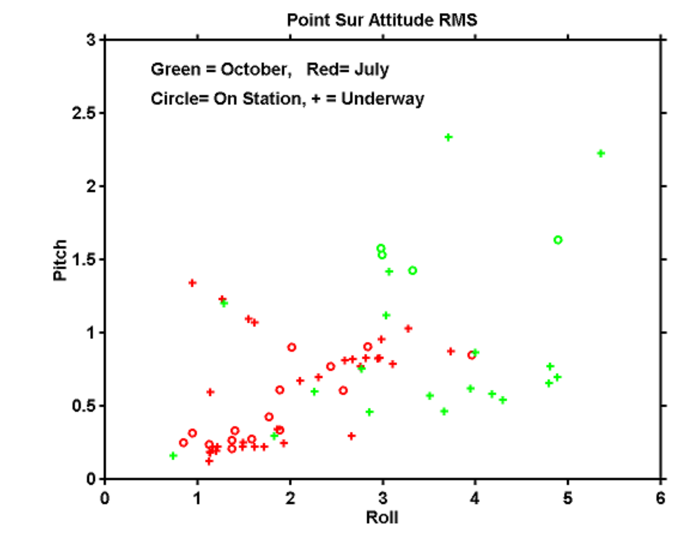

Figure 2. RMS Motions for *Pt Sur*.

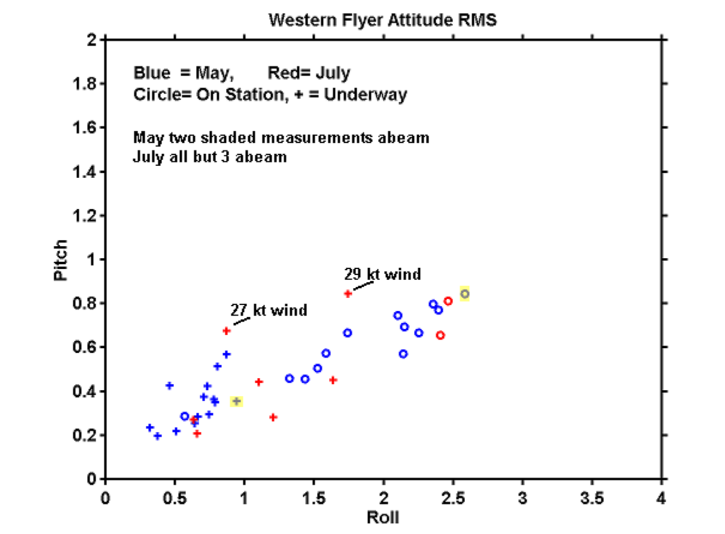

Figure 3. RMS Motions for *Western Flyer*.

It is clear that the monohull had much larger angular motions than the SWATH vessel. For the *Pt. Sur*, the motions were more dependent on wave motion than for the *Western Flyer*. In addition there were conditions where the pitch exceeded the roll on *Pt Sur*. This occurred when the *Pt Sur* was going directly into 3 to 5 ft seas. While the motion on station (when the vessel was hove to) was generally greater than the underway cases, it was not larger by a large multiple.

The motion of the *Western Flyer* was much less than the *Pt.* Sur and is shown in figure 3. The "on station" samples for the *Western Flyer* were usually larger by a factor of two than the underway motion in the same seas. However, the SWATH samples for the largest pitch and roll were lower by a factor of about a 3 than the monohull in the same environment (see below). In July (red symbols), the seas encountered by the *Western Flyer* were somewhat higher than those observed by the *Pt. Sur*. There were only two samples with swell abeam in the data taken from the *Western Flyer*. These have been shaded yellow. In addition two samples with strong winds are marked.

The 110 Hz data was examined to see of a lower sample rate was satisfactory. An example is shown in figures 5 and 6 where spectra to 50 Hz are shown for samples collected while the ship was hove to at two different stations. "On station" data were used because motions higher than 1 Hz were smaller than for the underway case (see below). There were spectral peaks evident at higher frequency, but none were at levels that would contaminate lower frequency roll and pitch when slower sampling was used. Note that semi-log axes are used in figures 5 and 6 so that the frequency of the high-frequency peaks can be easily seen.

