UNIVERSITY OF MINNESOTA

St. Anthony Falls Hydraulic Laboratory

Project Report No. 153

HYDRAULIC MODEL STUDY OF SOUTH YARD PIER AND WAVE SCREENS

by

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Conducted for

Sverdrup & Parcel, St. Louis

and

Electric Boat Division
General Dynamics Corporation
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CONTENTS

PREFACE

The model test described in this report was sponsored by Sverdrup & Parcel, St. Louis, and the Electric Boat Division of the General Dynamics Corporation, Groton, Connecticut. The model was constructed between May and July of 1974. The tests were started immediately thereafter and were completed on October 15, 1974.

The experiments were performed at the St. Anthony Falls Hydraulic Laboratory under the supervision of Charles C.S. Song. The submarine model was furnished by Sverdrup & Parcel. All other models were fabricated in the Laboratory shop. Details of the test program, including model designs, measurements, and data analysis, were carried out by Messrs. Steven M. Klein, Jeffery Ferguson, Dean Randall, and Julio Wong.

SUMMARY

This report describes the results of a hydraulic model test carried out to study the effectiveness of the proposed South Yard pier in sheltering a submarine, two APL models, and a YRBM model from wave action. Various types of wave screens were also tested.

The submarine model was found to be very stable in waves with periods ranging from 2.8 seconds to 8.2 seconds with no wave screen. In fact, no screen tested in the study was found to contribute significantly to the stability of the submarine.

The existence of the proposed pier alone reduced the amplitudes of pitching, rolling, and heave oscillations of an APL model by roughly 50 percent. A submarine model moored to the pier reduced the oscillations of an APL by another 50 percent.

I. INTRODUCTION

This report describes the procedure followed and the results of a hydraulic model study performed at the St. Anthony Falls Hydraulic Laboratory during May through October of 1974 for the purpose of evaluating the wave screening properties of a proposed pier structure.

A 1:80 scale model representing a 2,000 ft by 3,000 ft area of the Thames River surrounding the proposed pier site was constructed. Regular waves were generated using plunger-type wave generators located at the south end of the model. Wave height distributions in the vicinity of the proposed site were measured with and without the pier and also with wave screens of various solidity. For example, a wave screen of 25 percent solidity consists of 1 ft wide sheet piles spaced 4 ft between centers. Wave-induced motions of a submarine model, a YRBM, and two APL models were also measured.

The test results show that the proposed pier offers substantial protection for an APL and YRBM moored in the sheltered area. Additional protection for these small craft can also be provided by wave screens having 50 percent or greater solidity. The presence of a submarine moored along the pier also provides a significant amount of protection for the small craft. In contrast, no wave screen limited to the length of the pier was found to significantly increase the stability of the submarine. The submarine is very stable when exposed to waves for periods less than 8 seconds moving from south to north. A more detailed description of the experimental results is given in the following sections.

II. DESCRIPTION OF THE MODEL

As with many other river and harbor models, the main consideration with regard to model size is the limit imposed by the vertical dimension, including water depth and wave height. To insure reasonable accuracy of measurement and avoid excessive viscous effects, a certain minimum vertical dimension has to be maintained. Model distortion, often used in river models, was ruled out because the test involves the dynamics of ship motions. These considerations led to the choice of a 1:80 undistorted model. This scale gives a reasonable average water depth of about 5 inches. However, the wave heights used in the model had to be somewhat greater than the prevailing wave heights in the field so that the wave height and the ship's oscillations could be accurately measured. This does not result in significant errors as long as the waves are not too steep.

The overall arrangement of the model is shown in Fig. 1. This model configuration is based on the preliminary design by Sverdrup & Parcel*. The model covers a portion of the shoreline immediately upstream and downstream of the proposed pier so that reflection and diffraction from the boundary can be simulated. Three plunger-type wave generators, each 8 ft long, are installed at the south end of the model. These wave makers can be rotated 15° about their vertical axis to permit changing the direction of the waves. In their neutral positions the wave makers generate waves that travel from south to north. All the tests described in this report deal with southerly waves. This is the direction of the longest fetch and, hence, represents the severest wave condition.

A wave absorber was installed along the northern boundary of the model. This wave absorber, acting as a sink and reducing wave reflection, simulates the river as it extends far upstream beyond this boundary. Although the west wall also cut through the water, no wave absorber was needed there, because only south-north waves were tested.

One YRBM and two APL models were constructed at the Laboratory. These models were ballasted to insure dynamical similarity with the corresponding prototypes for three modes of motion: heave, roll, and pitch. This necessitated the scaling of the water line and the radii of gyrations about the longitudinal and transverse axes. A ballasted submarine model was furnished by the sponsor of the project.

Two resistance-type wave sensors were used to measure the wave height, a stationary sensor located at point O, marked in Fig. 1, and a movable wave sensor mounted on a carriage. The fixed wave sensor was used to measure the incident wave and the movable sensor was used in wave surveying.

The motions of the ship models were measured using the sonar principle. A pair of sonic transducers mounted on a carriage measured the distances

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*Sverdrup & Parcel, "South Yard Piers, Preliminary Design Study," St. Louis, Missouri, March 1973.

from the transducers to a platform mounted on the model. Data from transducers lined up with the longitudinal axis of a ship model yield heaving and pitching motions. When the transducers are turned 90° heave and roll can be measured. This type of sensor is excellent for the present purpose because it exerts no external force on the ship models. The models had to be restrained against drifting so that a stable target was provided for the sonar.

Figure 2 shows the mooring methods adopted for the models. The purpose of the mooring was to limit drifting while external constraints on heave, roll, and pitch were minimized. No attempt was made to simulate the mooring forces that may exist in the prototype. Thus little or no initial tension was applied to the mooring strings attached to the models.

Figure 3 is an overall view of the model showing wave diffraction and transmission in the presence of a pier. Figure 4 is a close-up view of the test area with all the models in place.

III. RESULTS OF MODEL TESTS

According to the field measurements reported by Leone*, waves of periods ranging from 2.8 seconds to 8.2 seconds were relevant for this study. The maximum wave height observed for the period November 12, 1973, through April 13, 1974, was 1.5 ft. For the 1:80 scale model, the period of the required waves should range from 0.313 seconds to 0.917 seconds, giving a frequency range of 3.19 to 1.09 Hz. In the actual tests the wave frequency was varied in steps from 1 Hz to 3 Hz at 0.5 Hz intervals. When necessary, additional data were also taken to obtain the peak amplitude and the corresponding frequency. The maximum wave height of 1.5 ft is rather small to be accurately duplicated in the model. The actual wave height used in the model tests ranged from 0.025 ft to 0.05 ft, which corresponds to 2 ft to 4.8 ft prototype. The increased wave height did not cause excessive error, because the wave steepness was substantially below that of a breaking wave. This was confirmed by repeating some tests with different wave heights.

A. Wave Survey

Because of the complicated reflection and diffraction patterns, the

*Leone, Donald E., "Thames River Wave Monitoring Study," Electric Boat Division, General Dynamics, June 3, 1974.

wave height may vary significantly from location to location. Figure 5 shows the results of wave measurements carried out at the five points shown in Fig. 1 near the proposed pier site under existing conditions (without pier). The values plotted here are relative values referred to the wave heights measured at the reference point 0. Here, the reference point 0 was located somewhat north of the station where the field measurements were taken. This point was selected as the reference point because the field station was not included in the model. A very large spread in the wave heights between stations for a 0.17 Hz or 5.9 second wave indicates the existence of large standing waves at this frequency. This may explain why the APL and YRBM models oscillate most severely at or near this frequency; this will be discussed later.

The effects of the pier and wave screens on wave height distribution are indicated in Figs. 6 through 10. These figures show, in general, that the pier and wave screens reduce the wave height on the sheltered side (points 3,4, and 5), but increase it on the exposed side (points 1 and 2). As can be seen in Figs. 6 and 7, the effect of the wave screen on the exposed side is more pronounced for shorter waves than for longer waves; that is, the relative wave amplitude as compared with the existing conditions on the exposed side increases as the wave frequency increases. On the other hand, Fig. 8 shows that the wave height on the sheltered side decreases with the wave frequency. Clearly, this is due to the fact that the wave screens are more effective wave reflectors for shorter waves than for longer waves. In other words, longer waves can pass through porous screens more readily than shorter waves.

B. Oscillations of Submarine Model

The motions of a submarine model placed on the north (sheltered) side without a wave screen are plotted in Fig. 11. In this figure the measured amplitudes of pitch, roll, and heave were normalized using the length of the ship and the wave height as follows:

$$\text{Normalized pitch} = PL/W_o$$
$$\text{Normalized roll} = RL/W_o$$
$$\text{Normalized heave} = H/W_o$$

where P = Twice the pitch amplitude (peak to trough) in radians

R = Twice the roll amplitude (peak to trough) in radians

H = Twice the heave amplitude (peak to trough) in feet

L = Length of ship in feet

W_o = Incident wave height (at point 0) in feet

The prototype frequency in Hz is used as the independent variable in this and all subsequent figures. As shown in Fig. 11, the amplitude of oscillations increases monotonically with decreasing frequency or increasing wave length. For wave frequencies greater than 0.17 Hz. the submarine would be practically motionless. Even for the longest wave tested, the stability of the submarine is, perhaps, of no great concern. For example, at the worst condition of 0.11 Hz and the maximum wave height of 2 ft, the magnitude of oscillation would be

$$P = 1.44 \times 2/550 = 5.24 \times 10^{-3} \text{ radian} = 0.30^\circ$$
$$R = 5.10 \times 2/550 = 18.6 \times 10^{-3} \text{ radian} = 1.06^\circ$$
$$H = 0.36 \times 2 = 0.72 \text{ ft}$$

To study the effect of wave screens on the stability of the submarine model, a 50 percent screen consisting of 2-ft-wide piles spaced at 4-ft intervals between centers was fitted to each side of the pier model. The resulting motion of the model is shown in Fig. 12. There is a noticeable improvement over the previous case in the lower range of wave frequencies. A similar experiment carried out for 100 percent wave screens (solid plates), as indicated in Fig. 13, showed no further improvement over the 50 percent screens.

In the next series of tests, the submarine model was placed on the south side of the pier and subjected to waves from the south. The results with 50 and 100 percent wave screens are shown in Figs. 14 and 15, respectively. Comparison of these two figures with Figs. 12 and 13 indicates that the submarine would be slightly less stable, especially for longer waves, on the exposed side of the pier as it would be on the sheltered side. A possible explanation of this result is that the submarine is so large that it responds very little to the relatively short waves used in the experiment. Since the submarine is about the same length as the pier, the mutual interaction between the ship model and the waves is comparable to that of the pier model and the waves. That is to say, for the range of wave lengths for which the pier modifies the wave pattern, the submarine is also effective and stable. As clearly indicated in Figs. 6 and 7, large amplitude standing waves are produced on the exposed side of the pier only in the relatively high frequency, or short wave, range. On the other hand, Figs. 11 through 15 indicate that the submarine responds only to relatively low frequency waves or long waves.

C. Effect of Pier and Wave Screens on the APL and YRBM

The first series of experiments involving APL and YRBM models were carried out for the purpose of reproducing the existing condition and to serve as a reference. A single APL model was moored normal to the wall. No pier or wave screens were installed. Waves were generated and the oscillations of the model measured. Figure 16 shows the normalized amplitude of pitch, roll, and heave plotted as a function of the prototype wave frequency. This and other figures show that an APL would resonate at a frequency of about 0.13 Hz. At this resonant frequency, the amplitudes of the motions should be very sensitive to any restraining or damping force that may exist in the system. Therefore, this peak amplitude should not be scaled up for the purpose of predicting the precise peak amplitude of the prototype. For an order-of-magnitude estimate, a 2-ft wave at 0.13 Hz would cause rolling, peak to trough, of

$$R = 14 \times 2/260 = 0.108 \text{ radian} = 6.2^{\circ}$$

At much higher frequences this would be reduced to 0.35°.

Figure 17 shows the results of similar tests for a single YRBM moored normal to the wall. This and other figures show that a YRBM resonates at 0.17 Hz. Figure 17 shows that the maximum pitching motion for a 2 ft wave at 0.17 Hz is approximately

$$P = 2.3 \times 2/147 = 0.0313 \text{ radian} = 1.8^{\circ}$$

For the next series of experiments a pier model was installed and an area around the pier was excavated according to the design outlined by Sverdrup & Parcel. Each test involved either a single APL model or a single YRBM model moored normal to the wall. The results are shown in Figs. 18 and 19. Improved stability, especially in the pitching mode, is noticeable.

Next, a series of experiments were carried out to determine the effectiveness of various wave screens on reducing dynamic motions of the models.

In each case, two identical wave screens were attached to the pier model, one on each side of the pier. Figures 20, 21, and 22 show the effect of 25 percent, 50 percent, and 100 percent screens, respectively, on an APL model moored normal to the wall. Corresponding results for the YRBM model are shown in Figs. 23, 24, and 25. Because of the sharp peaks that occurred at the resonant frequencies, these figures do not show the overall effect of the wave screens clearly. For this reason, the amplitudes of oscillation were averaged over the range of frequencies tested and plotted in Figs. 26 and 27. Here the relative magnitudes of the oscillations, referred to the case with the pier only, were plotted as a function of wave screen solidity. The existing condition, with no pier, is plotted arbitrarily on the left edge of the graph. These figures indicate that (1) the presence of the pier alone reduces oscillation by roughly 50 percent and (2) the addition of the 25 percent wave screens actually increases the oscillation of the YRBM.

D. Effect of Mooring Orientation on the Stability of the APL

For all the tests carried out previously, the APL and YRBM models were moored normal to the wall. To study the effect of the mooring orientation on the stability of the models, tests were carried out for three additional mooring orientations: parallel to the wall, normal to the pier, and parallel to the pier. The results for an APL model with the 100 percent wave screens are shown in Figs. 28, 29, and 30. These figures should be compared with Fig. 22. The test results indicate very little directional effect on the ship's oscillation when 100 percent wave screens are in place. This is probably an indication of the sheltering effect of the wave screens, which reduced not only the amplitude, but also the directional characteristics of the waves in the sheltered area.

The results are quite different when 50 percent wave screens are used. Figures 31 and 32 show the APL moored parallel to the wall and normal to the pier, respectively. From these figures and Fig. 21, it can be concluded that the best orientation is normal to the wall and the worst is parallel to the wall. This conclusion is reasonable, because when the incident waves are nearly normal to the wall, large-amplitude standing waves are set up by the wall. These standing waves would hit broadside on ships moored parallel to the wall and cause large-amplitude oscillations. Unless the area is well sheltered, it is recommended that the APL and YRBM be moored normal to the wall. If the area is well sheltered, then the mooring orientation is not important.

