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REPORT ON THE USS ORTOLAN (ASR-22) FORWARD FOIL SEAKEEPING TRIALS

D. A. Woolaver

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Development Center

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FINAL REPORT ON THE USS ORTOLAN (ASR-22)
FORWARD FOIL SEAKEEPING TRIALS

by

D. A. Woolaver

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This report presents and discusses the results of seaworthiness trials conducted aboard the USS ORTOLAN (ASR-22) subsequent to the installation of a between-hull forward foil and modifications to the forward bridging structure. Ship motion, hull strains, and bridging structure impacts are presented with comparisons made between the 'as built' and the "modified" conditions. Results indicate that the addition of the foil, along with the bridging structure

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modifications, significantly improved the seaworthiness characteristics and operational limits of ORTOLAN, yielding a capable, seaworthy craft.

Bridging structure impacts did not limit ORTOLAN's ability to transit at any heading or speed in seas up to and including a state 6 sea. Ship motions, while large, are not abnormal and strain measurements indicate that the main structural integrity of the ship at the locations investigated was not endangered at any time during the trials. However, local structural modifications are required on the second deck between Frames 12 through 21 along the port and starboard inboard hull plating. The foil did not break the water surface in seas having a maximum wave height over 30 feet.

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ABSTRACT

This report presents and discusses the results of seaworthiness trials conducted aboard the USS ORTOLAN (ASR-22) subsequent to the installation of a between-hull forward foil and modifications to the forward bridging structure. Ship motion, hull strains, and bridging structure impacts are presented with comparisons made between the 'as built' and the "modified" conditions. Results indicate that the addition of the foil, along with the bridging structure modifications, significantly improved the seaworthiness characteristics and operational limits of ORTOLAN, yielding a capable, seaworthy craft.

Bridging structure impacts did not limit ORTOLAN's ability to transit at any heading or speed in seas up to and including a state 6 sea. Ship motions, while large, are not abnormal and strain measurements indicate that the main structural integrity of the ship at the locations investigated was not endangered at any time during the trials. However, local structural modifications are required on the second deck between Frames 12 through 21 along the port and starboard inboard hull plating. The foil did not break the water surface in seas having a maximum wave height over 30 feet.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

Full-scale trials conducted aboard the USS ORTOLAN (ASR-22)[1] in the 'as built' configuration confirmed reports of poor seaworthiness characteristics due to severe bridging structure impacts in moderate to heavy seas. These

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[1] Woolaver, D.A. and E.W. Foley, "ASR ORTOLAN Seakeeping Trials (As Built Configuration)," NSRDC Report SPD-122-18, Feb 1975.

impacts limited ORTOLAN's ability to transit in heavy seas and structurally endangered the plating and stringers of that structure. Seaworthiness investigations[2] employing physical and mathematical models of ORTOLAN and a similar catamaran, USNS HAYES (AGOR-16), suggested that a between-hull foil, at the keel near the bow, would reduce the frequency and intensity of bridging structure impacts. A between-hull foil has been fitted to ORTOLAN and modifications made to the forward bridging structure to increase its calm water clearance. It was anticipated that the combination of these modifications, as shown in Figures 1 and 2, would yield acceptable seaworthiness characteristics. During April 1975, ORTOLAN underwent full-scale trials for the purpose of determining the effect of these modifications on the seaworthiness characteristics of the craft. This report presents the result of those trials.

TRIAL SITE AND TRIAL PROCEDURE

Runs 1 through 6 were conducted in 35 to 45 fathoms of water in the vicinity of New London, Connecticut. The remaining runs were conducted in 500 fathoms or more of water while enroute from New London to Norfolk, Virginia.

The trial procedure employed was as follows:

a. the trial director would request a particular heading and ship speed,

b. the bridge would inform the director when the ship course and steady speed had been obtained,

c. the trial director would notify the electronic technicians to commence collecting data,

d. the trial director would inform the bridge of the run completion and request the next trial condition.

Each trial run would commence when the ship had reached the steady speed requested for a particular heading. The run would continue for approximately

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[2] Hadler, J.B. et al., "Ocean Catamaran Seakeeping Design, Based on Experiences of USNS HAYES," presented at Annual Meeting SNAME, Nov 1974.

30 minutes during which time the ship maintained heading and speed with a minimum of rudder activity.

DATA COLLECTION

Measurements were recorded on magnetic tape using a single 14 channel recorder and several strip charts. The original data collection scheme employed the use of two 14 channel magnetic recorders; however, one recorder malfunctioned during the first run and could not be repaired at sea. Other equipment failures included the Tucker Sea State Meter, one of the two transducers used to measure wave height, and the Ryan radar unit, used to measure relative bow motion. None of these failures are attributable to the shipboard environment.

Table 1 presents the trial measurements and channel designations with the location for each measurement. A detailed description of the measurement system is given in reference 1.

PRESENTATION AND DISCUSSION OF POST-FOIL TRIAL RESULTS

A summary of trial conditions, vertical motion at the stern and at Frame 87½, and pitch and roll motions are presented in Table 2. It should be noted that a zero knot ship speed is indicative of turns for steerage and not a true zero speed. With the exception of Run 34 (recorded at the entrance of Chesapeake Bay), the trial was conducted in state 4, 5, and 6 seas. Ship motion magnitudes reported here, while large, are not abnormal for a ship of this size for the conditions indicated. While these motions were detrimental to complex shipboard tasks, they did not impair the ability of ORTOLAN to transit, maintain station, or perform the duties normal to operation in heavy seas.

It should be noted that large values of roll occurred during head sea operations and that large values of pitch occurred during beam sea operations. These results are indicative of the confused, short crested nature of the sea at the time of the trial and similar results would not be expected during operations in conditions of swell or unidirectional seas.

Significant values indicating the average of the highest one-third stress cycles observed in the hull and cross structure are presented in Table 3. Also presented are the maximum values observed for tension and for compression as indicated in the typical strain time history shown in Figure 3. Stress values presented are derived from strain measurements and include both normal wave stress due to the hogging and sagging action of the hull as well as whipping stresses induced as a result of wave impacts. Stress values given for Frame 55 are indicative of the longitudinal bending moment (averaged for the two hulls) while stress values for Frames 34 and 96 are indicative of the transverse bending moment on the cross structure.

The strain gauge output for Frame 34 had a tendency to drift during the trial. This signal drift resulted in incorrect time dependent averages upon analysis, hence significant amplitude values are not presented for stress at this location. The maximum values have been corrected for drift.

Table 4 presents a summary of the foil stresses obtained during the trial. These stresses are indicative of the athwartship, or transverse, bending of the foil. The foil did not break the water surface during the trial and therefore did not suffer wave impacts directly. However, some stress was transmitted to the foil from impacts incident to the cross structure and/or ship hull. The values presented include this "impact related" stress as well as the stress due to normal wave action and hull movement. Strain gauge time histories indicate a fundamental frequency of 3.1 Hz in the transverse direction and a fundamental frequency of 29.5 Hz in the longitudinal direction. The wide separation of these frequencies negates the occurrence of a longitudinal-transverse resonance.

Table 5 presents the number of impacts, average, and maximum impact pressures observed at six locations on the cross structure, as shown in Figure 1. Cross structure impacts occurred most frequently in head seas with no impacts occurring in quartering and following seas at the gauge locations. Impacts above 40 PSI occurred during Runs 2 and 11; Run 2 recorded six such impacts, the largest being 87.6 PSI, while Run 11 recorded one such impact of 42.6 PSI. All impacts above 40 PSI occurred at Frame 13½. Prior to Run 14 some dishing of the cross structure plating did occur, however, no damage to weldments or stringers was observed. Damage did occur during Run 14 to the area between Frames 15 and 18 on the second deck at the inboard starboard hull shell plating. Tees in this area were bent inboard and several breaks in the welds securing the tees to the hull plating were observed. This area, which was previously protected by the unmodified cross structure, had not been strengthened during the modifications and was now exposed to wave impacts. Modifications to this area to increase its strength should not be difficult and need to be made as soon as possible.

It is of interest to note that this damage occurred at a ship speed of 7 knots, while no similar damage was observed in comparable seaways at 12 knots. To investigate the effect of speed on pitch and cross structure impacts, Runs 30, 31, and 33 were conducted in the same seaway at speeds of 3, 7, and 14 knots (see Table 2). It was found that pitch decreased as speed increased. One cross structure impact occurred at 3 and 14 knots, while four impacts occurred at 7 knots (see Table 5). Based on this limited data and on the judgment of the operators, ORTOLAN appears to have a more favorable pitch response as speed is increased. Further comments on this observation are made in the following section. A more detailed analysis of the seakeeping characteristics of catamarans, especially with regard to the speed influence on catamaran responses is contained in reference 3.

COMPARISON WITH PRE-FOIL RESULTS

The intent of the modifications to ORTOLAN as described earlier was to improve the seaworthiness by reducing or eliminating severe wave impacts on the cross structure. The foil was to accomplish this by reducing the pitching motion and by changing the phase of the bow motion with respect to the wave peaks. That is, enable the bow to more closely follow the wave contour, thereby decreasing the relative motion between the cross structure and the water surface. The structural modifications to the cross structure were

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[3] Baitis, A.E. et al., "A Seakeeping Comparison Between Three Monohulls, Two SWATHs, and A Column Stabilized Catamaran Designed for the Same Mission," DTNSRDC Report SPD-622-01, July 1975.

incorporated to increase the calm water clearance of the forward cross structure, thereby reducing the number and intensity of impacts for a given magnitude of relative bow motion. Thus the foil acts to decrease the relative motion while the reconfiguration of the cross structure increases the limit of acceptable relative motion. The 'fix' then is seen to be based upon two different principles which, in combination, complement one another.