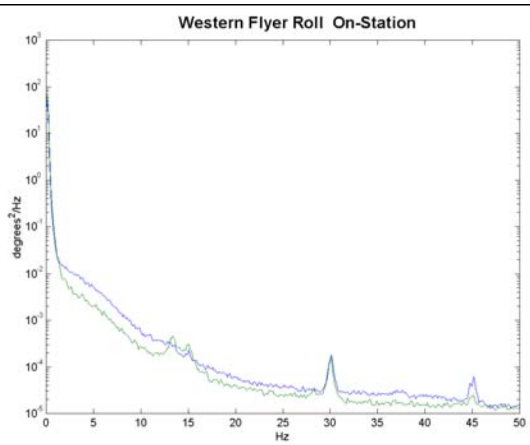

Figure 5. *Western Flyer* roll to 50 Hz.

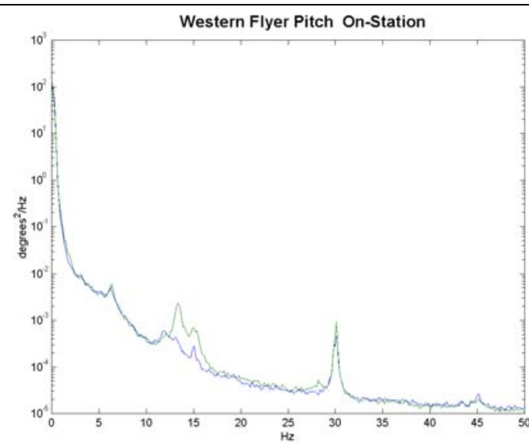

Figure 6. *Western Flyer* pitch to 50 Hz.

Most of the pitch and roll energy, as expected, was lower than 1 Hz. Tilt meter data from all *Western Flyer* samples are shown together on a log-log plot to 2.5 Hz in figures below. The roll data are shown in figure 7. The underway spectral levels under 0.1 Hz (10 second period) increased significantly on station. This accounts for most of the increased rms value. This was a very broad (low Q) peak for the roll spectra (fig. 7).

A similar pair of spectra for the pitch is shown in figure 8. Here the very low frequency motion was not as large as for roll, but included peaks at 0.15 and 0.2 Hz. Spectral levels were larger for these low frequency motions when the vessel was on station. The spectra peaks for pitch were sharper (higher Q) than the roll peaks.