E. Two APL's and a YRBM as a Group

When three boats are moored parallel to each other as a group, mutual interactions may influence the oscillations. Figure 33 shows the motions of an APL model when three models are arranged as indicated by the sketch, with the YRBM in the center. No pier or wave screen was used in this test, and this figure should be compared with Fig. 16. Figure 33 indicates that in the presence of other models, an APL model becomes more stable in the rolling mode, but oscillates more severely in the pitching mode. Note that the rolling amplitude exceeds the pitching amplitude in Fig. 16, but the opposite is true in Fig. 33. Figure 34 shows the motions of the YRBM model under the same conditions as are shown in Fig. 33. Comparison of this figure with Fig. 17 reveals increased instability in the pitching mode due to the presence of the two APL models. Severe pitching oscillation of the YRBM at high frequencies suggests the existence of standing waves trapped between the APL models. Therefore, this mooring configuration is not recommended. Figure 35 shows the oscillations of the YRBM with the pier in place and the three models rearranged so that the YRBM model is in the corner. Exact comparison of this figure with Fig. 34 is not possible because of the pier. However, it seems likely that the elimination of the severe standing waves in the higher frequency range can be attributed to the rearrangement. Figure 35 shows a slight lessening of stability compared with Fig. 19 due to the presence of the other craft. Much as with the single model, solid-wall wave screens also provide some protection for the APL's and the YRBM; this is indicated in Figs. 36 and 37.

F. Effect of Submarine on APL

As was stated in Section III-2, the submarine was very stable for the range of wave lengths tested. Also, because the submarine is comparable in size to the pier, its sheltering effect relative to smaller craft is also comparable to that of the pier with a wave screen. Figure 38 shows the results of measurements on an APL moored normal to the wall with the submarine model moored on the north side of the pier. This figure should be compared with Figs. 20, 21, and 22. The average amplitudes for the five frequencies tested were also computed and plotted in Fig. 26. It appears that the sheltering effect of the submarine model with respect to an APL is comparable to that of 50 percent wave screens.

A similar experiment was conducted for the case of an APL moored parallel to the wall. The results are plotted in Fig. 39. This figure also shows that the sheltering effect of a submarine varies for the three modes and is roughly equivalent to that of 50 percent wave screens.

G. Other Wave Screen Configurations

The experiments described in the previous sections deal only with wave screens of uniformly distributed porosity extending from one end of the pier to the other, one on each side of the pier. It was suggested that, if they proved to be as effective, solid walls covering part of the length of the pier might be more economical than porous wave screens extending the total length of the pier. Therefore, a test was conducted using solid walls attached to the offshore half of the pier. The resulting rolling motions of the submarine model moored along the north side of the pier are plotted in Fig. 12 and compared with the corresponding data for the 50 percent uniform wave screens. Clearly, the alternate configuration is more effective than the corresponding uniform wave screens.

Placing wave screens on both sides of the pier, especially if solid walls are used, may not be as economical as using only one screen. The measured rolling amplitudes of the submarine model moored along the north side of the pier with a solid wall attached to the south side of the pier are plotted in Fig. 13. This figure shows that a single solid wave screen is actually more effective than two screens. A single solid-wall wave screen is also more effective than two solid walls in protecting small craft. This fact is illustrated in Fig. 22, in which the rolling amplitude of an APL model is plotted for both cases.

VI. CONCLUSION

Based on the experimental data presented above, the following conclusions are offered:

1. For southerly waves of period less than 8 seconds and heights less than 2 ft, the submarine needs little or no protection. This

applies to a submarine moored on either side of the pier. Slightly larger amplitude oscillation can be expected for a submarine moored or south side of the pier when subjected to long waves.

2. Because the submarine is basically very stable, wave screens do not contribute much to the stability of the ship.

3. Severe oscillation problems exist for APL and YRBM models moored to the wall in the original exposed position. With the proposed pier and dredging, these oscillations may be reduced by roughly 50 percent.

4. Wave screens further reduce all three modes of oscillation of an APL model. The use of two 50 percent wave screens may cut the amplitude of oscillation by roughly 50 percent.

5. The use of two 25 percent wave screens actually decreases the stability of a YRBM model.

6. One wave screen is about as effective as two identical screens placed one on each side of the pier.

7. Solid-wall wave screens placed on the offshore half of the pier are more effective than 50 percent wave screens placed along the total length of the pier.

8. When two APL's and one YRBM are moored as a group, the YRBM should not be placed in the middle.

9. The best mooring orientation for both the APL and the YRBM is normal to the wall. This is particularly important when the area is not protected by wave screens or a submarine. The worst orientation is parallel to the wall.

LIST OF FIGURES

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LIST OF FIGURES [Continued]

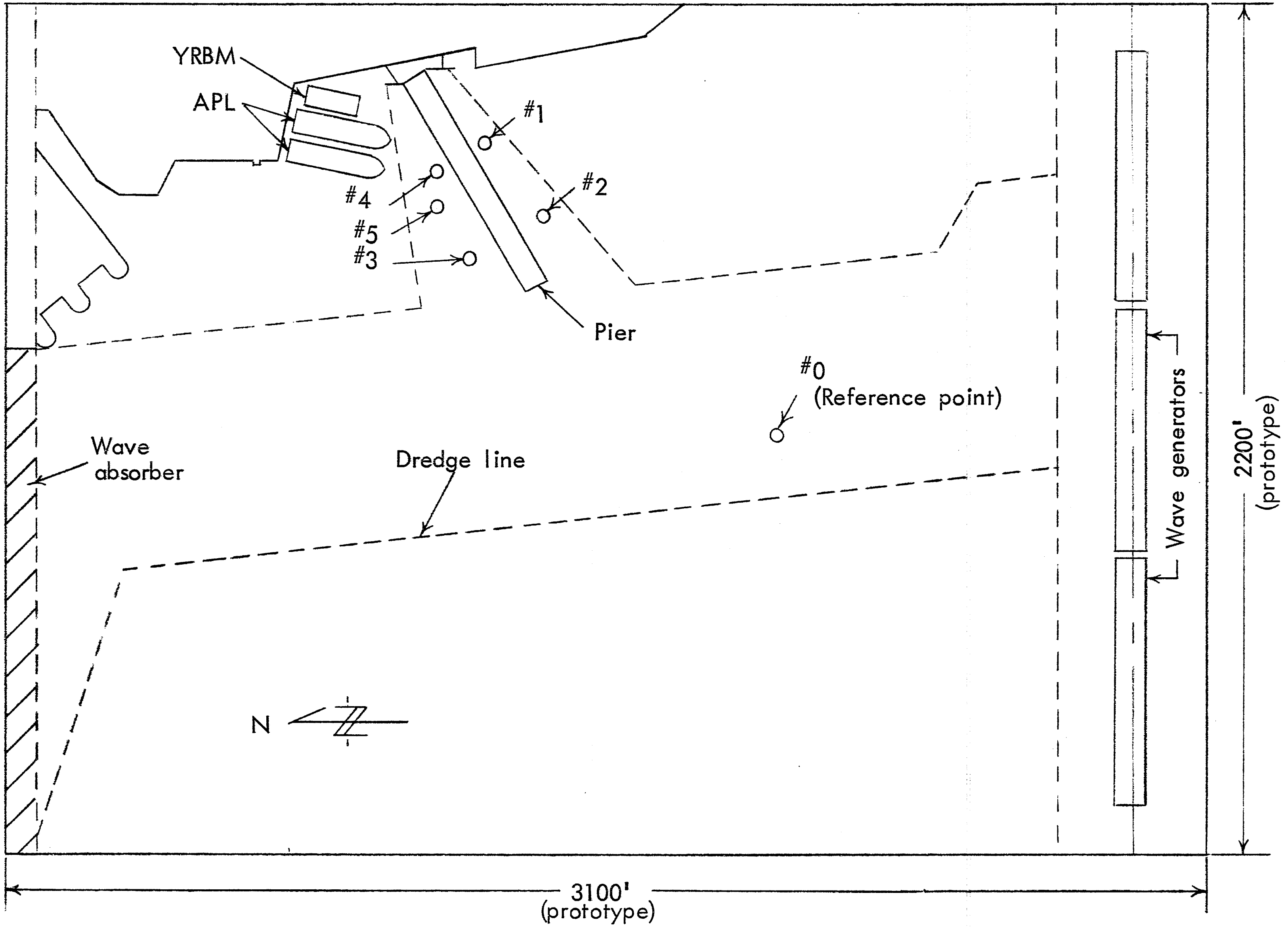

Fig. 1 - General layout of the model

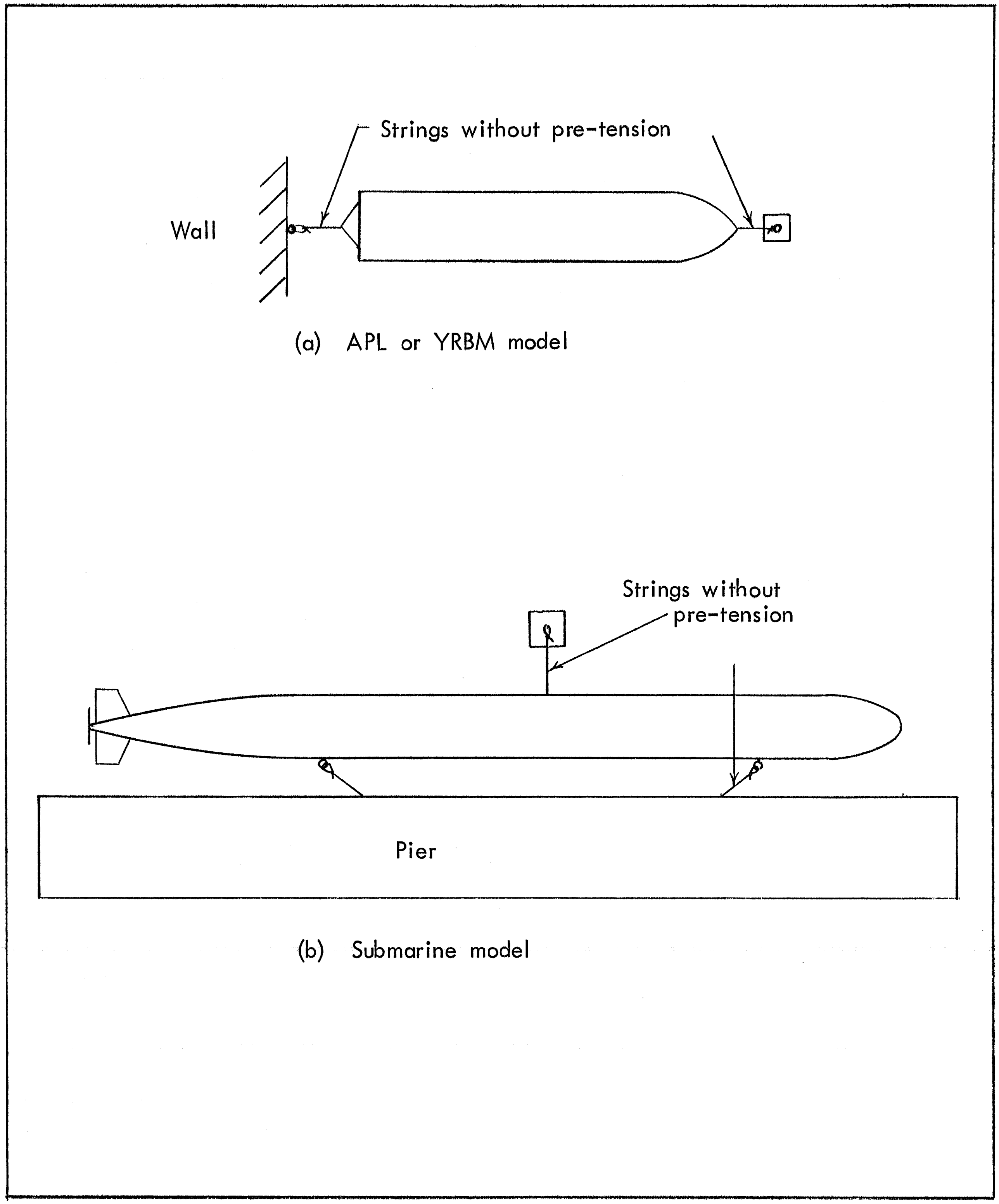

Fig. 2 - Mooring methods for ship models

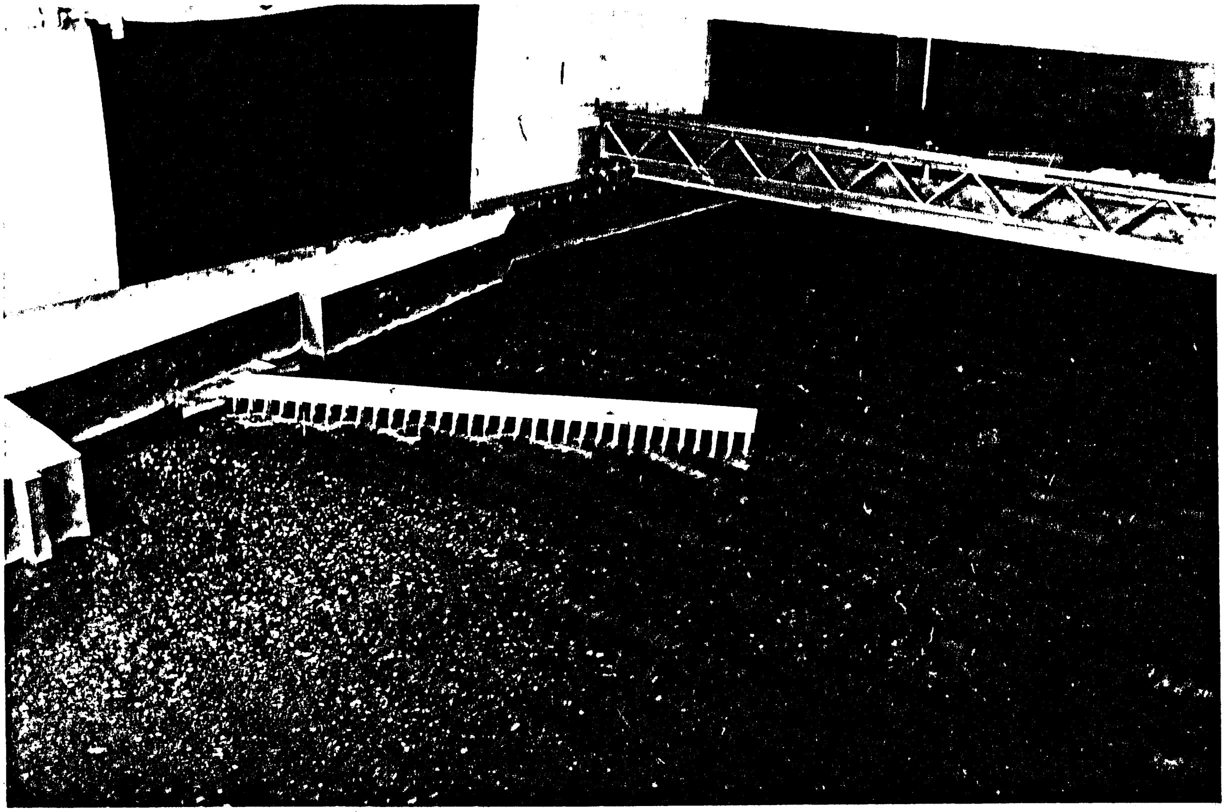

Fig. 3 - (Ser. No. 235-13) Overall view of the model showing wave reflection and transmission