Tables 2 and 6 presenting the trial conditions, pitch, roll, vertical stern motion, and vertical acceleration at Frame 87½ for the post-foil and pre-foil trials, respectively, will be found useful in the following comparisons.

Figures 4, 5, and 6 present pitch transfer functions obtained in head seas for 0, 7, and 12 knot ship speeds, respectively. A transfer function is essentially a measure of how a system will react to an input. In this case the system is ORTOLAN, the reaction is pitch angle, and the input is a seaway. Thus the larger the transfer function, the more pitch produced by a given seaway. It should be noted that a reduction in pitch angles does not necessarily produce a reduction in cross structure impacts for if the bow motion is moved further out of phase with the wave profile, impacts could remain unchanged or worsen.

Referring to Figure 4, we find that the addition of the foil tends to reduce pitch response in the frequency range from approximately 0.55 radians/second to 0.80 radians/second; increase pitch response in the frequency range from 0.80 radians/second to 0.95 radians/second and has little or no effect elsewhere. By referring to the alternate scales in the figure, these ranges may also be defined by wavelength (topmost scale) and/or by encounter period (bottom scale). The slight differences in the transfer functions for zero ship speed in head seas with and without the foil indicate that the foil will have little or no effect on the magnitude of pitch response. No cross structure impacts were observed at zero speed at any of the gauge locations.

Figure 5 presents similar transfer functions for a nominal ship speed of 7 knots. Here, however, we note two traces for the pre-foil configuration representing an impacting condition (solid trace) and a nonimpacting condition (dotted trace). The nonimpacting trace was established through model studies at DTNSRDC while the impacting trace is the result of the pre-foil full-scale trial analysis. The introduction of model scale results at this point is considered necessary since a nonimpacting transfer function could not be obtained from analysis of the pre-foil trial data due to inadequate weather conditions. The validity of a model scale to full-scale comparison in this case may be found in the agreement between them. Model scale results for both the pre-foil and post-foil configurations agree well with the full-scale results presented in Figure 4 and in Figure 6, which is yet to be discussed. Additionally, model results for the impacting condition agree very well with those obtained during the full-scale trial.

It is seen that the impacting condition yields a lower transfer function than does the nonimpacting condition in the 6 to 9 second range of encounter periods. This decrease is a result of the cross structure impacts which act to dampen the pitching motion. That is, the ship does not realize as great a pitch angle as it would in the absence of impacts. The magnitude of the decrease in pitch angle is dependent upon the number and severity of the impacts which occur. Greater severity and increased occurrences causing a greater damping effect which results in a corresponding decrease in the magnitude of the transfer function. The effectiveness of the foil in reducing pitch may be determined only by comparing transfer functions which do not contain impact damping.

Returning to Figure 5, we see that post-foil pitch response is significantly less than that of the pre-foil condition. This indicates that the foil is effective in reducing pitch response at 7 knots.

When ship speed is increased to 12 knots we obtain the transfer functions shown in Figure 6. A significant reduction is shown for encounter periods from 6 to 9 seconds, with an increase found for the shorter wavelengths. Note that all pitch response transfer functions tend to unity for the long wavelengths. This indicates physically that the ship is following the wave profile and is true for all freely floating craft, although the wavelength necessary for this to occur varies from ship to ship. The transfer functions also tend to zero for very short wavelengths indicating that the ship will not respond in pitch to very short wavelengths.

The transfer functions presented in Figures 4, 5, and 6 may be used to determine the significant pitch angles expected for various seaways through the use of spectral techniques. By applying the same seaway to the pre-foil and post-foil transfer functions, a direct comparison between the two configurations may be made. This technique is based on the accepted assumption that pitch angle is linear with respect to wave height. That is, as the spectral wave energy (wave height) is increased, a corresponding increase occurs in the spectral pitch energy (pitch angle). The use of spectral terminology is necessary so that the effect of frequency is included. In practical terms, this means that transfer functions obtained in seas of varying height but with the same basic frequency content will be essentially identical provided no nonlinear effects are observed.[4] Examples of conditions which produce nonlinear effects are high speeds, unusual hull forms, severely breaking waves, and the occurrence of impacts on the hull or, in this case, the cross structure. For this reason only nonimpacting transfer functions can be used in the development of comparative data.

The results of an analysis using the transfer functions presented in Figures 4, 5, and 6 are presented in Table 7. A 10-foot significant wave height, corresponding to a state 5 sea, was selected for this analysis. The spectral shape developed by Bretschneider[5] was used to model the seaway and to allow for the use of variations in the modal period of the seaway. By varying the modal period, this is the period of maximum wave energy, some insight to the frequency dependence of the pitch response may be gained.

As shown in Table 7, modal periods of 8, 10, and 14 seconds were selected and pitch response calculated for ship speeds of 0, 7, and 12 knots. A modal period of 10 seconds corresponds closely with observed seaways during Runs 1 to 22. The pre-foil values shown in parentheses for the 7-knot condition were

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[4] Cummins, W.E., "Pathologies of the Transfer Functions," presented 18-19 October 1973 at the Seakeeping Symposium Commemorating the 20th Anniversary of the St. Denis-Pierson Paper.

[5] "Estuary and Coastline Hydrodynamics," Edited by Arthur Ippen, McGraw-Hill, Inc., "Wave Generation by Wind, Deep and Shallow Water," (C.L. Bretschneider) pp. 133-196 (1966).

obtained using the transfer function of Figure 5 for which cross structure impacts are included. Hence these values should be viewed only as in indication of the relative magnitude of damping caused by cross structure impacts during the pre-foil trial. In comparing pre-foil with post-foil values, we see that for the modal periods and ship speeds presented the addition of the foil results in a reduction of pitch response for all cases. The greatest reduction occurs for a ship speed of 7 knots, slightly less reduction occurs at 12 knots, and only a slight reduction occurs at zero knots. We also find that pitch response is largest for a seaway with a 10-second modal period, being somewhat less for the 8- and 14-second modal periods. We also notice that in the pre-foil configuration pitch response increases with an increase of speed from 0 to 7 knots and then decreases with a speed increase from 7 knots to 12 knots. The post-foil configuration, however, shows a tendency for pitch response to decrease monotonically as ship speed is increased. These results compare well in trend and magnitude with values found in Tables 2 and 6 and indicate that the addition of the foil has reduced pitch response for all conditions shown. Indeed the foil appears to be more advantageous as ship speed is increased as was noted during Runs 30, 31, and 33 (Table 2).

In the same manner that modal period was varied in Table 7 to show the effect of wave frequency, wave energy may be varied to show the effect of wave height. Table 8 presents the results of such an approach using wave heights of 5.6, 9.8, and 15.1 feet corresponding to state 4, 5, and 6 seas, respectively. A modal period of 10 seconds was selected to model the three different seaways.

Referring to Table 8, we find that pitch increases with increasing wave height in all cases. In the pre-foil, or 'as built' configuration, pitch tends to increase with an increase in ship speed from 0 to 7 knots and then decrease with a further increase in speed from 7 to 12 knots. However, in the post-foil configuration, pitch tends to decrease monotonically with an increase in speed. We also note that the addition of the foil results in a reduction of pitch response for all cases, being greatest at 7 and 12 knots. These same tendencies are thus shown to hold constant over frequency variations (Table 7) and also over wave height variations.

To ascertain the effect of the foil on cross structure impacts, we refer to Figures 7 and 8.

Figure 7 presents the number of impacts per hour at Frame 23½ for head seas with and without the foil versus wave height. The figure shows that more impacts occur at 12 knots than at 7 knots for a given wave height. The figure also indicates that the foil reduces the number of impacts at all wave heights for both speeds, the most significant reduction being at 7 knots. We may also note that while minor local impacts did occur at zero knots, no impacts were recorded at the impact gauge locations during the pre-foil or post-foil trial while at zero knots. This indicates that the foil is providing assistance when it is most needed, namely, when the ship is underway.

Figure 8 presents the average and maximum impact pressures observed at Frame 23½ versus wave height. Significant improvement is shown in both figures since the addition of the foil with the 7-knot reduction being greater than for 12 knots. Impact data for 12 knots in wave heights above 8 feet is not available for the pre-foil configuration due to the possibility of severe structural damage as reported in Reference 1. It is noted that the operation of ORTOLAN in head seas at 12 knots has been expanded from seas of 8 feet to seas of 16 feet. Indeed, ORTOLAN with the foil is capable of transiting at or near full power at all headings in seas up to mid state 6. This was demonstrated during one evening's transit when ORTOLAN maintained an average speed over ground of 13 knots for 7 hours in a state 6 sea. This transit was made at a bow sea heading which is conducive to roll, pitch, and cross structure impacts.

Synchronous pitching in swell will still occur under certain combinations of wavelength, speed and heading. In head seas at 7 knots this will occur predominantly in swell having a wavelength of approximately 390 feet which corresponds to an encounter period of approximately 7 seconds. At 12 knots it will most likely occur in swell with a 450-foot wavelength corresponding to an encounter period of approximately 6.6 seconds. Referring again to Figures 4 and 5, we see that in the areas of interest the pitch transfer functions show a reduction of 25 to 40 percent due to the action of the foil. This indicates that a 25 to 40 percent increase in swell height is now necessary to produce the same effect which would be found in the pre-foil condition, all other factors remaining fixed.