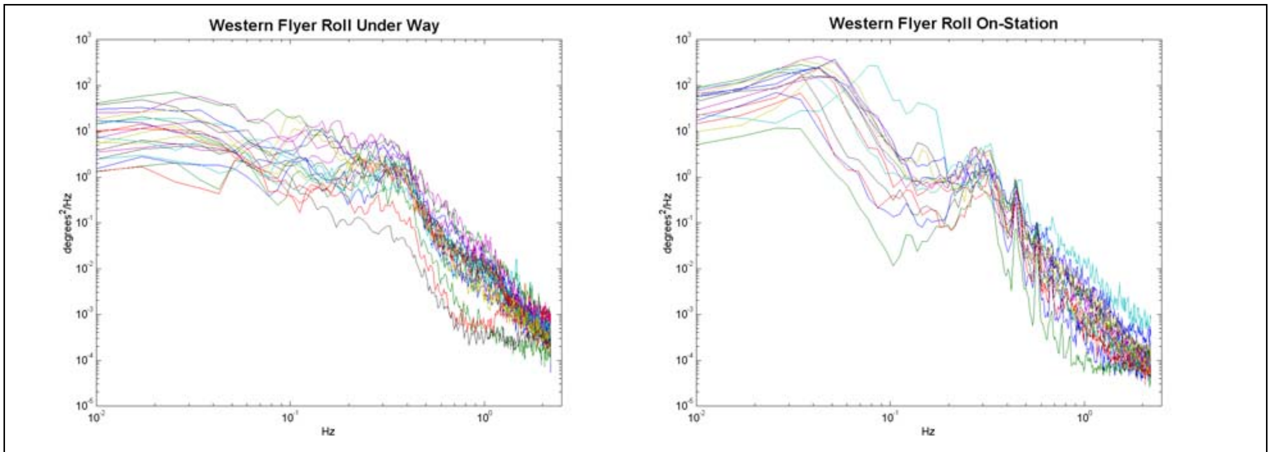

Figure 7   *Western Flyer* roll spectra. (left) Underway. (right) Hove to.

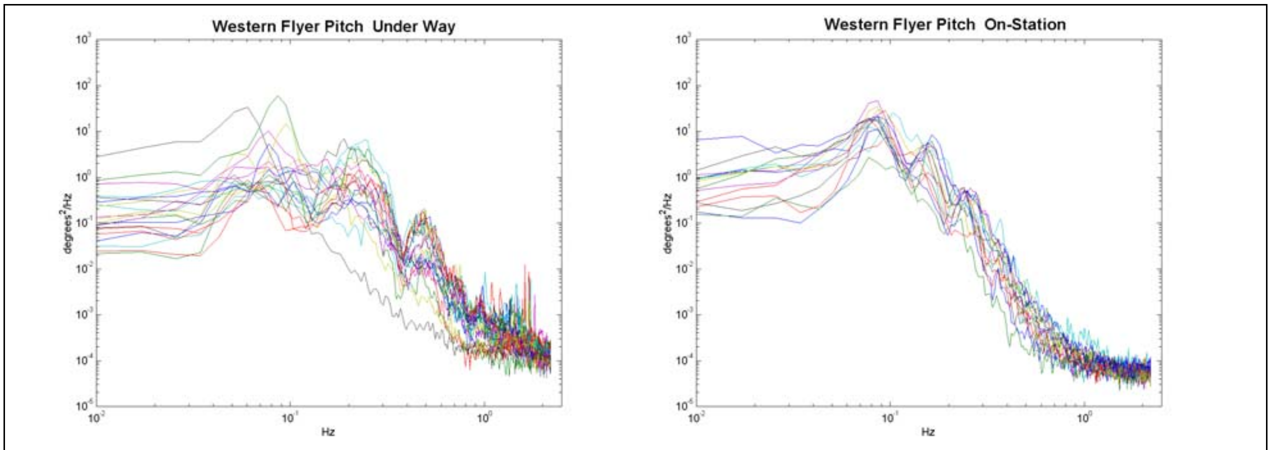

Figure 8. *Western Flyer* pitch spectra. (left) Underway. (right) Hove to.