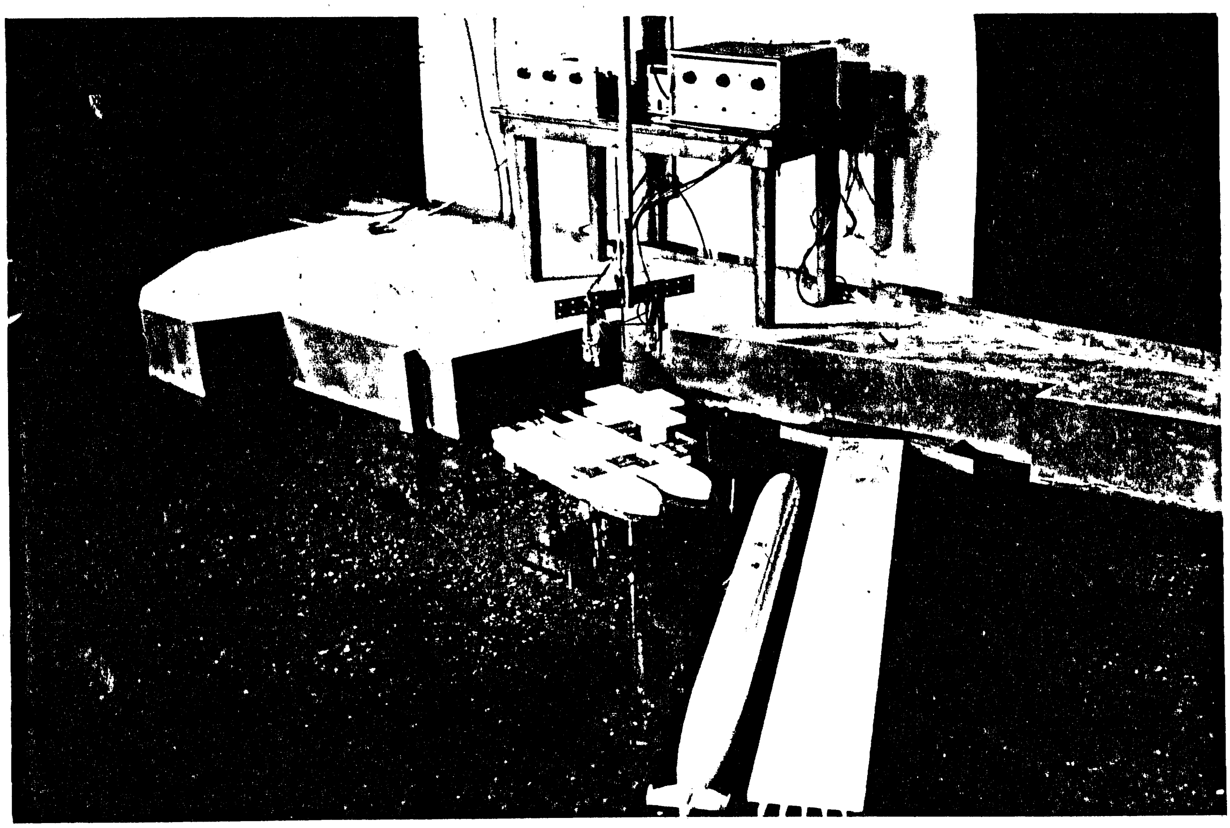

Fig. 4 - (Ser. No. 235-35) Close-up view of the sheltered area showing all models in place

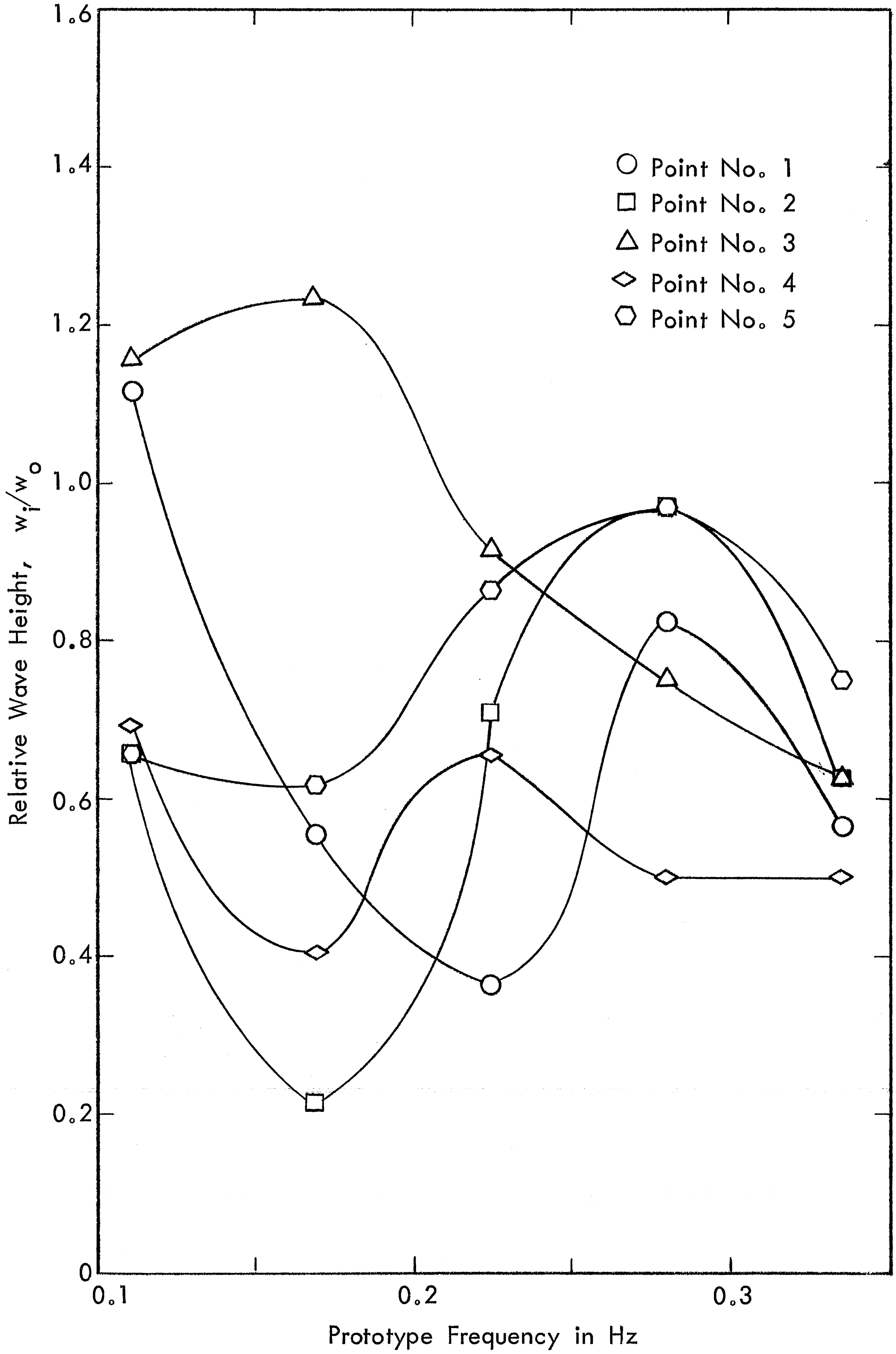

Fig. 5 - Relative wave height measured near proposed pier site - existing condition