However, other factors have not remained fixed, the two most important being cross structure clearance and bow motion to wave profile phasing. The increase in forward cross structure clearance will require a further increase in swell height to produce impacts similar in magnitude to those which would result if the clearance were not increased.

Referring to Figure 2, we see that the cross structure has been raised 40 inches in the area most likely to sustain the most severe impacts, while at Frames 13½ and 23½, corresponding to pressure gauge locations, it has been raised approximately 2½ and 2 feet, respectively. Comparison between static drafts before and after the completion of the modifications indicate that the draft at the bow has been increased 6 inches. Investigations indicate that cross structure clearance is further reduced by the dynamic action of the ship-foil system. The magnitude of this reduction is dependent on the longitudinal and transverse location of the measurement as well as ship speed. For the area between Frames 12 and 21, where impacts are most likely, a decrease in clearance of 1-foot at 14 knots is generally attributed to the addition of the foil. Lower ship speeds yield a lower loss in clearance. The combination of increased static bow draft and dynamic ship-foil effects are thus seen to cancel 18 inches of the clearance gained by the cross structure modification at a speed of 14 knots. If we conservatively estimate that a gain in clearance of 36 inches was realized between Frames 12 and 21 by the modification, we are left with a net increase of 18 inches (36 inches minus 18 inches) at 14 knots. Since dynamic effects are not operative at zero knots, we find a net increase in clearance of 30 inches at zero speed for this same area.

The results of the post-foil trial do not provide us with the data necessary to determine the phase shift between the bow motion and the wave profile. However, they do indicate, through the decreased number and severity of impacts, that this phase shift, if any, has not been detrimental. Observations by DTNSRDC trial director during the trial support this conclusion.

In view of the above considerations, it is expected that while synchronous impacting will not be eliminated, it will require swell heights in excess of 50 percent greater than those which were necessary for its occurrence in the pre-foil configuration.

The pre-foil trial confirmed that ORTOLAN displayed poor seakeeping characteristics. Two areas of major concern were shown to be the severe cross structure impacts experienced in moderate to heavy seas and secondly, the occurrence of synchronous pitching in swell under varying conditions of speed and heading which also produced severe cross structure impacts. A limiting condition in head seas was determined to be 7 knots or less in seas having a significant wave height in excess of 8 feet. Other areas of concern were: extreme deck wetness, especially in the forecastle area; large quantities of spray which obscured visibility from the pilothouse; and large, but not abnormal, pitch and roll motions which are generally uncomfortable to the operators.

The post-foil trial documents the improvement realized by the cross structure modification and addition of the foil. Figures 4, 5, and 6, in conjunction with Table 6, show that pitching motions in head seas have been reduced up to 29 percent. The greater improvements being displayed while underway where they are most needed for improved seaworthiness.

Table 5 and Figures 7 and 8 display the reduction in impact occurrence and severity, especially evident at 7 knots. As a result of these improvements, ORTOLAN can, if necessary, transit at or near full power on any course in seas below a high state 6 once the area around Frames 15 through 20 is strengthened, as mentioned earlier.

Synchronous pitching in swell will still occur under certain combinations of wavelength, speed, and heading. However, the swell height necessary to produce cross structure impacts has been increased by an estimated 50 percent or more. Therefore, the occurrence of synchronous impacting in swell should occur significantly less often than observed prior to the modifications. It should be stated that synchronous pitching and attendant impacting is not unique to the catamaran design. Monohulled ships of 200- to 400-foot lengths would also experience difficulty in the conditions necessary for ORTOLAN to impact (Reference 4).

Deck wetness and spray does not appear to have been reduced through the addition of the foil. The visibility loss due to spray has been somewhat overcome by the installation of circular wipers in the pilothouse. Since ORTOLAN uses these wipers and the standard blade wipers on clear days, due to bow spray in moderate to heavy seas, as well as in inclement weather, it is recommended that additional circular wipers be installed; the effectiveness of the circular wipers being far superior to the blade type. Forecastle deck wetness is prevalent in moderate and heavy seas during bow and head sea operations. Water depths of 1 to 2 feet were observed on the deck during the more severe runs. Such modifications as are practical should be made to increase the watertight integrity of the forward chain lockers. Currently these lockers tend to fill with sea water when the decks are awash, adding additional undesirable weight forward which is detrimental to ORTOLAN's seaworthiness.

CONCLUSIONS AND RECOMMENDATIONS

1. The modifications to the cross structure and addition of the foil have significantly improved the seaworthiness and operational limits of ORTOLAN.
2. ORTOLAN is capable of transit at or near full power for all headings in seas up to and including a state 6 (i.e., significant wave height of 16 feet).
3. Synchronous impacting during conditions of swell is expected to require swells 50 percent greater than those necessary to produce synchronous impacting in the 'as built' configuration.
4. Ship motions are not abnormal for a craft of this size and displacement.
5. Measured values of stress indicate the main structural integrity of the ship was not endangered during the trial.
6 The foil did not break the water surface in seas having maximum wave heights in excess of 30 feet.

It is recommended that:

1. The inboard hull area between Frames 15 through 20 on the second deck be strengthened to withstand wave impacts of 40 PSI.
2. Chain locker covers in the forecastle area be made as watertight as practical.
3. Additional circular wipers be installed in the pilothouse.

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The full-scale trials conducted aboard ORTOLAN were made possible by the active support received from several activities. Primary among these were: NAVSEC (Mr. Jack Berner and Mr. Jerry Synder), NAVSEA (Commanders Bob Christensen and Steve Turner), Naval Shipyard Philadelphia (Mr. Ed Dragan, Mr. Frank Barbarito, Mr. Guido Mitrovich, Mr. Joe Krauss, and Mr. Frank O'Connor), and especially the officers and crew of ORTOLAN. The enthusiasm, professional guidance, and experience which these individuals, and many others, gave to the author and to the trial effort is responsible for the successful completion of this task.

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5. "Estuary and Coastline Hydrodynamics," Edited by Arthur Ippen, McGraw-Hill, Inc., "Wave Generation by Wind, Deep and Shallow Water," (C.L. Bretschneider) pp. 133-196 (1966).

TABLE 1 - TRIAL MEASUREMENT TRANSDUCER LOCATIONS

Measurement	Location
1. Pressure Gauge 1	Bottom plating of cross structure, 16" port of centerline, 12" forward of Frame 14.
2. Pressure Gauge 2	Bottom plating of cross structure, 16" port of centerline, 7" aft of Frame 23.
3. Pressure Gauge 3	Bottom plating of cross structure, 16" port of centerline, 9" forward of Frame 35.
4. Pressure Gauge 4	Bottom plating of cross structure, 16" port of centerline, 11" forward of Frame 45.
5. Pressure Gauge 5	Bottom plating of cross structure, 16" port of centerline, 7" aft of Frame 87.
6. Pressure Gauge 6	Bottom plating of cross structure, 16" port of centerline, 9" aft of Frame 108.
7. Pressure Gauge 7	Top plating of between hull foil, 12" port of centerline, 6" aft of Frame 26.
8. Pressure Gauge 8	Bottom plating of between hull foil, 12" port of centerline, 6" aft of Frame 26.
9. Pressure Gauge 9	Port hull, 6" aft of Frame 27, 12" above between hull foil fairing plate.
10. Mode	Internal to instrument package.
11. Tucker Sea State Meter	Outboard port and starboard hulls, 8¼"forward of Frame 53, 7'8" above baseline.
12. Wave Rider Buoy (Launched)	Buoy launched in seaway.

TABLE 1 - TRIAL MEASUREMENT TRANSDUCER LOCATIONS (Cont.)

	Measurement	Location
12a.	Wave Rider Buoy (Secured)	Port hull fantail, 5'9" forward of stern deck edge, 1'8" port of center well deck edge.
13.	Bow Acceleration	On ship's centerline, approximately 50' above baseline, Frame 2½.
14.	Ryan Radar Unit	As for bow acceleration.
15.	Ship's Course	Ship's gyro, approximately S-4-33-0.
16.	Pitch and Roll Angles, Heave, Surge, and Sway Accelerations	On ship's centerline, 14½" above main deck, Frame 87½.
17.	Ship Speed	Ship's speed log, approximately P-5-27-1-T.
18.	Bridge Crane Rail Acceleration	Port aft bridge crane rail, 52' above baseline, Frame 68 with arm secured (Frame 84 with arm extended), 43' port of centerline with arm secured (75' port of centerline with arm extended).
19.*	Longitudinal Stress 37	Bulkhead 37, 8' starboard of centerline, 3" below main deck.
20.*	Longitudinal Stress 96	Bulkhead 96, 8' starboard of centerline, 3" below main deck.
21.*	Vertical Bending Stress	Outboard port and starboard sheet strake in passageway S-2-52-1-L and P-2-52-2-L.
22.*	Top Athwartship Foil Stress 1	Proximity of pressure gauge 7.
23.*	Top Athwartship Foil Stress 2	Top of between hull foil plating, 6" aft of Frame 26, approximately 14' port of centerline.
24.*	Bottom Athwartship Foil Stress	Proximity of pressure gauge 8.
25.*	Video Camera	4 feet above main deck at port hull inboard bulwark, Frame 7.