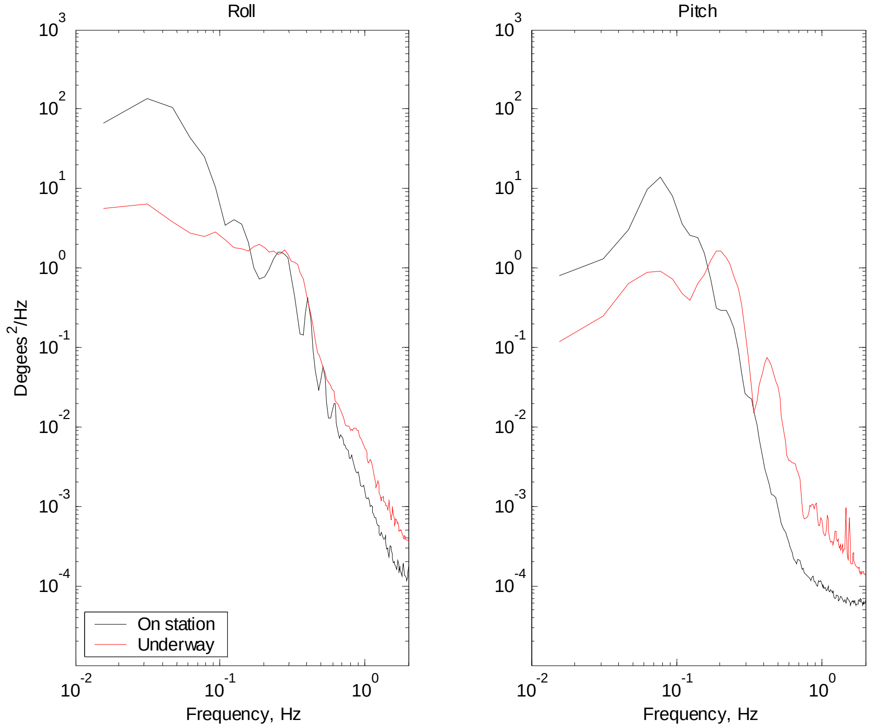

Figure 9. Mean spectra for the May 2003 *Western Flyer* cruise. The underway spectrum is shown in red and the on station spectrum is black. (left) Roll. (right) Pitch.

Mean spectra for pitch and roll for the May *Western Flyer* cruise are shown in Figure 9. These further illustrate the change in motion behavior that occurred between the on station and underway conditions. As noted above, the amplitude of the pitch and role while on station exceeded that while underway by a factor of about ten for frequencies lower than 0.2 Hz. Both the inertial of the vessel and the action of canards (mounted inboard of the subsurface hulls, see Fig. 1, right panel) dampen underway motion. But the underway propulsion increased pitch, and to a lesser extent roll, at frequencies higher than 0.2 Hz. As a practical matter, the higher frequency motion was noticeable only on the *Western Flyer* stern.

Corresponding plots for the *Pt. Sur* have been generated. They are not included to shorten this report. The on station motion of the *Pt. Sur* and *Western Flyer* are compared in Figure 10 as a function of wave and swell height. Lines were fitted to the data using the method of least squares. As the combined wave and swell height increased to ~10 ft., the rate of increase of *Western Flyer* motion (as indicated by the slope of the lines) was about half that of the *Point Sur.*