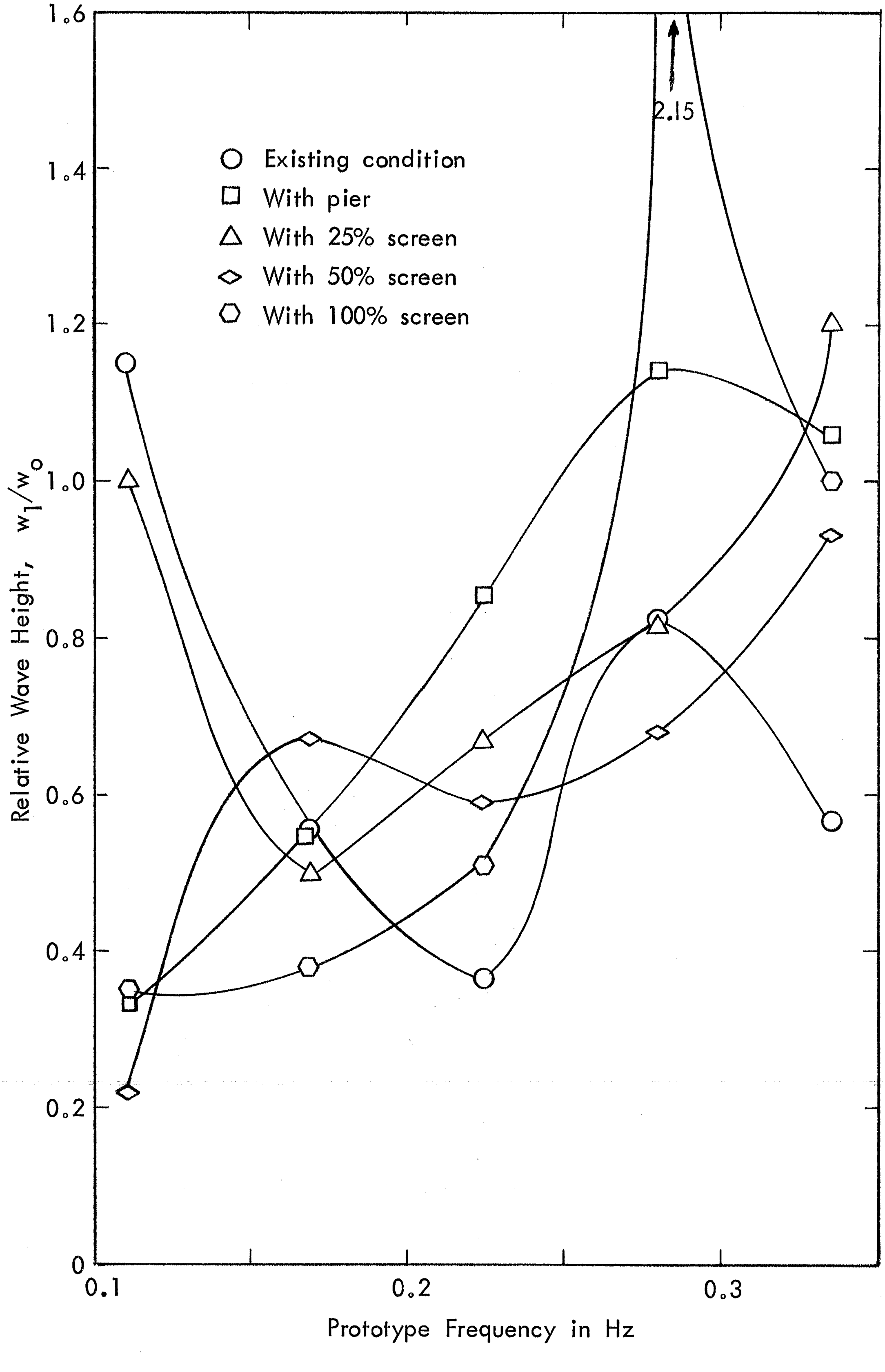

Fig. 6 - Effect of pier and wave screens on wave height at Point No. 1

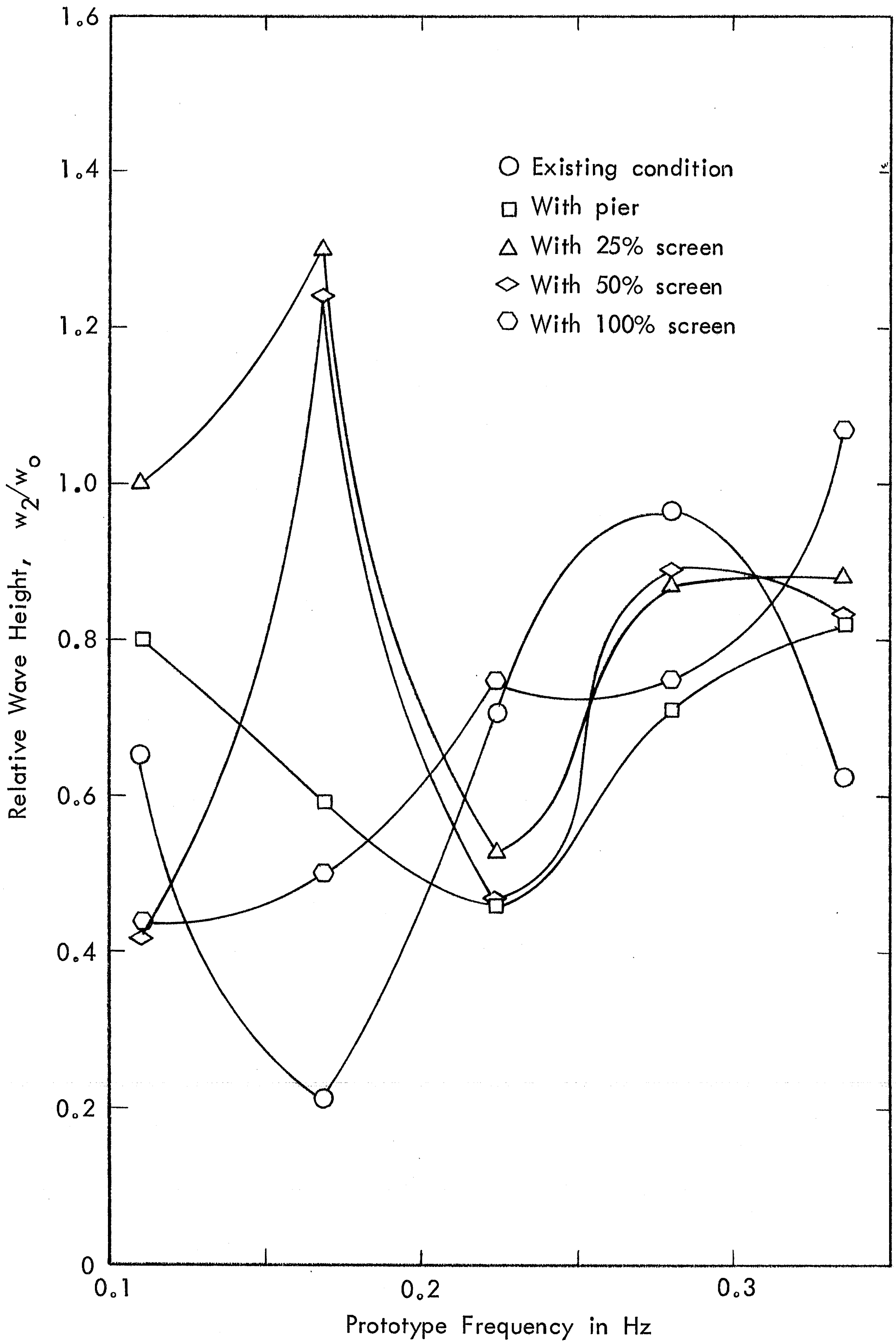

Fig. 7 - Effect of pier and wave screens on wave height at Point No. 2

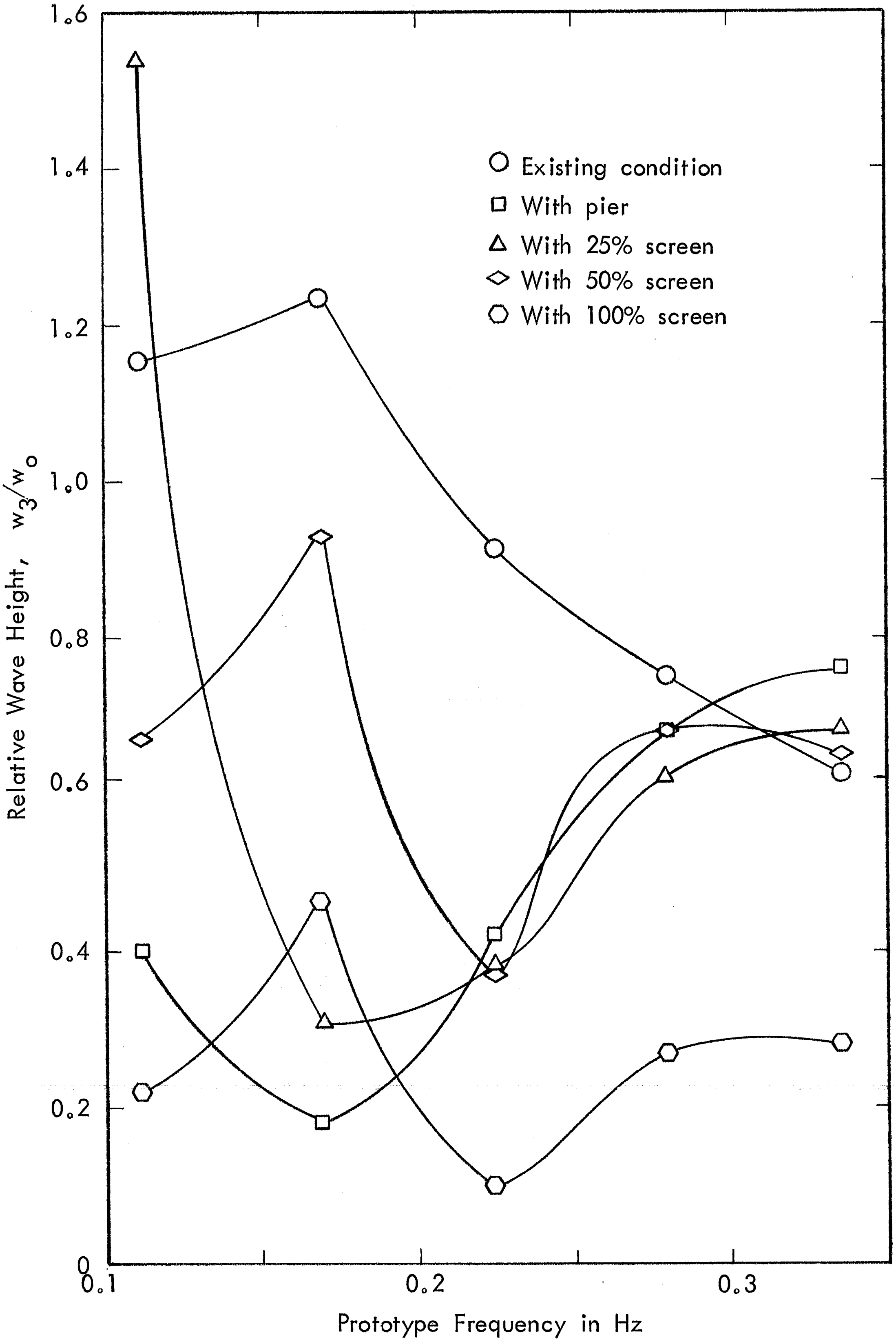

Fig. 8 - Effect of pier and wave screens on wave height at Point No. 3

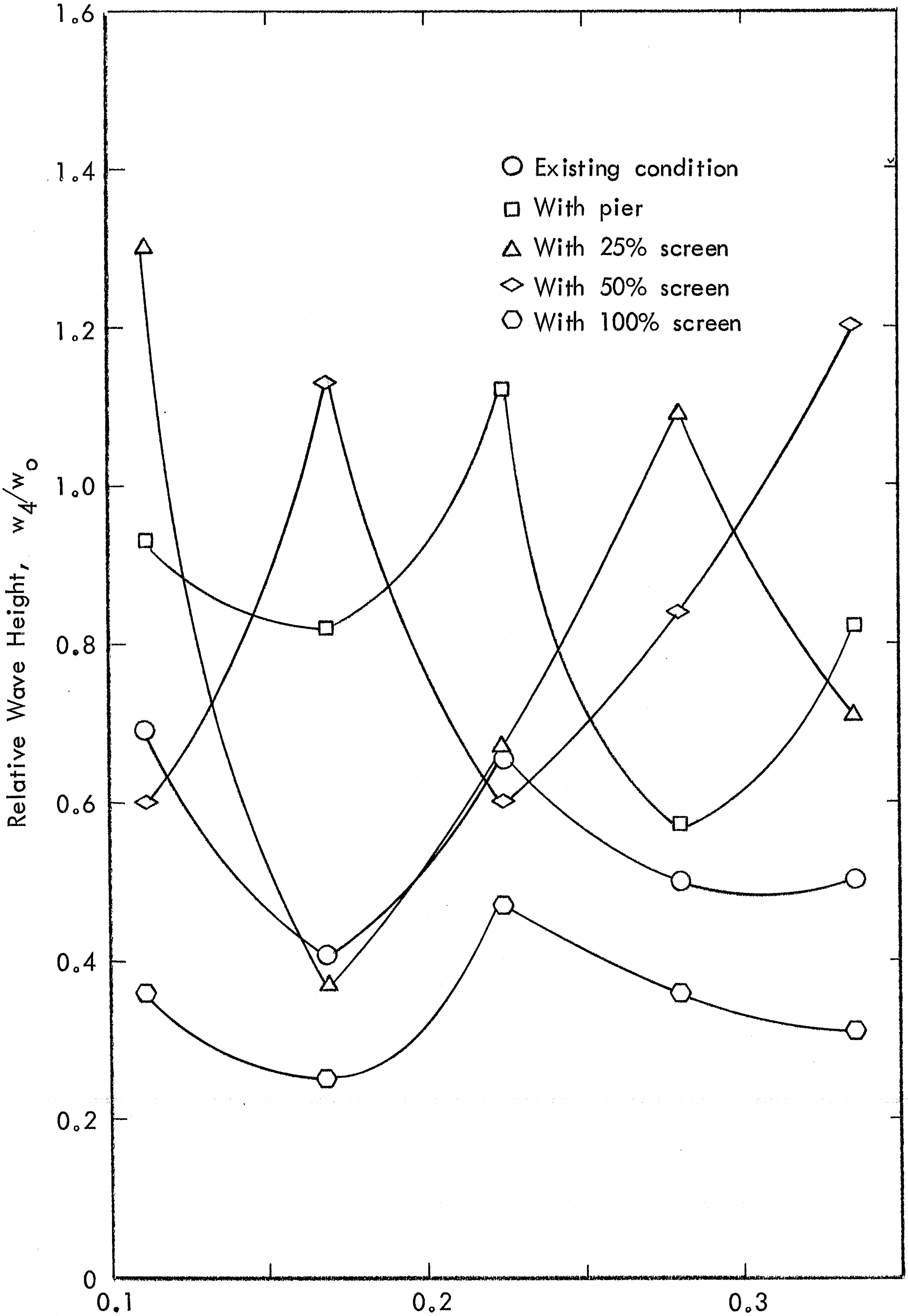

Fig. 9 - Effect of pier and wave screens on wave height at Point No. 4

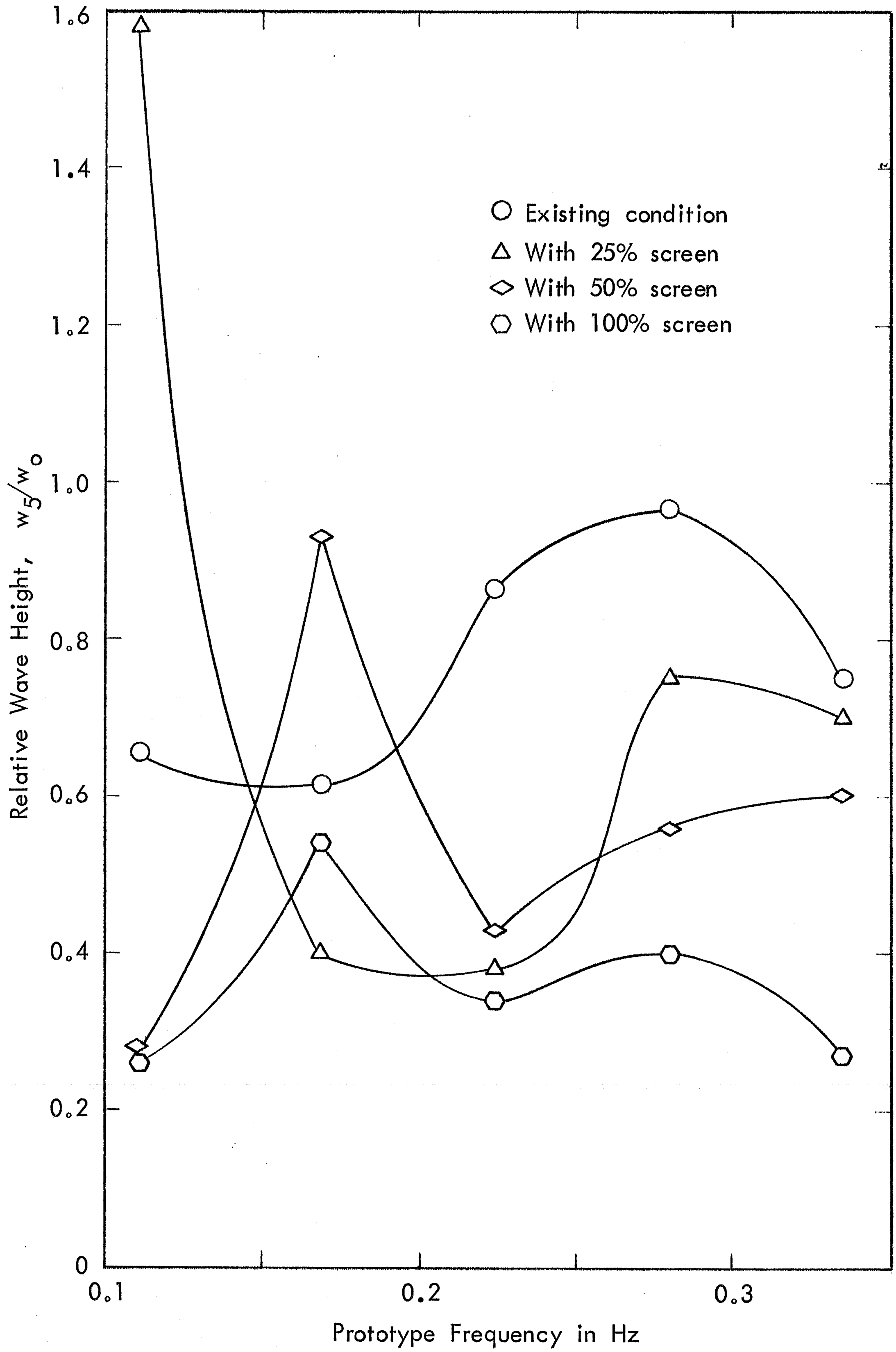

Fig. 10 - Effect of pier and wave screens on wave height at Point No. 5