* Structural Measurements.

TABLE 2 - SUMMARY OF TRIAL CONDITIONS, PITCH AND ROLL ANGLES, VERTICAL MOTION AT FRAME 87½, AND VERTICAL MOTION AT THE STERN

Run	Heading	Speed (Knots)	Wave Height* (Feet)	Vertical Stern Motion** (Feet)	Pitch** (Deg)	Roll** (Deg)	Vertical Motion** Frame 87½ (g's)
1	Head	0	16.5	-	5.1	4.9	0.08
2	Head	12		11.1	4.3	5.1	0.21
3	Quartering	12		7.5	3.0	5.4	0.06
4	Beam	12		10.1	3.5	8.9	0.15
5	Bow	12		-	3.4	8.9	0.17
6	Following	12		7.3	3.2	3.7	0.01
7	Head	0	14.3	-	4.1	6.1	0.05
8	Following	12		6.8	2.7	4.6	0.07
9	Bow	12		10.9	4.7	4.4	0.21
10	Beam	12		9.9	3.5	7.3	0.14
11	Head	12		10.4	4.2	5.8	0.21
12	Quartering	12		8.3	2.9	7.3	0.10
13	Head	0	16.1	-	5.1	6.2	0.12
14	Head	7		10.6	4.8	5.4	0.17
15	Quartering	7		7.8	3.0	5.7	0.08
16	Beam	7		10.1	4.0	7.3	0.14
17	Bow	7		9.1	3.9	7.9	0.14
18	Following	7		7.8	3.1	4.6	0.07
19	Head	0	15.7	-	3.8	5.8	0.10
20	Head	3		8.2	3.6	5.6	0.13
21	Bow	3		8.2	3.9	5.4	0.12
22	Quartering	3		7.7	2.6	6.3	0.08
23	Head	0	9.7	-	3.6	3.2	0.09
24	Head	12		7.4	3.1	2.4	0.20
25	Quartering	12		5.4	1.9	4.9	0.06
26	Bow	12		6.1	2.4	5.7	0.15
27	Following	12		3.6	1.6	2.1	0.03
28	Beam	12		6.3	2.1	7.4	0.12
29	Quartering	12		2.6	1.2	2.3	0.03
30	Head	3		4.5	2.2	3.9	0.10
31	Head	7	7	4.3	1.9	2.0	0.12
32	Beam	14		2.8	1.3	3.2	0.05
33	Head	14		3.5	1.3	1.8	0.11
34	Head	7	1	0.7	0.2	0.4	0.01

* Double amplitude significant values.

** Single amplitude significant values.

TABLE 3 - SUMMARY OF CROSS STRUCTURE AND HULL GIRDER STRESSES

	Frame 34 Stress			Frame 55 Stress			Frame 96 Stress		
Run No.	Sign. Amp. (KSI)	Max. Tens. (KSI)	Max. Comp. (KSI)	Sign. Amp. (KSI)	Max. Tens. (KSI)	Max. Comp. (KSI)	Sign. Amp. (KSI)	Max. Tens. (KSI)	Max. Comp. (KSI)
1	*	2.10	1.75	0.91	1.61	1.92	0.70	1.43	1.38
2	*	1.33	1.12	0.86	1.53	2.00	0.64	1.20	1.15
3	*	1.03	1.06	0.50	0.89	0.86	0.87	1.67	1.56
4	*	1.48	2.78	0.57	0.97	1.21	1.40	2.58	2.53
5	*	1.71	2.08	0.65	0.98	1.39	1.17	6.70	1.83
6	*	0.83	0.69	0.58	0.76	1.78	0.70	1.16	1.13
7	*	1.78	2.13	0.66	1.02	1.17	0.72	1.14	1.50
8	*	0.78	1.42	0.56	0.85	1.06	0.80	1.48	1.60
9	*	5.32	6.05	0.79	1.23	2.03	0.88	1.64	1.61
10	*	1.53	1.81	0.57	0.89	1.31	1.05	1.65	1.89
11	*	3.91	5.39	0.86	1.18	2.59	0.73	1.38	1.23
12	*	1.20	1.23	0.56	0.77	0.85	0.96	1.88	1.35
13	*	2.01	1.96	0.90	1.40	1.61	0.79	1.42	1.36
14	*	4.79	4.26	0.77	1.10	2.17	0.73	1.17	1.21
15	*	1.53	1.80	0.60	0.91	1.00	0.98	1.60	1.37
16	*	2.34	1.98	0.60	0.85	1.17	1.04	1.75	1.98
17	*	1.35	1.81	0.65	0.94	1.06	1.22	1.96	1.70
18	*	1.77	2.34	0.56	0.77	0.86	0.69	1.15	1.12
19	*	1.50	1.33	0.59	0.92	1.12	0.78	1.40	1.38
20	*	1.69	2.70	0.60	0.82	1.26	0.83	1.21	1.18
21	*	1.96	1.26	0.69	0.89	1.18	0.92	1.42	1.42
22	*	2.07	1.89	1.03	1.21	1.47	0.89	1.69	1.83
23	*	1.08	1.17	0.61	0.89	1.08	0.51	0.78	0.83
24	*	1.05	3.44	0.68	0.98	1.49	0.44	0.74	0.65
25	*	0.99	1.24	0.40	0.52	0.85	0.81	1.28	1.21
26	*	0.74	2.16	0.54	0.84	1.05	0.86	2.08	1.43
27	*	0.89	0.89	0.44	0.65	0.73	0.46	0.81	0.76
28	*	1.80	2.23	0.39	0.56	0.81	0.99	1.62	1.56
29	*	0.61	0.68	0.49	0.83	0.93	0.55	1.01	0.89
30	*	0.28	0.36	0.44	0.70	0.80	0.69	1.06	1.03
31	*	0.21	0.22	0.44	0.68	0.73	0.49	1.03	0.87
32	*	0.32	0.43	0.34	0.54	0.55	0.78	1.15	1.06
33	*	0.20	0.22	0.42	0.79	0.79	0.44	0.80	0.79
34	*	0.04	0.05	0.09	0.10	0.16	0.13	0.22	0.18

*See Text.

TABLE 4 - SUMMARY OF FOIL STRESSES

Run No.	Top Foil Stress			Bottom Foil Stress			Port Foil Stress		
	Sign. Amp. (KSI)	Max. Tens. (KSI)	Max. Comp. (KSI)	Sign. Amp. (KSI)	Max. Tens. (KSI)	Max. Comp. (KSI)	Sign. Amp. (KSI)	Max. Tens. (KSI)	Max. Comp. (KSI)
1	0.9	1.3	1.2	0.8	1.4	1.7	0.7	1.4	1.4
2	1.4	2.7	2.1	1.9	2.8	3.9	0.7	1.3	1.2
3	0.9	1.3	1.7	0.8	1.2	1.2	0.5	0.7	0.8
4	1.2	2.0	1.8	1.3	2.1	2.4	0.9	1.4	1.4
5	1.3	1.9	2.2	1.5	2.7	2.7	0.6	1.1	1.0
6	0.8	1.2	1.2	0.7	1.1	1.1	0.4	0.6	0.6
7	0.9	1.5	1.9	0.9	1.3	1.5	0.6	4.1	2.9
8	1.0	2.0	1.9	1.0	1.8	1.5	0.3	0.5	0.5
9	1.5	2.5	2.2	2.3	3.4	4.2	0.7	1.0	1.2
10	1.4	2.5	2.2	1.4	2.5	2.2	0.5	0.8	0.8
11	1.5	2.1	2.4	2.2	2.7	3.0	0.7	1.0	1.0
12	0.9	1.7	1.4	1.0	1.6	2.1	0.4	0.6	0.7
13	1.0	2.1	1.9	0.9	1.4	2.3	0.5	0.6	0.7
14	1.2	2.6	2.0	1.4	2.7	3.1	0.5	0.9	1.0
15	0.9	1.3	1.4	0.7	1.1	1.1	0.4	0.6	0.6
16	1.2	1.7	2.1	1.2	1.8	2.1	0.5	0.9	1.2
17	1.2	1.8	2.0	1.2	2.0	2.0	0.6	1.2	0.9
18	0.8	1.4	1.7	0.6	1.0	0.8	0.3	0.6	0.9
19	0.9	1.3	1.6	0.9	1.7	1.8	0.5	1.0	0.8
20	1.0	1.4	1.5	0.9	1.3	1.8	0.4	0.7	0.7
21	1.0	1.4	1.5	0.9	1.7	2.0	0.5	0.8	0.7
22	0.8	1.3	1.4	0.7	1.1	1.1	0.4	0.8	0.7
23	0.7	1.4	1.5	0.6	1.0	1.3	0.4	0.7	0.6
24	1.4	2.1	2.2	2.3	2.9	3.3	0.6	1.0	1.0
25	0.9	1.8	1.3	0.9	1.5	1.8	0.4	0.6	0.6
26	1.2	1.8	2.3	1.7	2.9	2.9	0.7	1.1	1.0
27	0.7	1.3	1.3	0.8	1.2	1.3	0.2	0.4	0.3
28	1.1	2.0	1.8	1.3	2.1	2.1	0.4	0.6	0.7
29	0.8	1.3	1.0	0.9	1.2	1.7	0.2	0.4	0.3
30	0.6	1.0	0.9	0.6	1.1	1.2	0.3	0.5	0.5
31	0.8	1.1	1.1	1.1	1.6	1.6	0.4	0.7	0.6
32	0.7	1.1	1.0	0.7	1.2	1.4	0.3	0.6	0.6
33	0.7	1.2	1.4	1.2	2.0	2.1	0.4	0.6	0.5
34	0.2	0.3	0.3	0.3	0.6	0.4	0.1	0.2	0.1