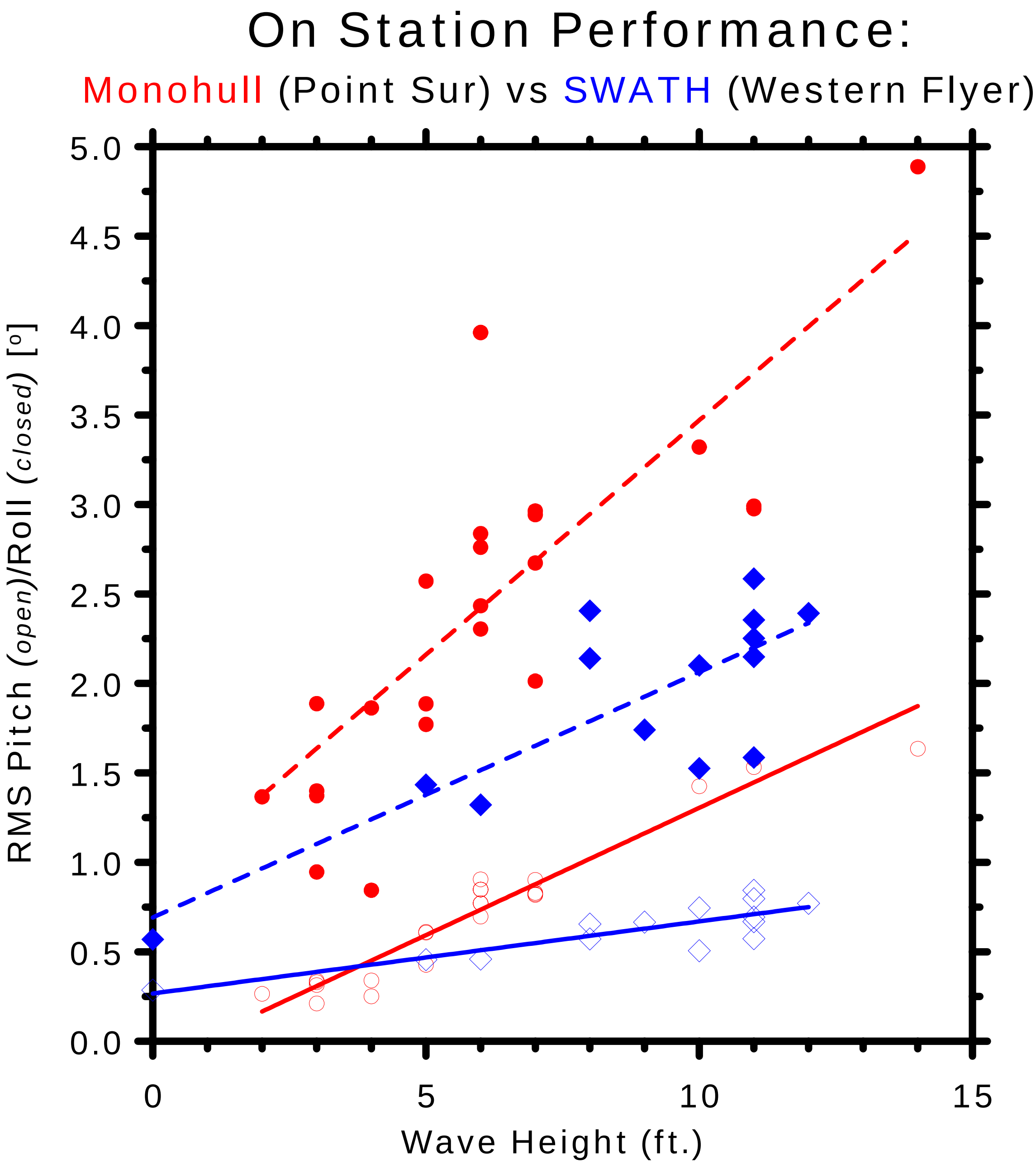

Figure 10. RMS pitch (open symbols) and roll (closed symbols) as a function of combined wave and swell height while vessels were hove to with their head into the seas. *Point Sur* data are shown in red and *Western Flyer* data are in blue. Lines were fitted to data using the method of least squares.