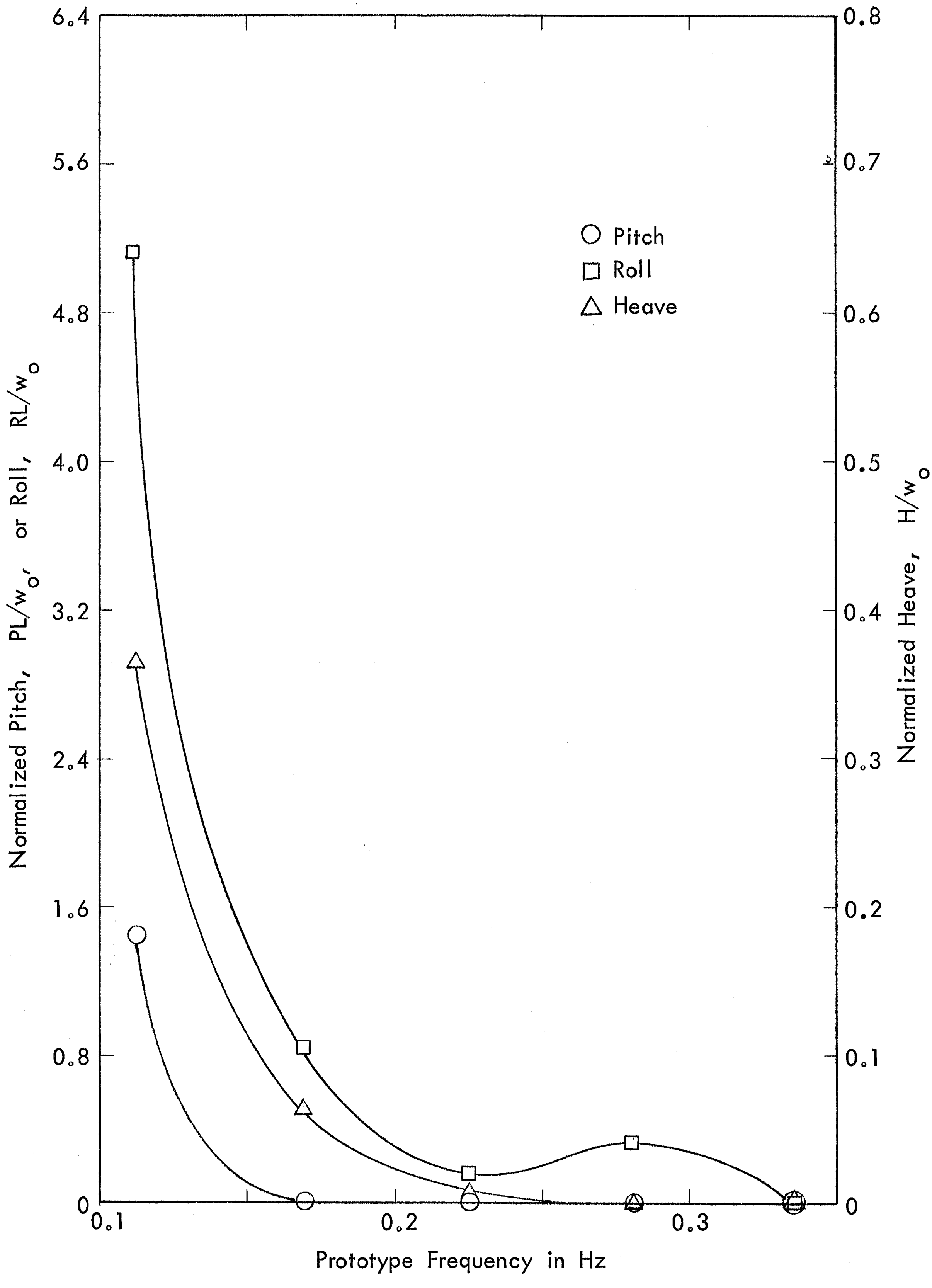

Fig. 11 - Oscillation of submarine moored on north side of pier

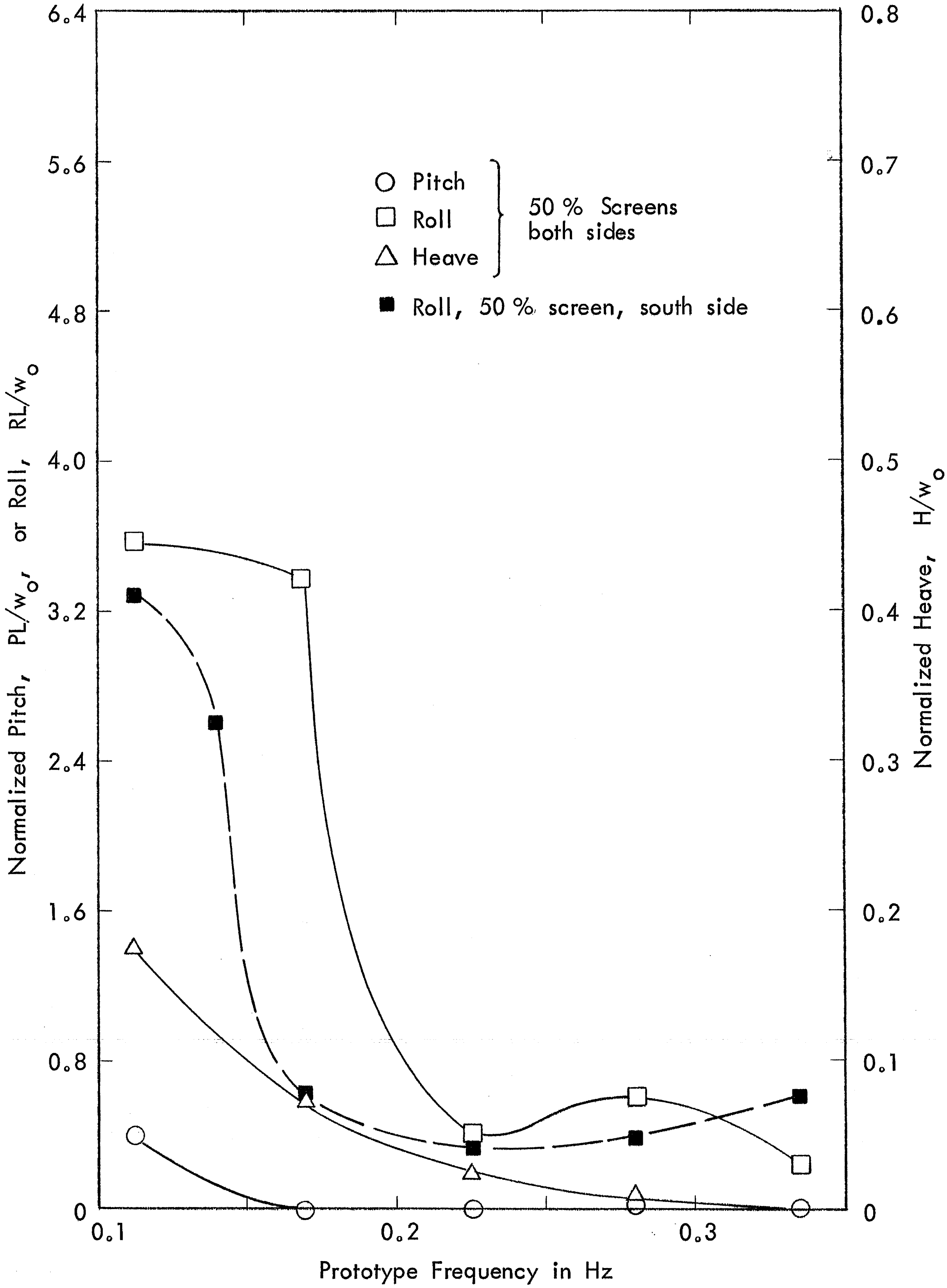

Fig. 12 - Oscillation of submarine moored on north side of pier with 50 per cent wave screens in place

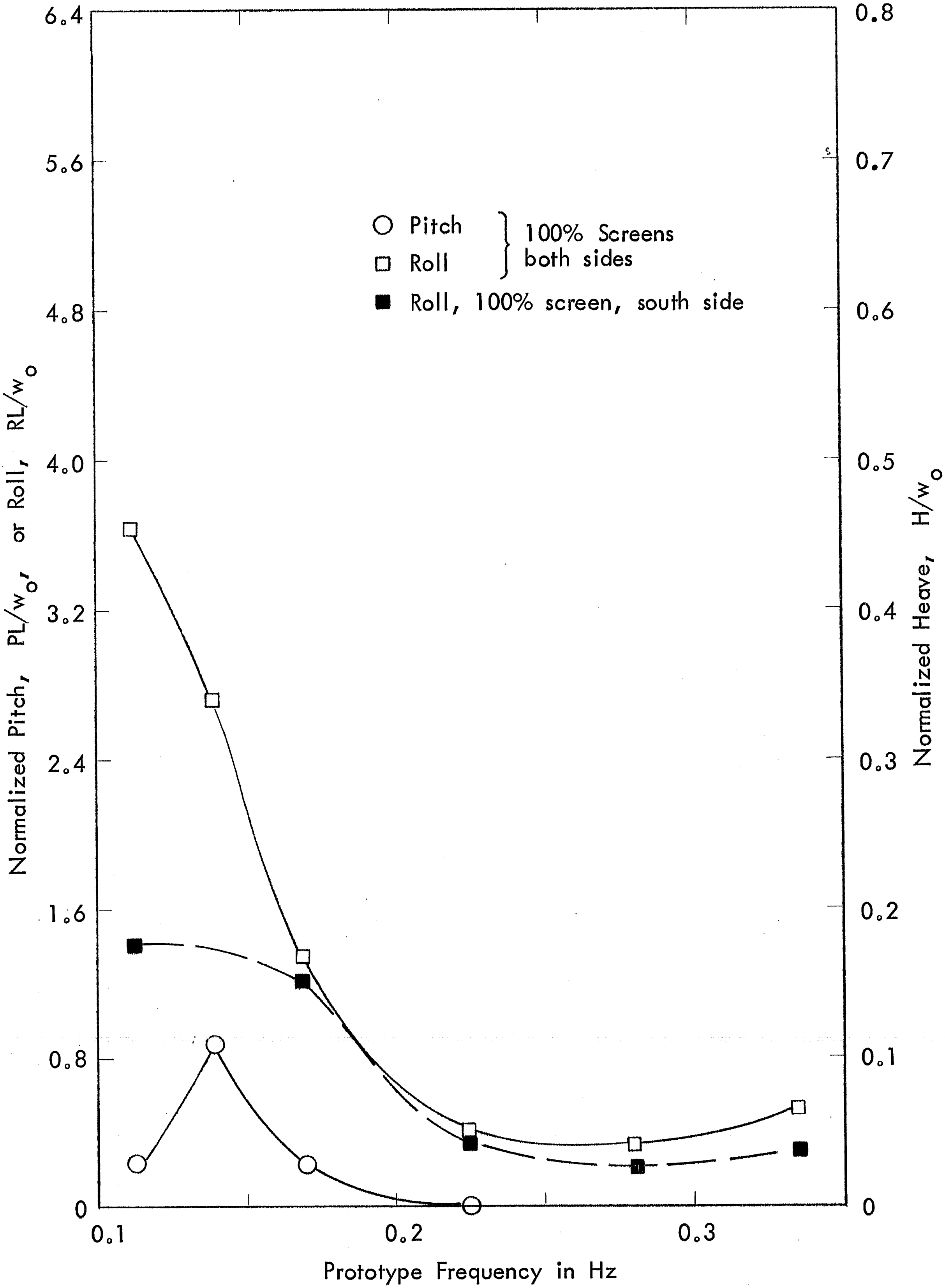

Fig. 13 - Oscillation of submarine moored on north side of pier with 100 per cent wave screens in place

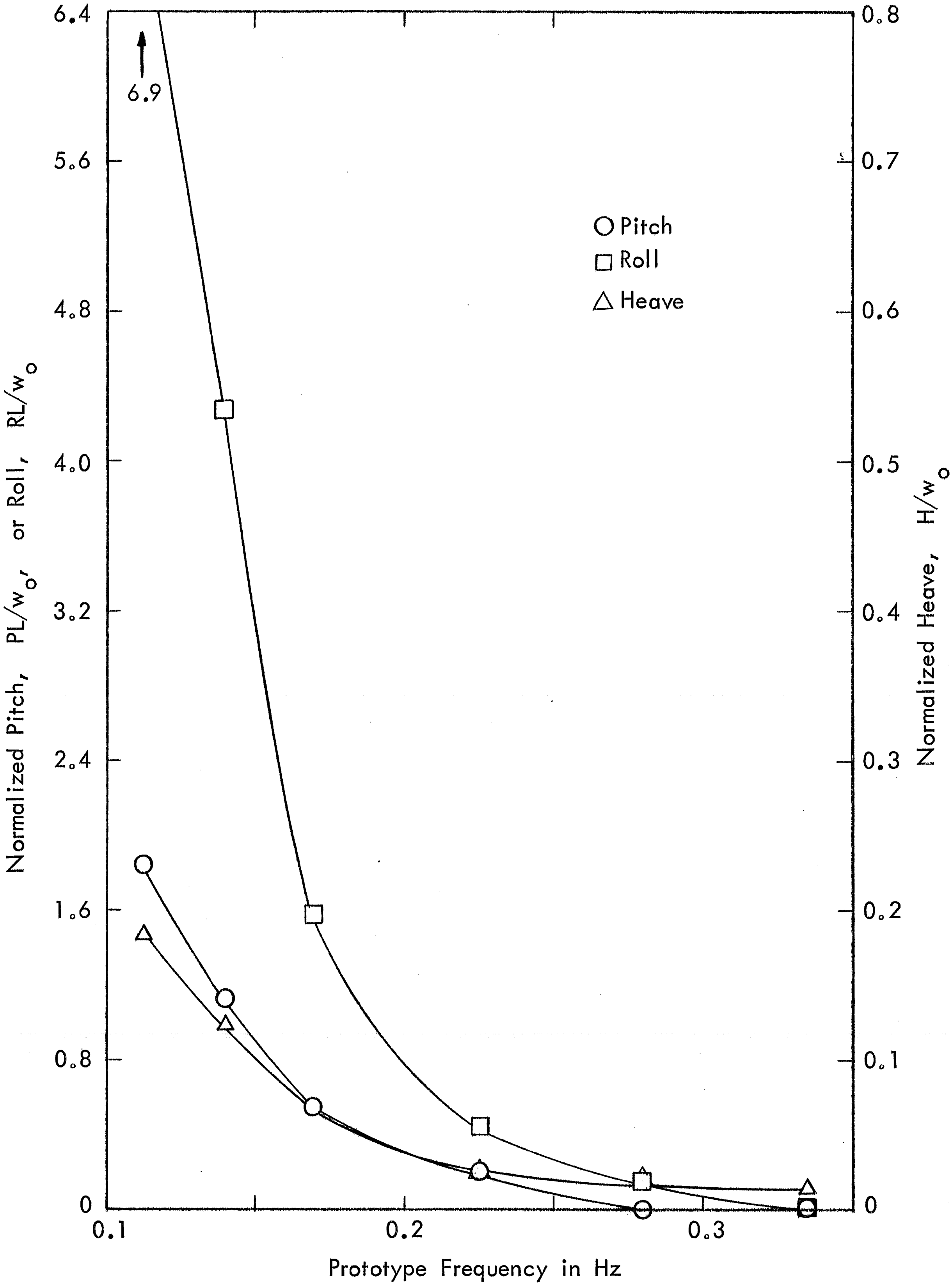

Fig. 14 - Oscillation of submarine moored on south side of pier with 50 per cent wave screens in place