TABLE 5 - SUMMARY OF CROSS STRUCTURE IMPACTS

	Frame 13½			Frame 23½			Frame 34½		
Run No.	Number of Impacts	Average Impact (PSI)	Maximum Impact (PSI)	Number of Impacts	Average Impact (PSI)	Maximum Impact (PSI)	Number of Impacts	Average Impact (PSI)	Maximum Impact (PSI)
2	21	30.0	87.6	9	13.4	28.2	7	8.9	15.6
4	1	18.8	18.8	1	12.5	12.5	0	-	-
5	6	14.2	27.0	4	6.3	9.1	8	6.8	14.2
9	10	10.2	25.2	12	11.6	37.5	2	4.4	8.8
11	9	19.8	42.6	20	13.7	35.0	1	3.8	3.8
14	13	12.4	32.4	11	9.7	22.5	5	9.8	20.0
16	1	7.6	7.6	0	-	-	0	-	-
17	1	17.6	17.6	1	6.3	6.3	0	-	-
21	1	5.1	5.1	2	13.2	13.8	0	-	-
24	3	11.8	12.6	5	11.0	13.8	0	-	-
28	0	-	-	1	5.0	5.0	0	-	-
30	1	12.6	12.6	0	-	-	0	-	-
31	0	-	-	0	-	-	0	-	-
33	1	12.6	12.6	0	-	-	0	-	-

TABLE 5 - SUMMARY OF CROSS STRUCTURE IMPACTS (Cont.)

	Frame 44½			Frame 87½			Frame 108½		
Run No.	Number of Impacts	Average Impact (PSI)	Maximum Impact (PSI)	Number of Impacts	Average Impact (PSI)	Maximum Impact (PSI)	Number of Impacts	Average Impact (PSI)	Maximum Impact (PSI)
2	0	-	-	0	-	-	0	-	-
4	0	-	-	0	-	-	0	-	-
5	0	-	-	0	-	-	0	-	-
9	0	-	-	0	-	-	0	-	-
11	0	-	-	0	-	-	0	-	-
14	0	-	-	0	-	-	0	-	-
16	0	-	-	0	-	-	0	-	-
17	0	-	-	0	-	-	0	-	-
21	0	-	-	0	-	-	0	-	-
24	1	26.2	26.2	1	35.0	35.0	5	18.4	22.5
28	0	-	-	0	-	-	0	-	-
30	0	-	-	0	-	-	1	18.8	18.8
31	0	-	-	2	12.2	12.5	2	22.5	25.0
33	0	-	-	0	-	-	0	-	-

TABLE 6 - SUMMARY OF PRE-FOIL TRIAL CONDITIONS, PITCH AND ROLL ANGLES, VERTICAL MOTION AT FRAME 87½, AND VERTICAL STERN MOTION

Run	Heading	Speed (Knots)	Wave Height* (Feet)	Vertical Stern Motion** (Feet)	Pitch** (Deg)	Roll** (Deg)	Vertical Motion** Frame 87½ (g's)
1	Head	0	2.9	-	0.46	0.81	0.024
2	Head	7		0.74	0.30	0.58	0.013
3	Quartering	7		1.20	0.50	1.13	0.042
4	Beam	7		1.46	0.58	0.75	0.039
5	Bow	7		0.71	0.25	0.42	0.017
6	Following	7		1.08	0.48	0.52	0.026
7	Head	0	4.2	-	0.60	0.71	0.042
8	Head	12		0.89	0.30	0.47	0.023
9	Quartering	13		1.18	0.44	1.15	0.023
10	Beam	12		1.76	0.60	1.06	0.047
11	Bow	12		0.72	0.25	0.53	0.024
12	Following	12		0.91	0.45	0.50	0.025
13	Head	0	3.9	-	0.58	0.91	0.046
14	Head	3		1.16	0.46	0.75	0.028
15	Quartering	3		1.18	0.52	1.21	0.027
16	Beam	4		1.54	0.68	0.65	0.045
17	Bow	1		1.83	0.68	0.90	0.061
18	Beam	2		2.57	1.31	3.30	0.065
19	Head	6		4.22	2.00	0.82	0.135
20	Head	0	8.4	-	2.41	5.95	0.067
21	Head	0	11.5	-	3.82	4.31	0.107
22	Head	5		8.38	4.52	2.96	0.140
23	Quartering	5		5.60	2.21	4.57	0.063
24	Beam	5		5.24	1.85	7.00	0.088
25	Bow	7		7.32	3.65	5.20	0.121
26	Following	7		3.91	1.75	2.19	0.033
27	Head	0	7.0	-	2.35	3.10	0.070
28	Bow	12		5.39	2.80	3.20	0.140
29	Beam	12		3.35	1.38	4.20	0.077
30	Head	12		4.45	2.43	2.14	0.132
31	Following	12		3.17	1.45	1.46	0.056
32	Quartering	12		3.62	1.05	3.98	0.106
33	Head	0	8.0	-	3.16	2.48	0.181
34	Beam	0		-	1.14	1.24	-

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* Double amplitude significant values.

** Single amplitude significant values.

TABLE 7 - PITCH COMPARISON BETWEEN PRE-FOIL AND POST-FOIL CONFIGURATIONS IN STATE 5 HEAD SEAS WITH 8, 10, AND 14 SECOND MODAL PERIODS

Ship Speed (knots)	Modal Period (seconds)	Significant Pitch Angle Pre-Foil (degrees)	Significant Pitch Angle Post-Foil (degrees)	Pitch Reduction (percent)
0	8	3.5	3.4	2.9
0	10	3.6	3.4	5.6
0	14	2.8	2.7	3.6
7	8	3.8 (3.5)*	2.7	28.9
7	10	4.1 (3.7)	3.0	26.8
7	14	3.2 (3.0)	2.4	25.0
12	8	3.1	2.4	22.6
12	10	3.7	2.6	29.7
12	14	3.0	2.4	20.0

*Parentheses indicate presence of cross structure impacts.

TABLE 8 - PITCH COMPARISON BETWEEN PRE-FOIL AND POST-FOIL CONFIGURATIONS IN STATE 4, 5 AND 6 HEAD SEAS

Ship Speed (knots)	Significant Wave Height (feet)	Significant Pitch Angle Pre-Foil (degrees)	Significant Pitch Angle Post-Foil (degrees)	Pitch Reduction (percent)
0	5.6	1.9	1.8	5.2
7	5.6	1.8	1.6	11.1
12	5.6	1.5	1.2	20.0
0	9.8	3.5	3.4	2.9
7	9.8	4.1	3.0	26.8
12	9.8	3.7	2.6	29.7
0	15.1	5.2	5.0	3.8
7	15.1	5.3	4.5	15.1
12	15.1	5.2	4.0	23.1