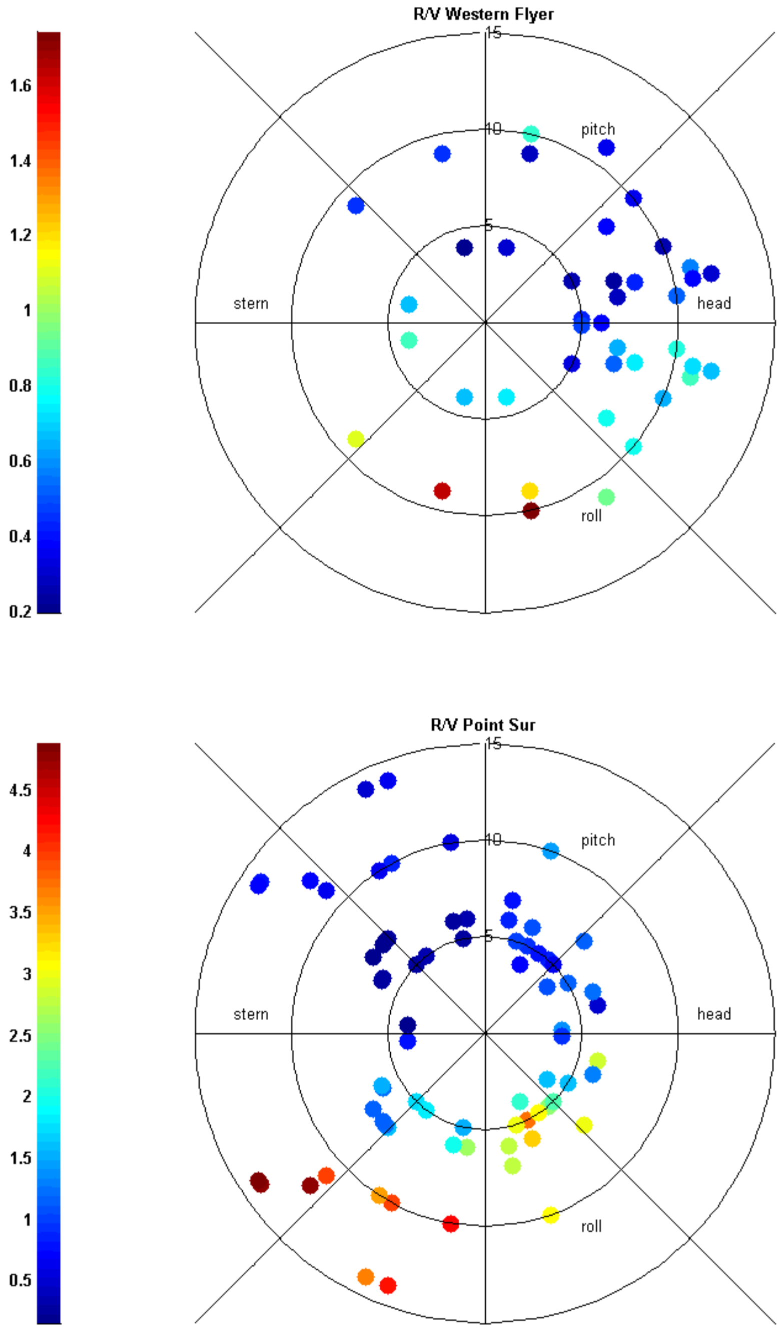

Figure 11. RMS pitch and roll at cruising speed. Data points are plotted at the head of a vector. The magnitude of the vector is the combined wave and swell height which is zero at the origin and increases to 15 feet at the outer circle. The direction of the seas wave are relative to the ship's head to the right and symmetric response was assumed. Pitch results are shown in the upper hemisphere and roll in the lower hemisphere. (upper) *Western Flyer.* (lower) *Point Sur.*

Figure 11 compares the motion of the two vessels while underway at cruising speed. Note that symmetric response has been assumed so that waves and swell from on the port bow are represented using the same angle as those on the starboard bow. The maximum for the *Western Flyer* measurements (fig. 11, upper) was 1.6 degrees, about one-third the maximum for the *Pt. Sur*, 1.5 degrees (fig. 11, lower). As seas approach 10 feet, the *Pt. Sur* cannot move into the seas at full speed and, similarly, riding in the trough is extremely uncomfortable. In these conditions, the *Pt. Sur* “tacks” between stations, moving into the seas at reduced speed, and then putting the seas on the ship’s quarter and increasing to full speed. Figure 11 (lower) reflects this practice; although large rms roll was shown, the period of the motion is long enough that the ride is quite comfortable.

VII. Work In Progress.

(1) *Point Sur* measurements. We collected an additional 12 days of measurements on *R/V Point Sur* in late January 2004. An additional 4 days of data will be collected in June during a cruise that will occupy a series of stations that are oriented along the trough of seas generated by steady 10 m/s winds from the northwest.

(2) *Western Flyer* measurements. We feel that we need an additional 20 days or so of data collection on the *Western Flyer*. We had hoped to be able to record data from the TSS on the *Western Flyer* but that unit has failed and been replaced by a Sperry fiber optic gyro which outputs a NMEA data stream at 2.5 Hz. We plan to work with MBARI to record these data. We are also working with MBARI to place an oceanographer and our tilt meter and vertical gyro on cruises when space is available.

(3) We will investigate the vertical gyro output to see if we can measure other components of ship motion, e.g. yaw, heave, surge. Some work will also be done to quantify the bandwidth of the motion, particularly for on station samples.

(4) A few samples appear anomalous and we intend to see if we can determine why.

(5) We would appreciate feedback from naval architects, ship operators, UNOLS, FIC, etc. regarding ways to make this study more useful for their work. Comments, etc. can be sent to collins@nps.navy.mil.