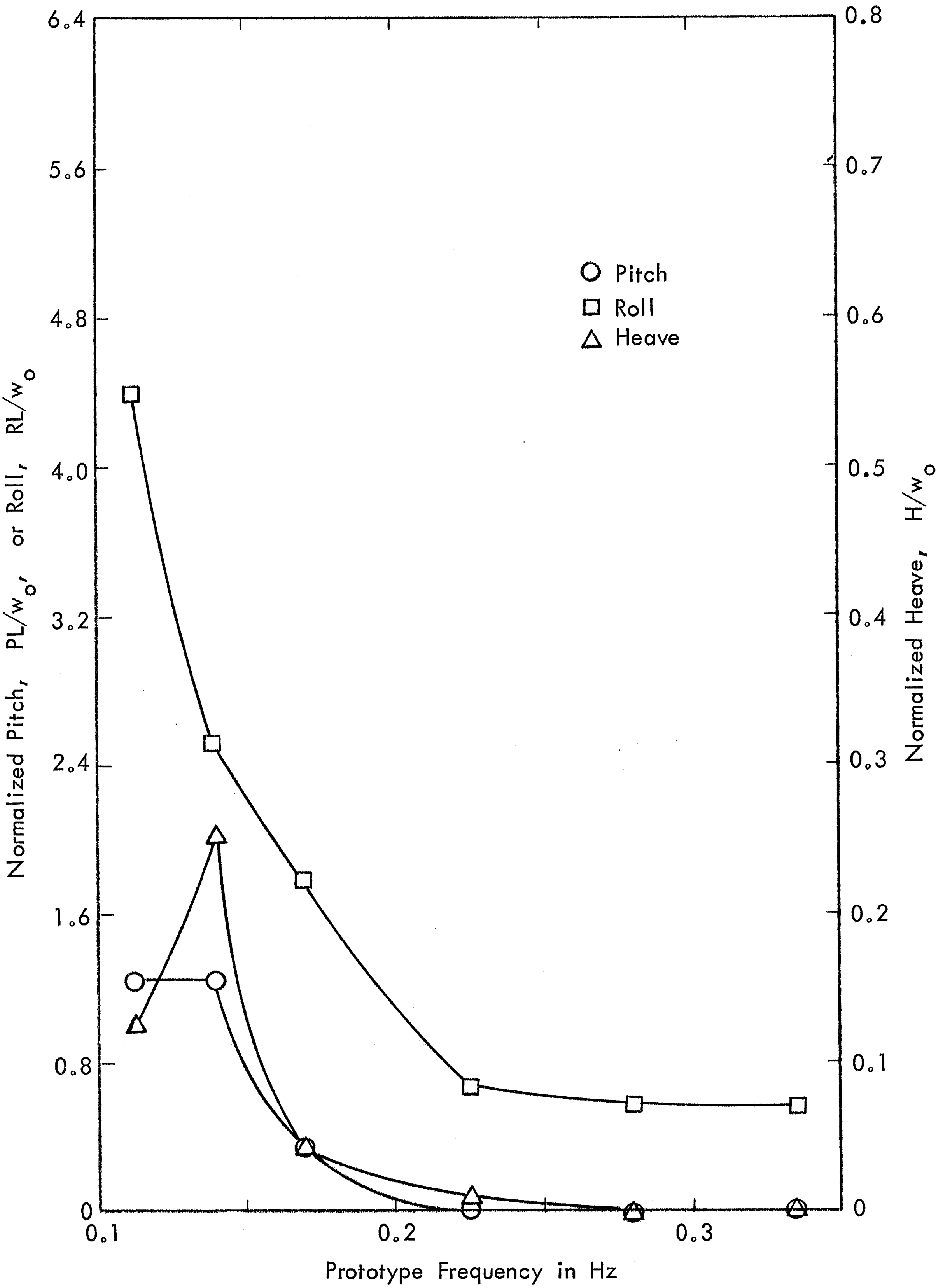

Fig. 15 - Oscillation of submarine moored on south side of pier with 100 per cent wave screens in place