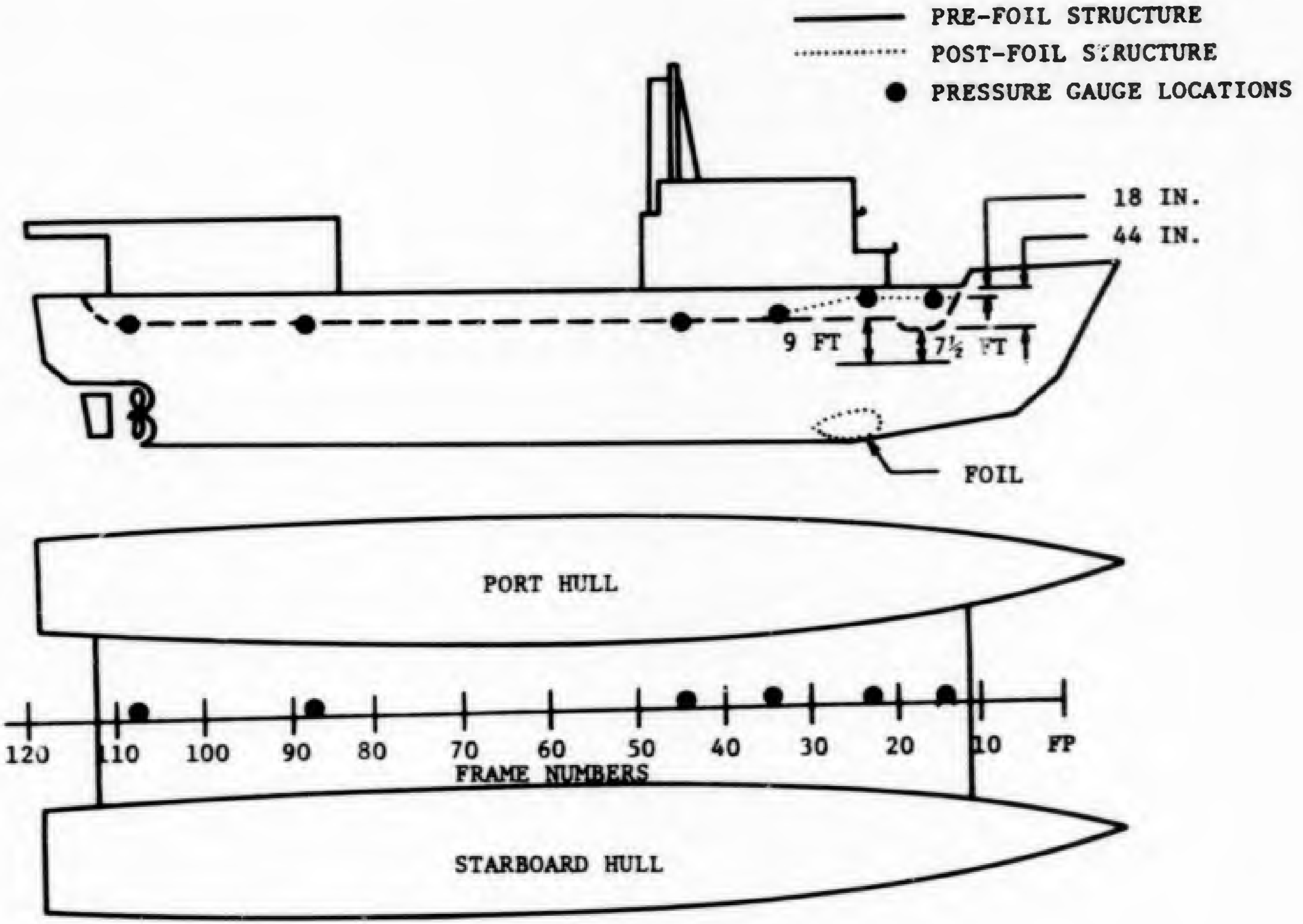

Figure 1 - Sketch of ORTOLAN Showing Pressure Gauge Locations and Structural Modifications

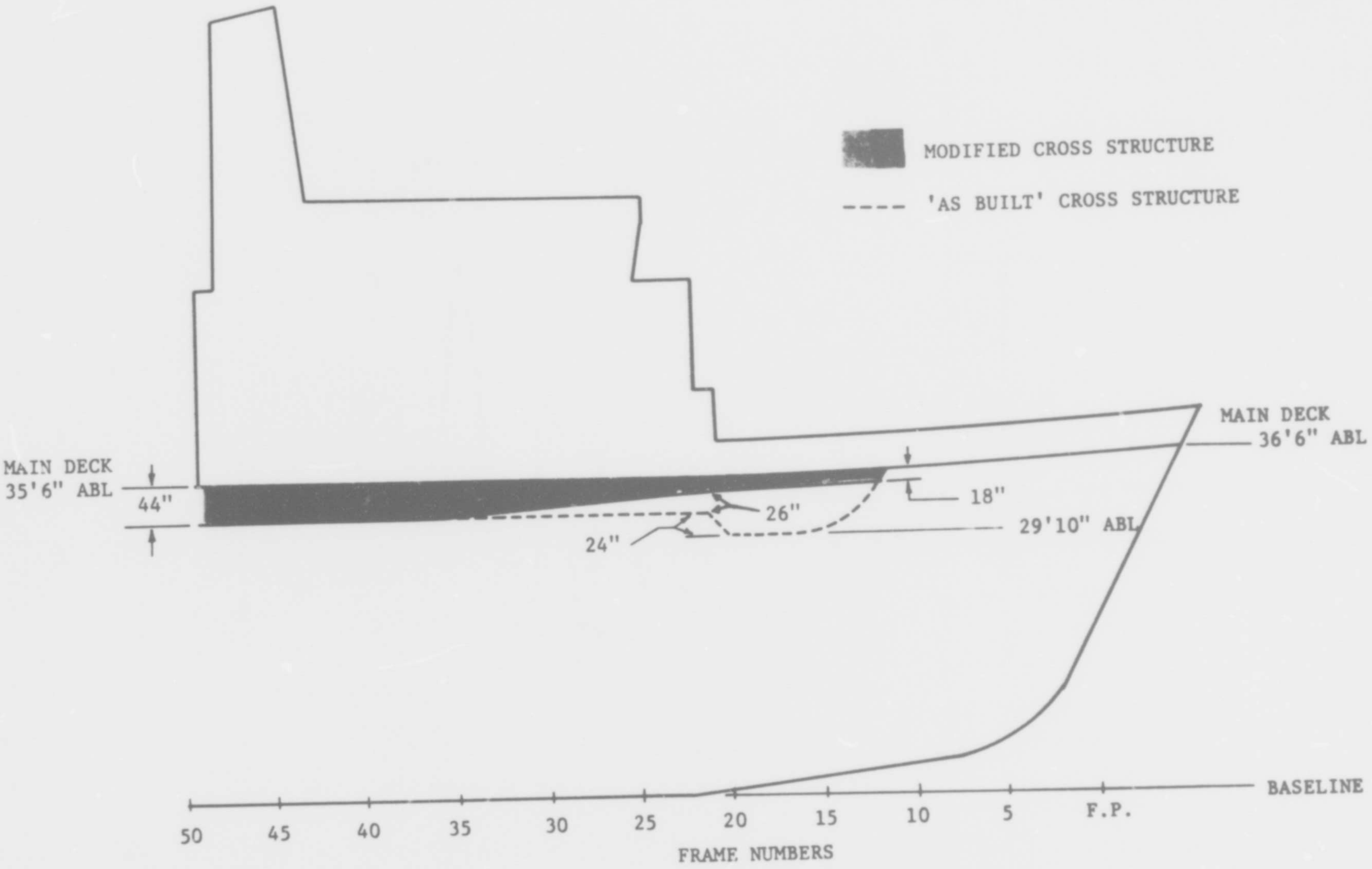

Figure 2 - Sketch Showing Modified and 'As Built' Cross Structure

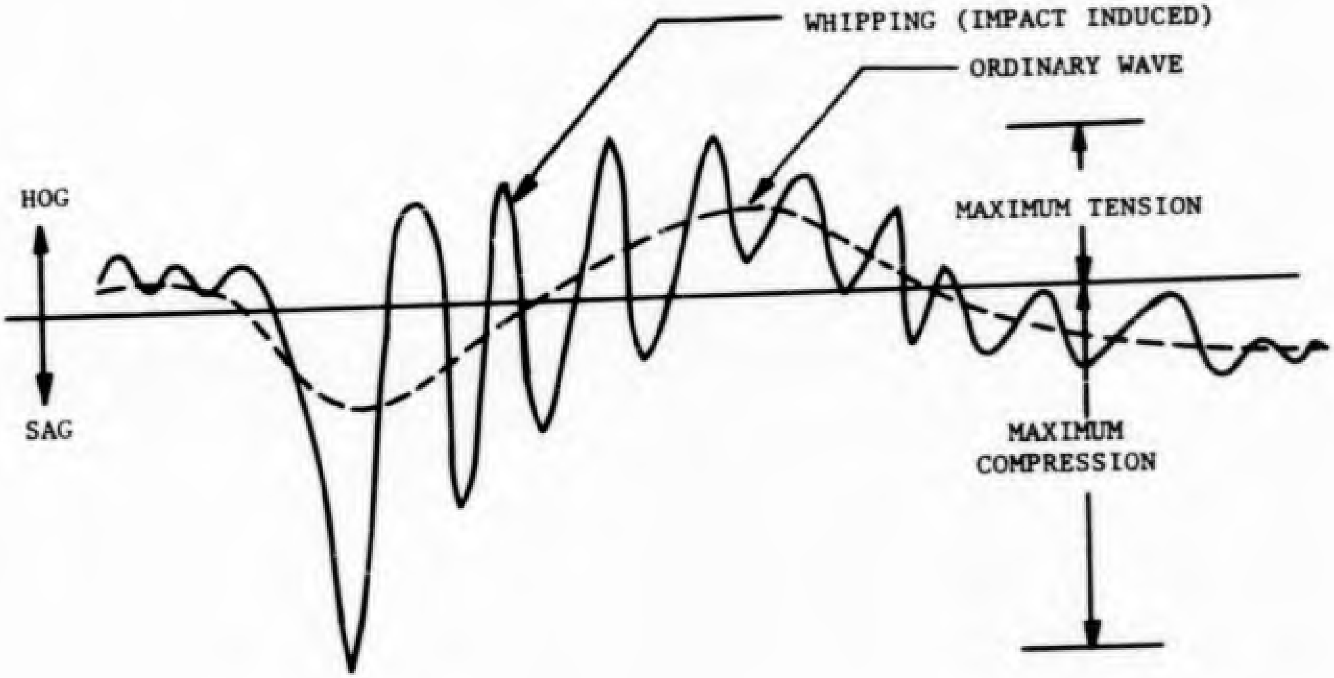

Figure 3 - Sketch of Typical Strain Gauge Time History

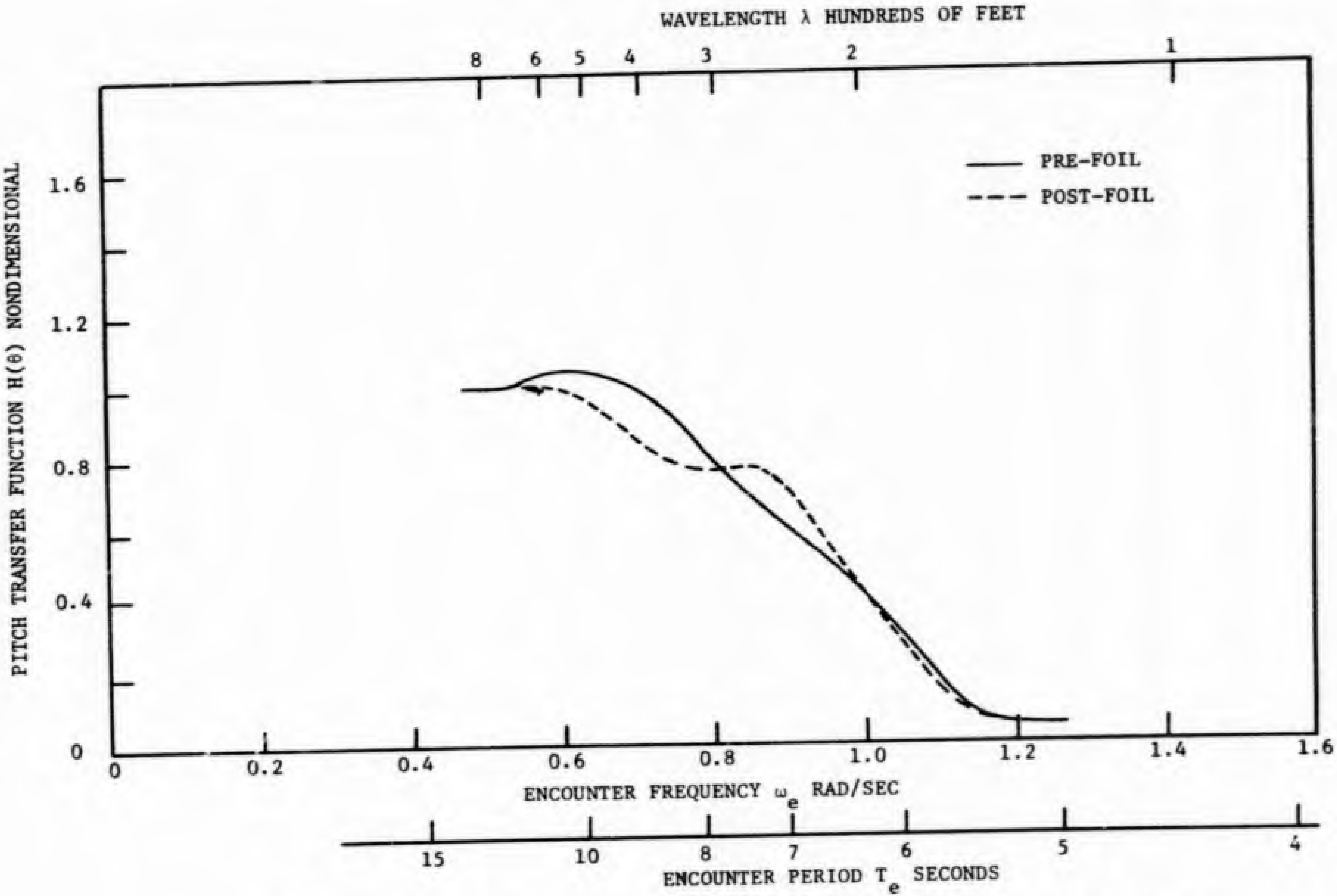

Figure 4 - Pitch Transfer Function for a Zero Knot Ship Speed in Head Seas

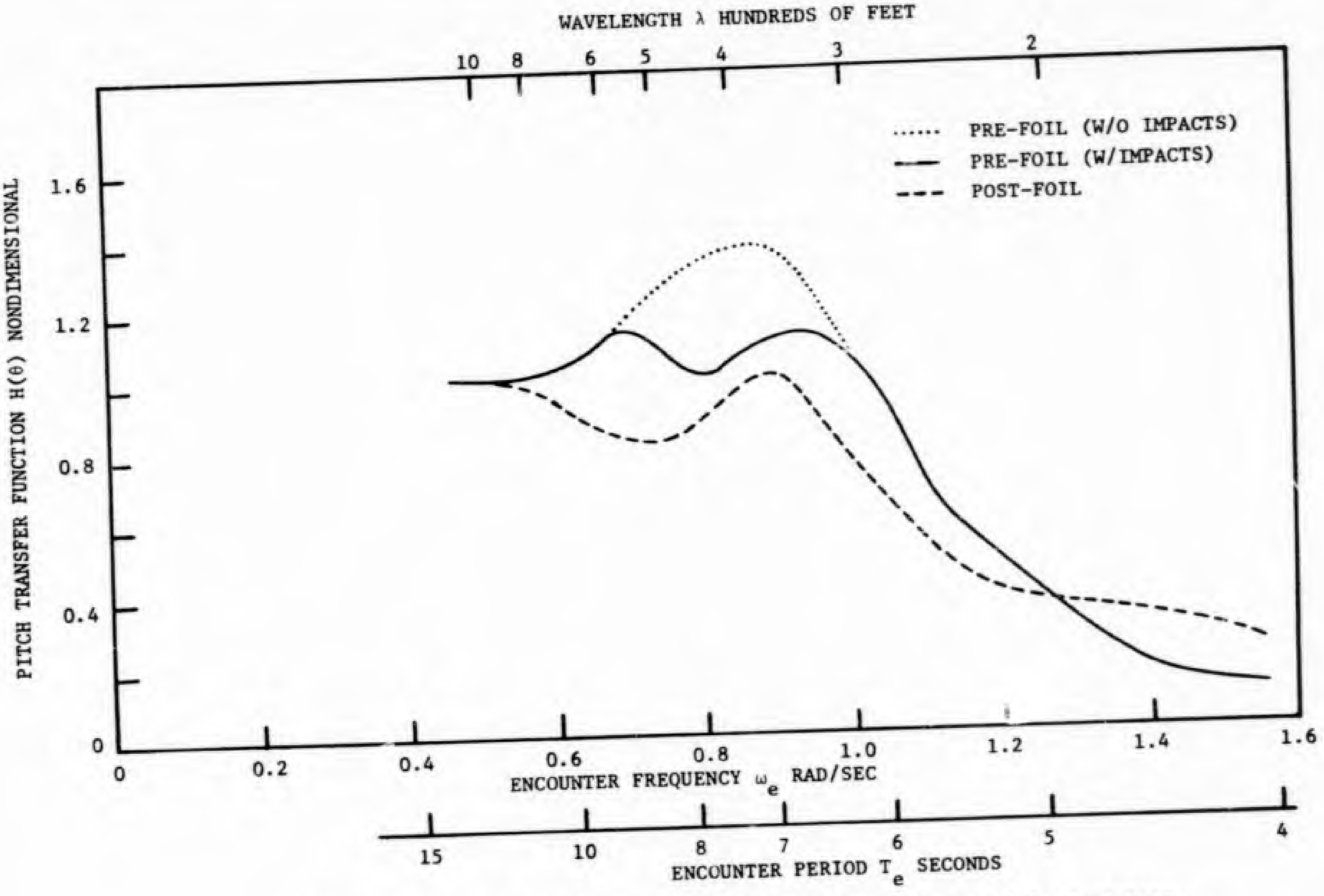

Figure 5 - Pitch Transfer Function for a 7 Knot Ship Speed in Head Seas