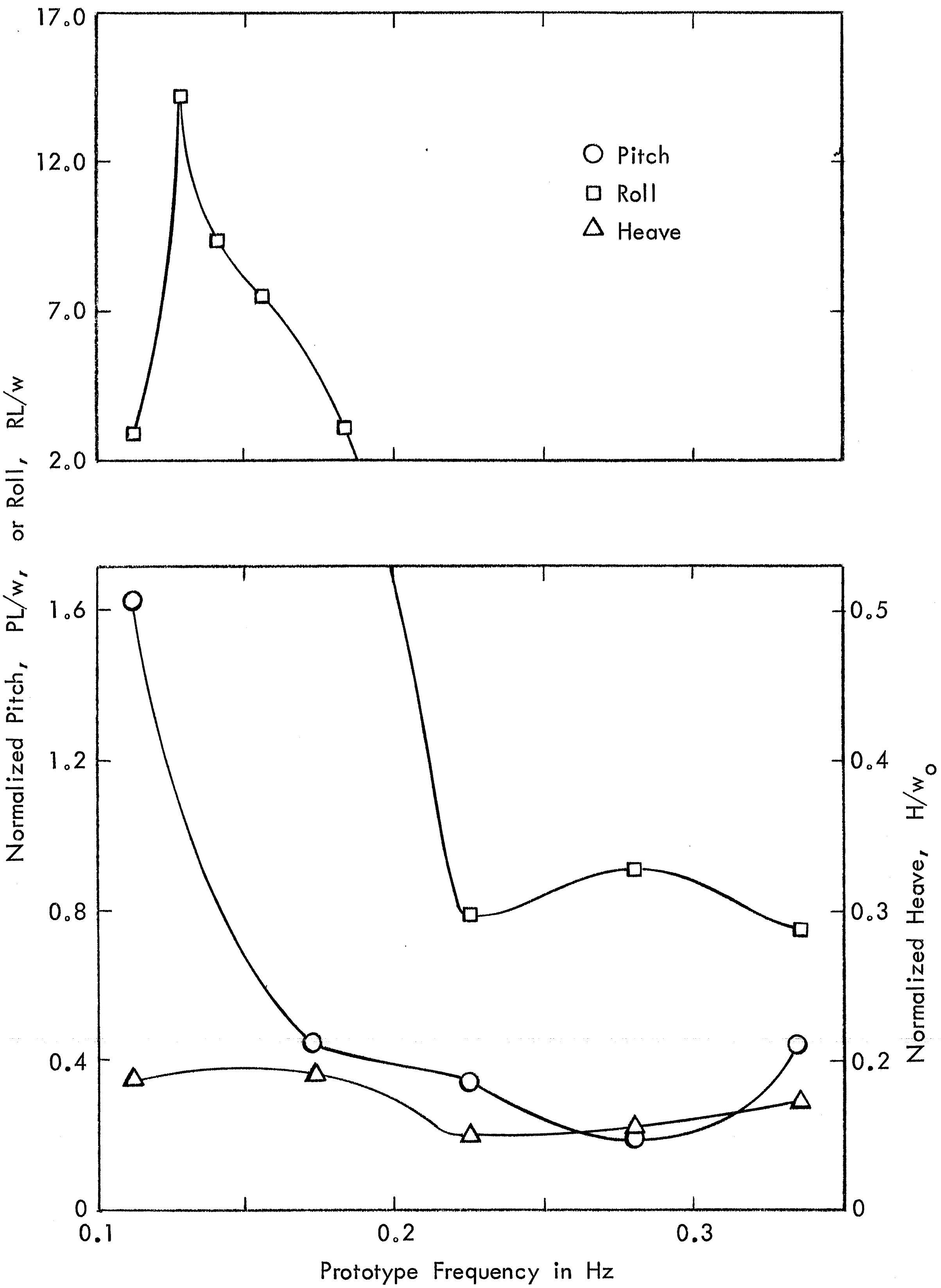

Fig. 16 - Single APL moored normal to wall with no pier or wave screen

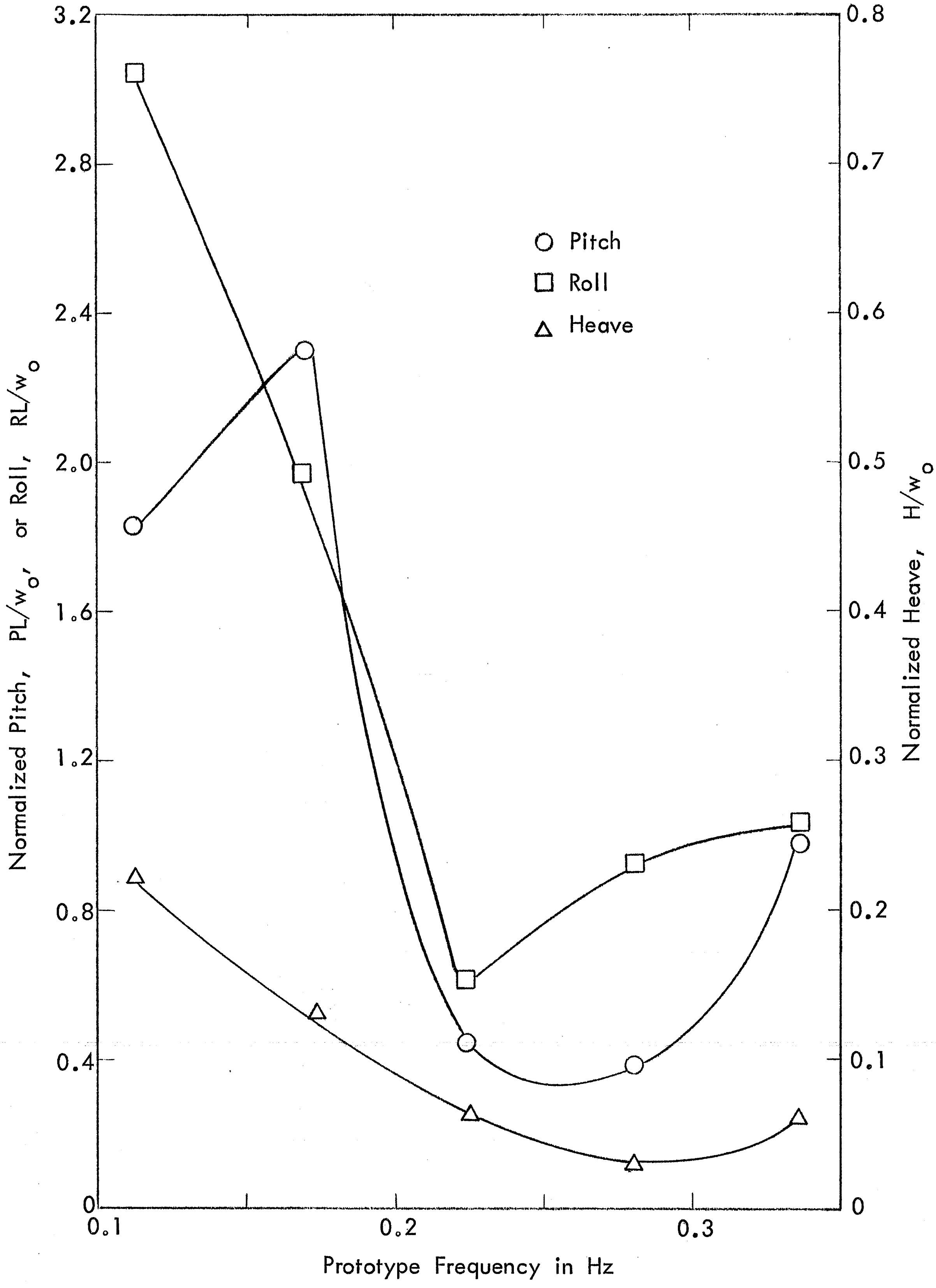

Fig. 17 - Single YRBM moored normal to wall with no pier or wave screen

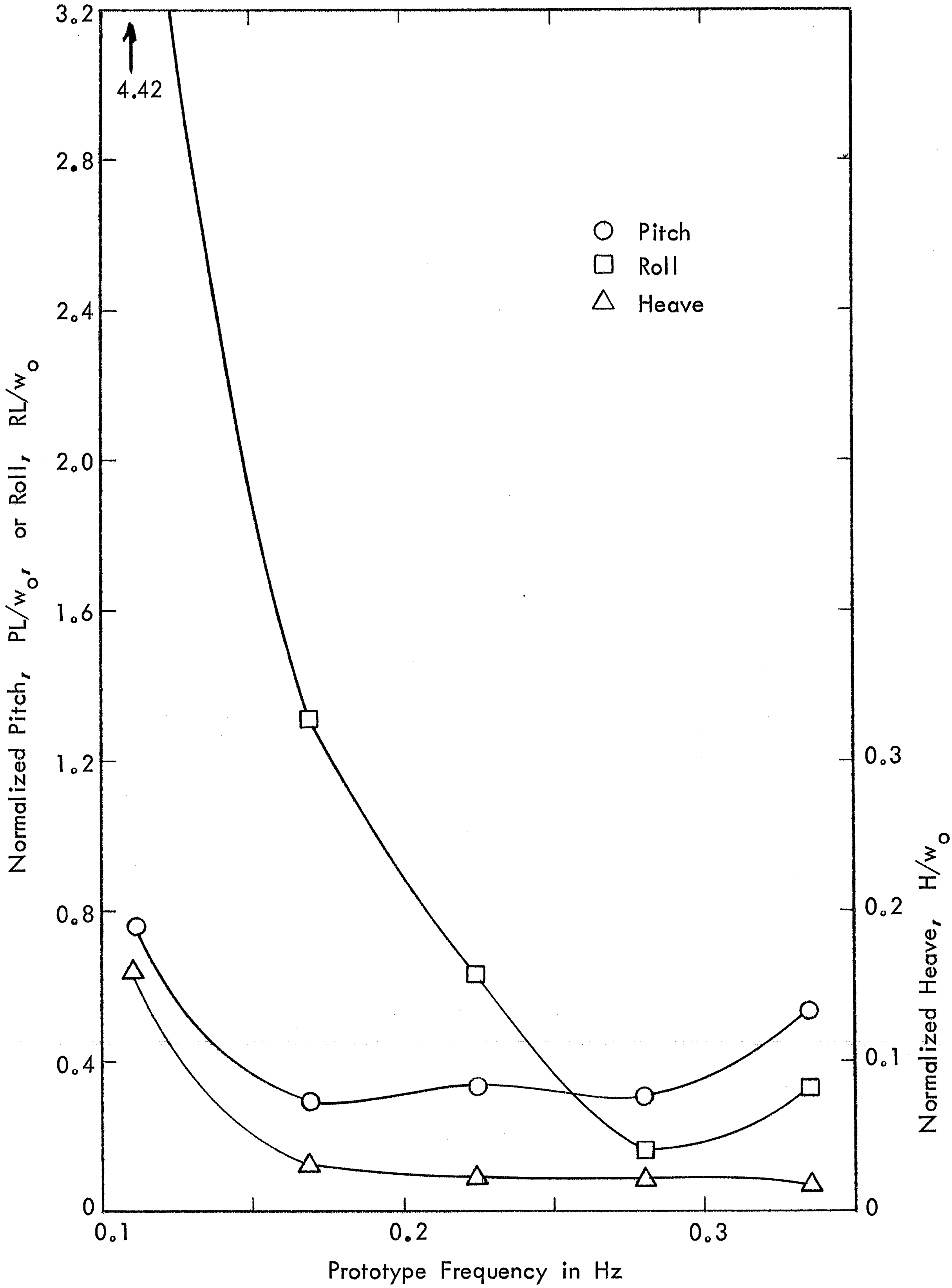

Fig. 18 - Single APL moored normal to wall with pier in place

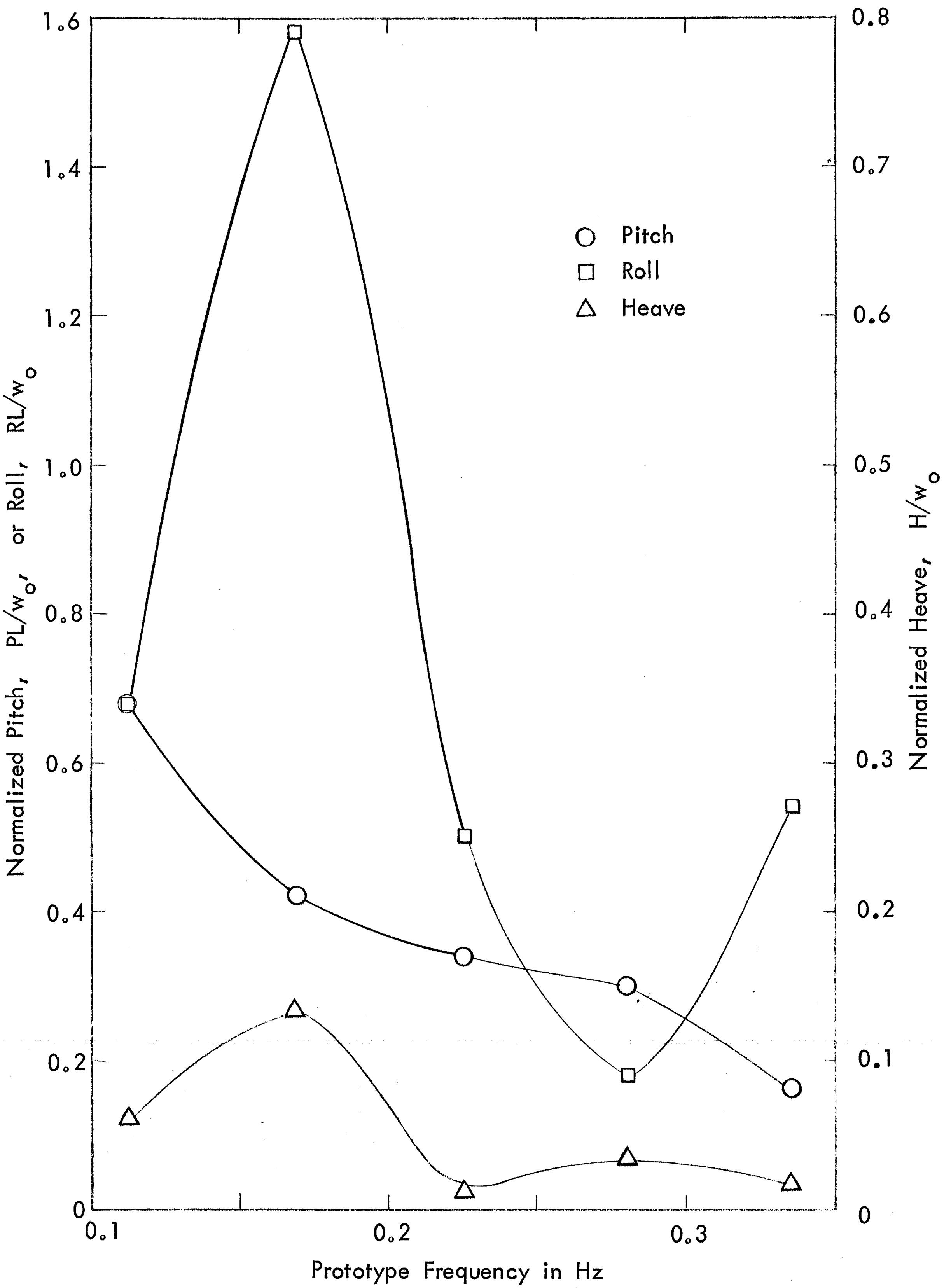

Fig. 19 - Single YRBM moored normal to wall with pier in place

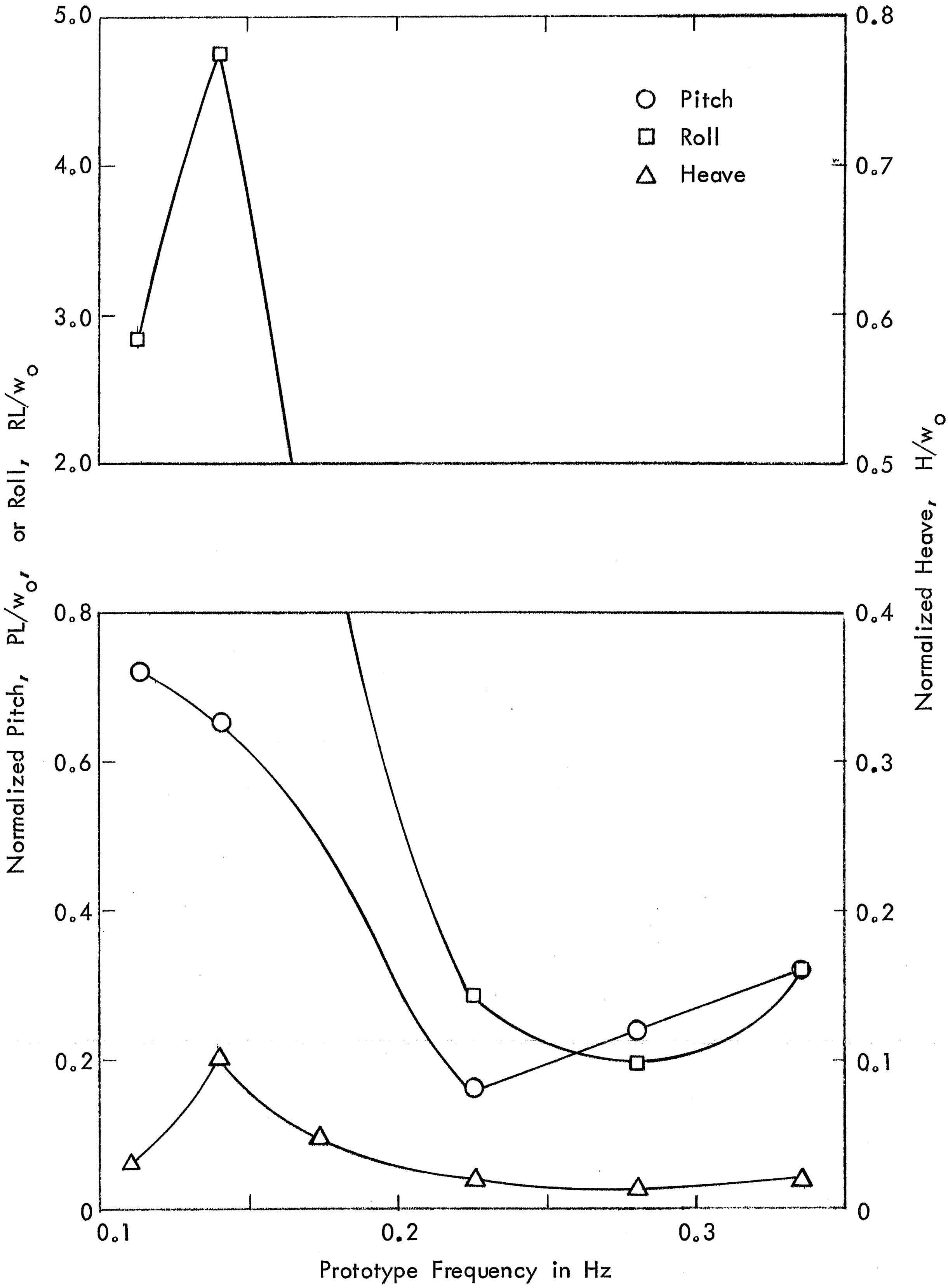

Fig. 20 - Single APL moored normal to wall with pier and 25 per cent wave screens in place

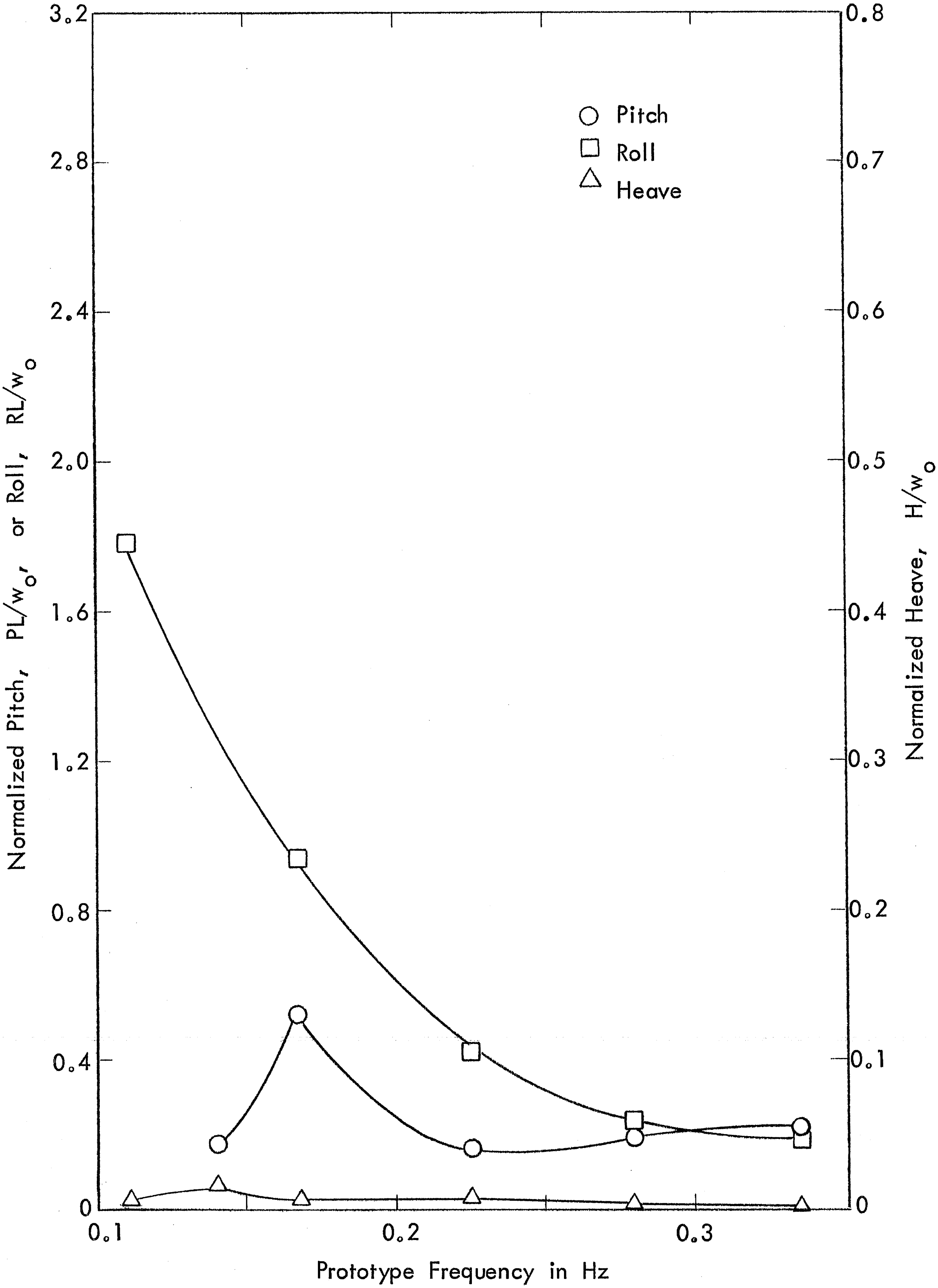

Fig. 21 - Single APL moored normal to wall with pier and 50 per cent wave screens in place