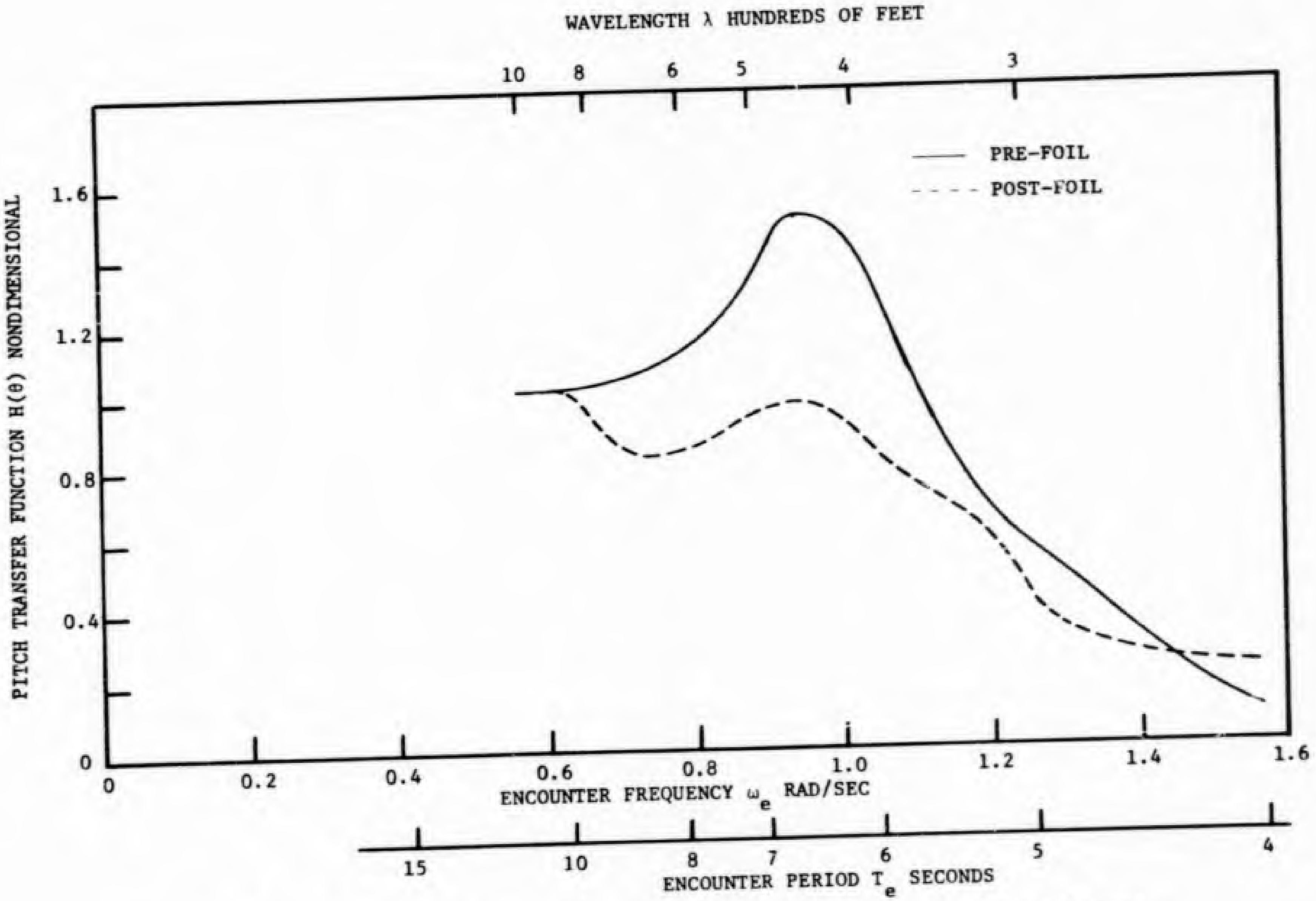

Figure 6 - Pitch Transfer Function for a 12 Knot Ship Speed in Head Seas

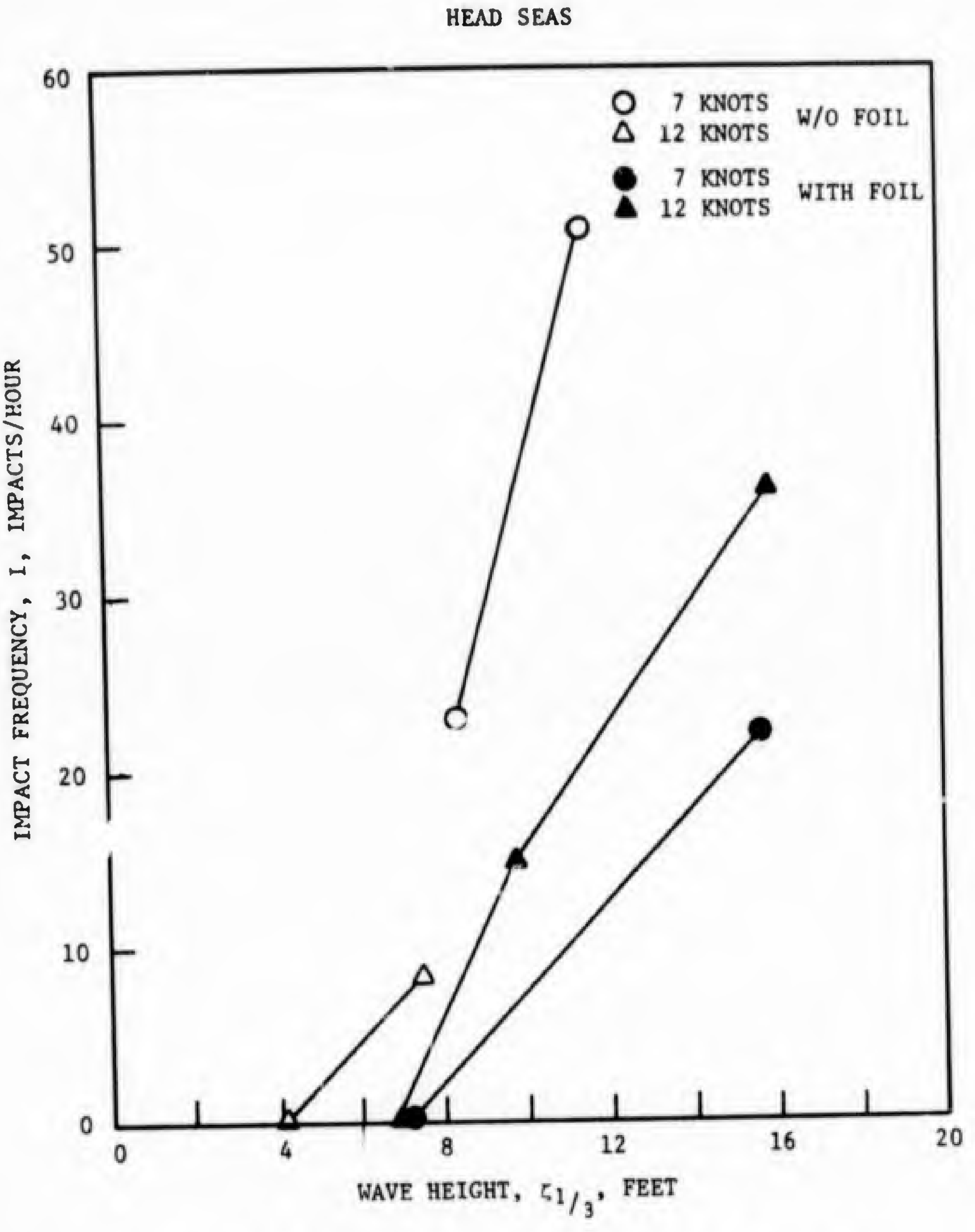

Figure 7 - Comparison Between Pre-Foil and Post-Foil Impact Frequency at Frame 23½

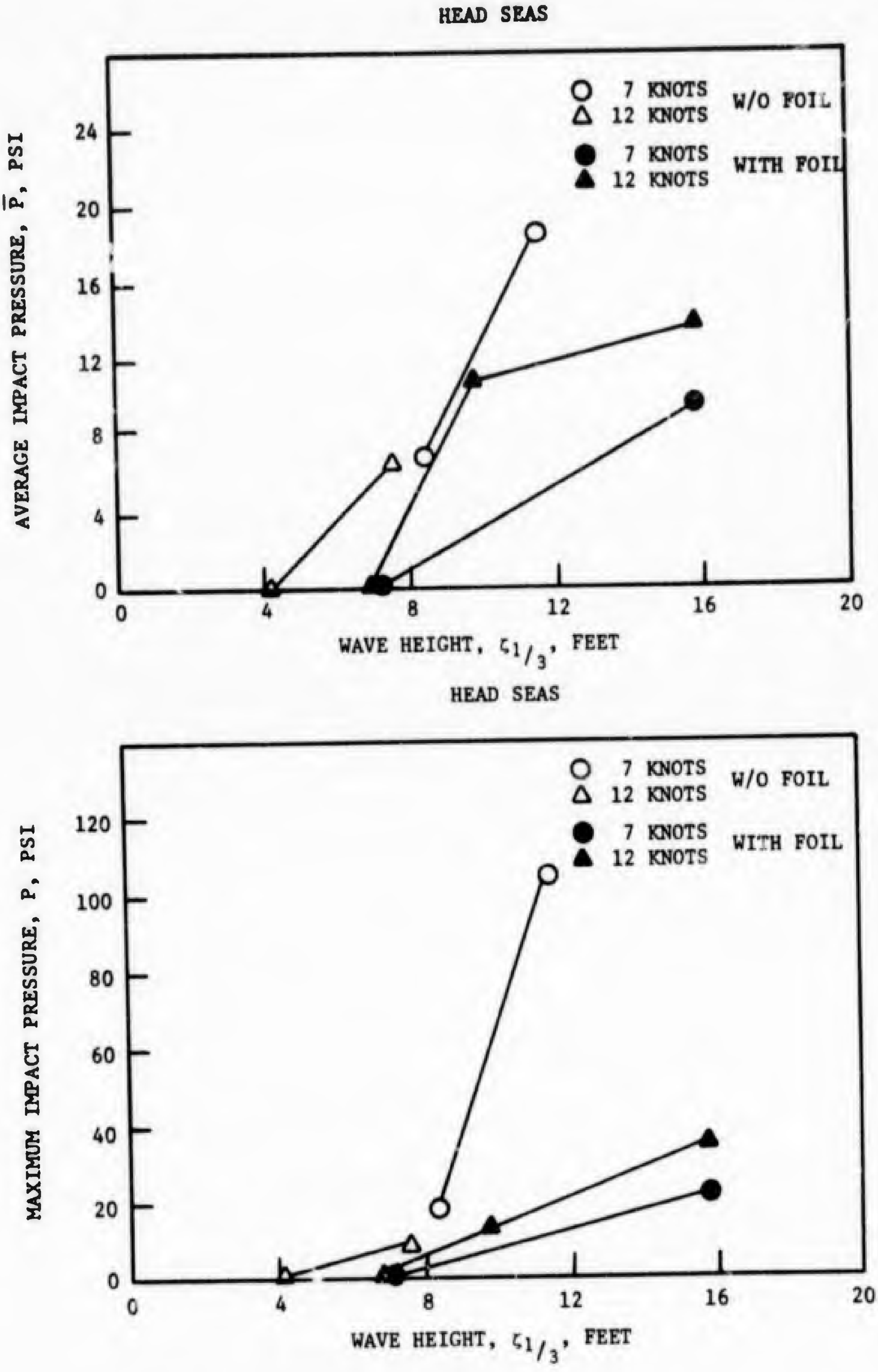

Figure 8 - Comparison Between Pre-Foil and Post-Foil Average and Maximum Impact Pressures at Frame 23½