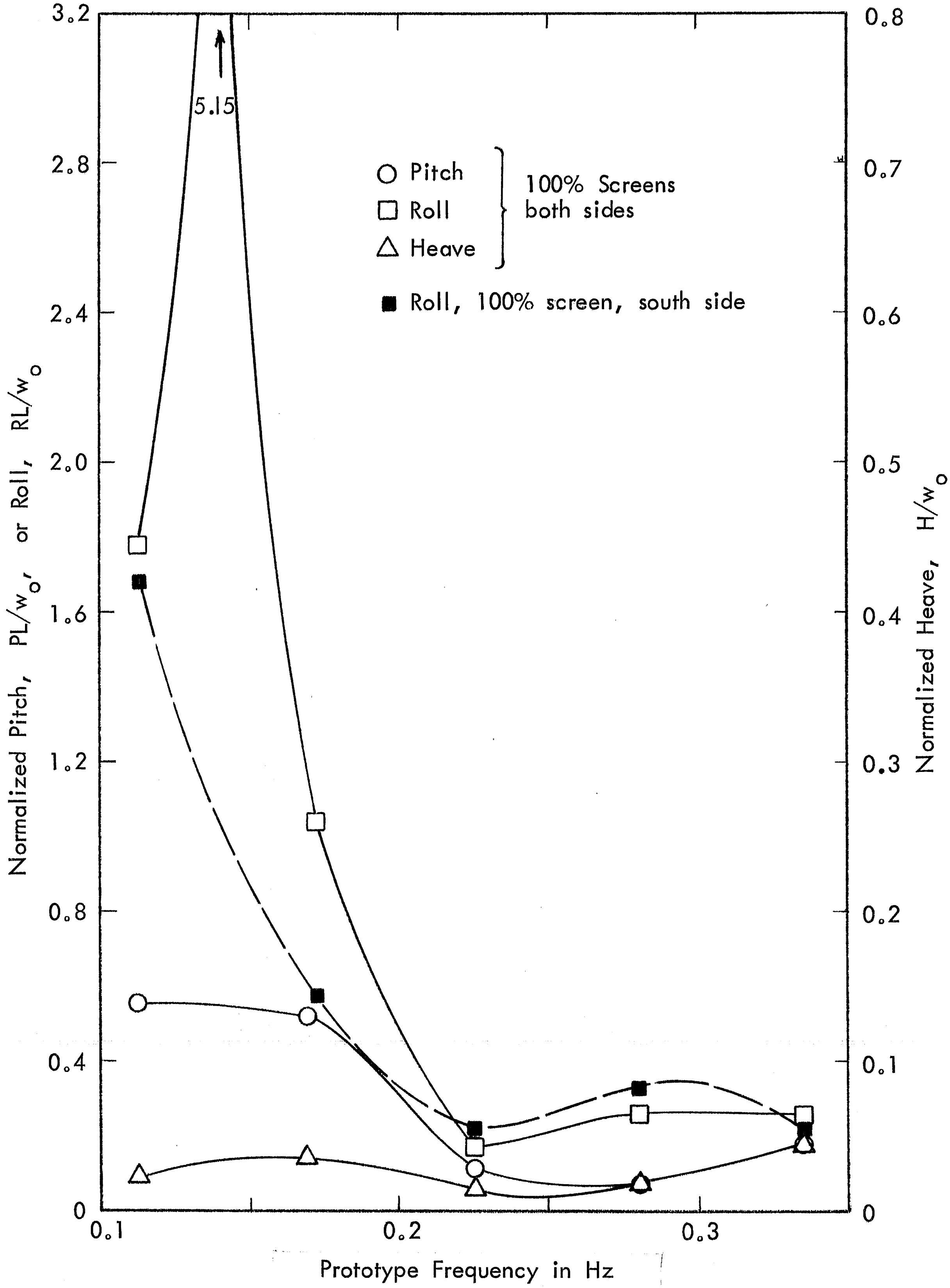

Fig. 22 - Single APL moored normal to wall with pier and 100 per cent wave screens in place

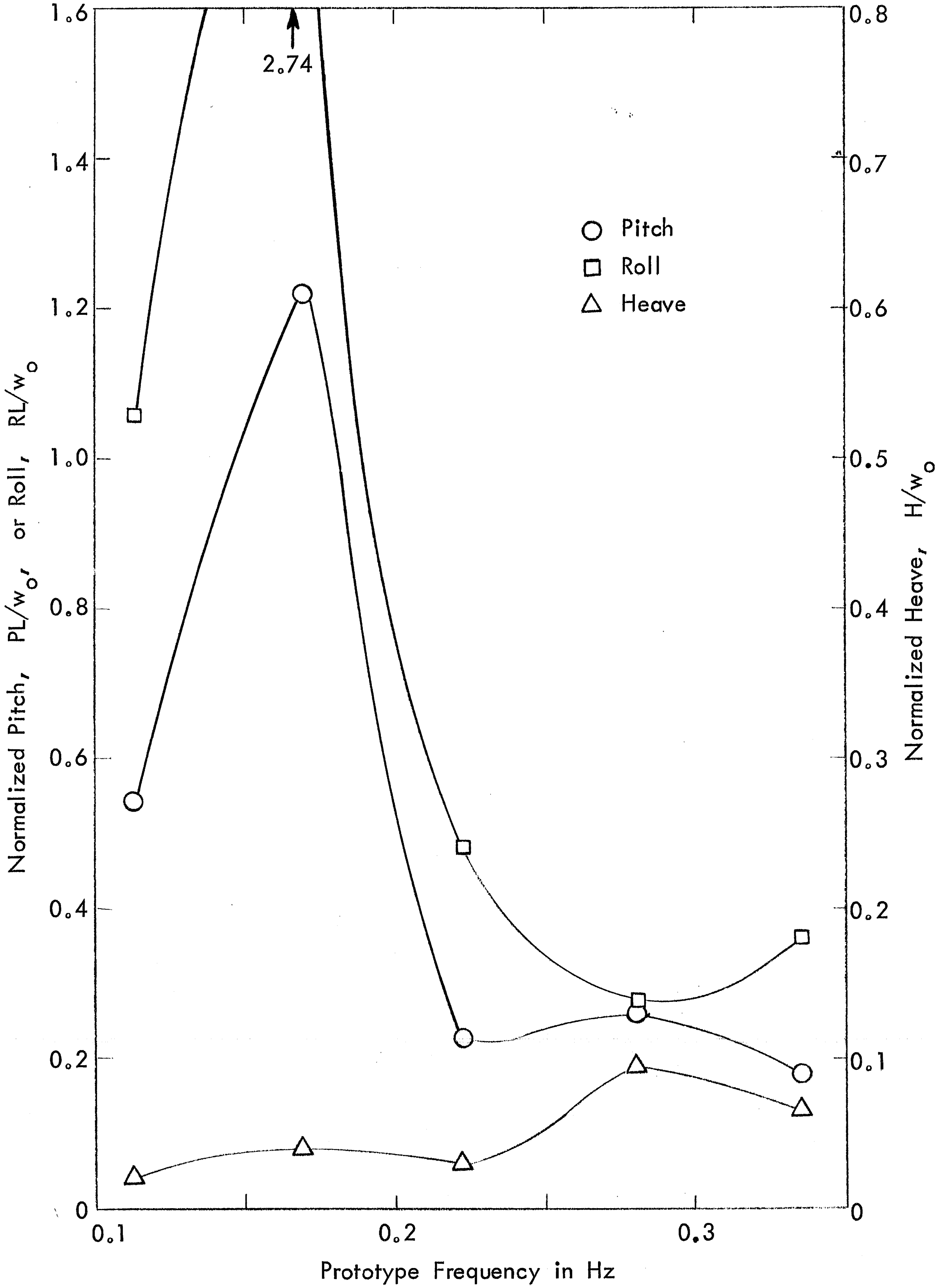

Fig. 23 - Single YRBM moored normal to wall with pier and 25 per cent wave screens in place

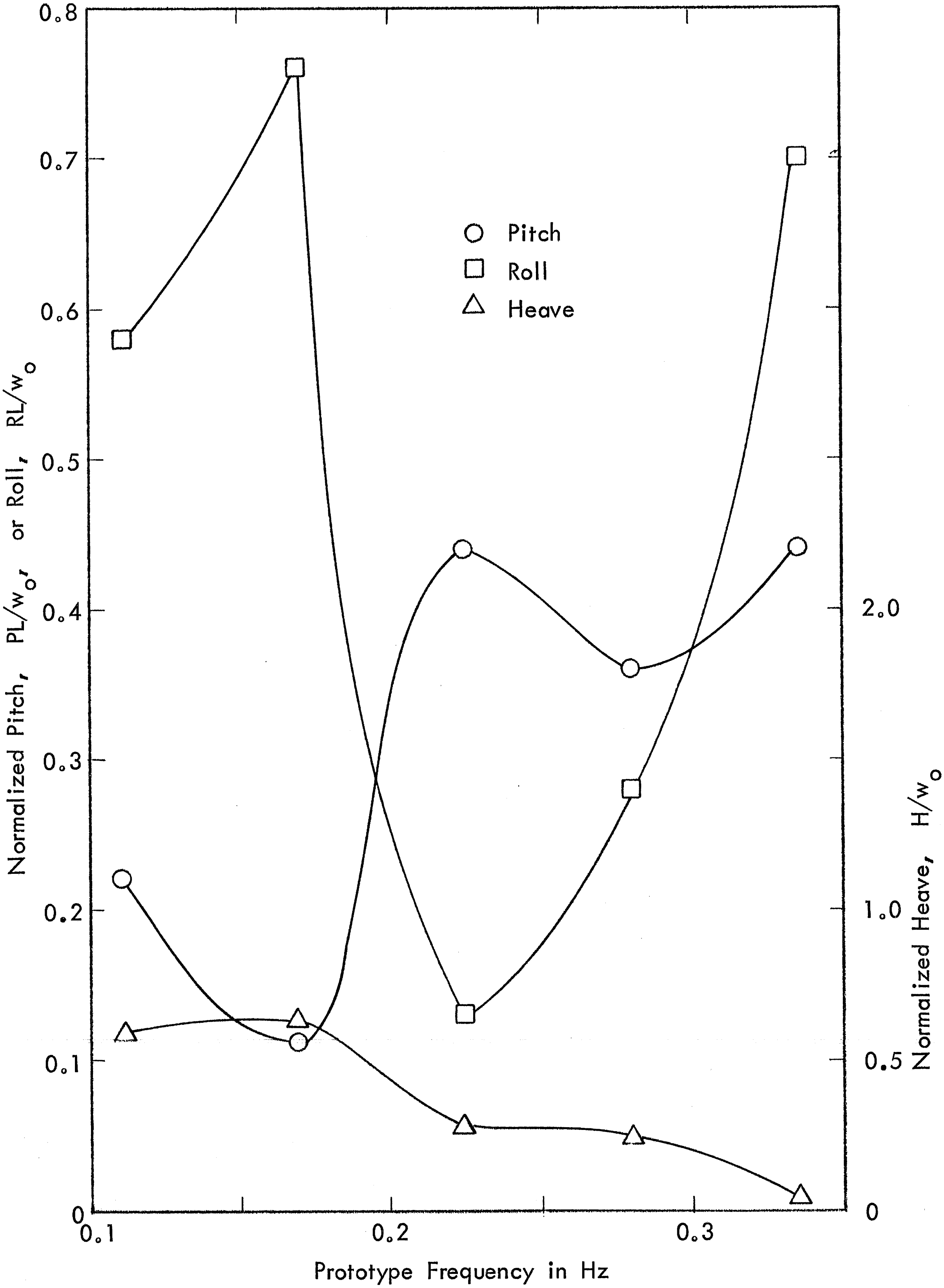

Fig. 24 - Single YRBM moored normal to wall with pier and 50 per cent wave screens in place

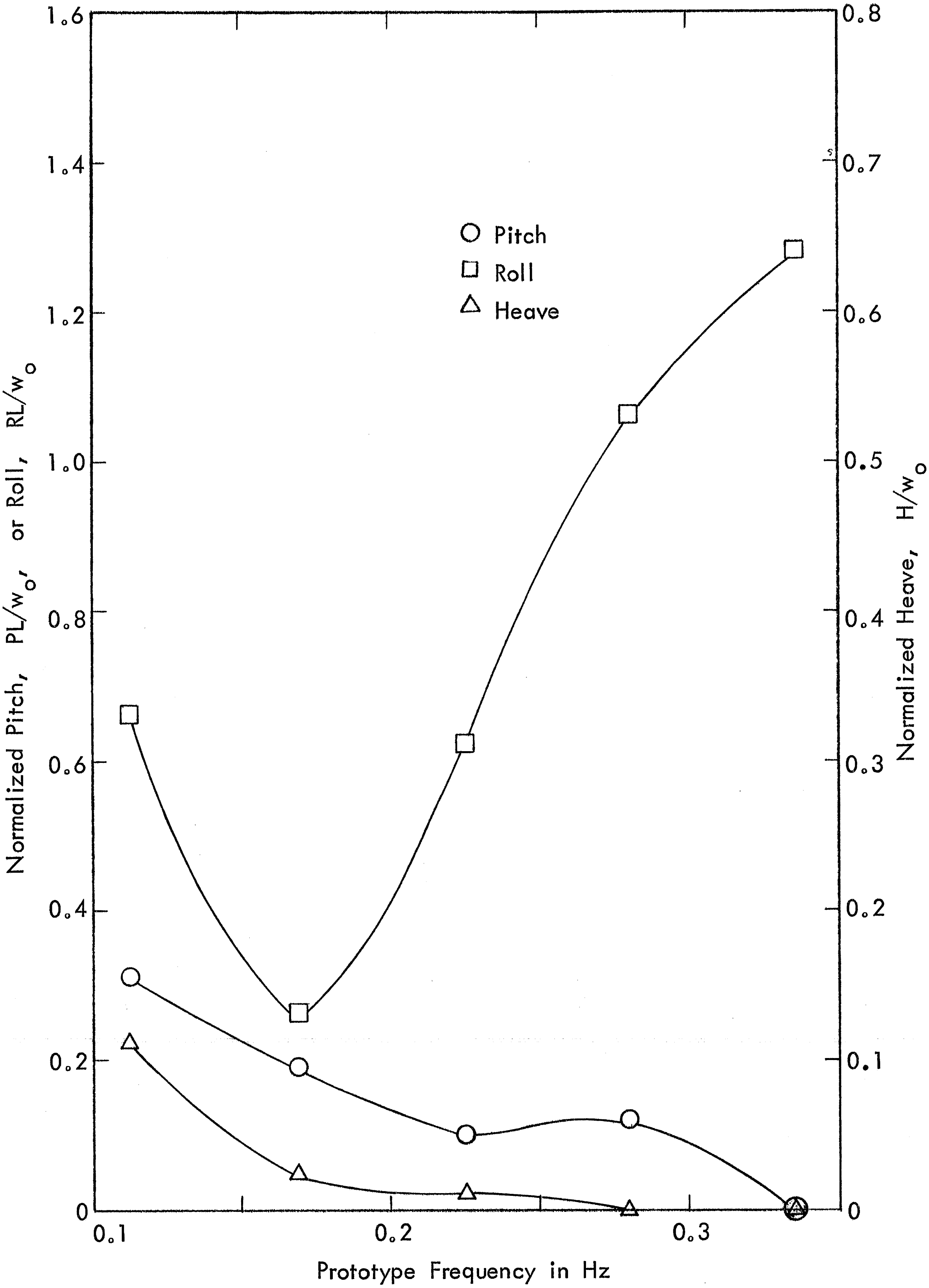

Fig. 25 - Single YRBM moored normal to wall with pier and 100 per cent wave screens in place

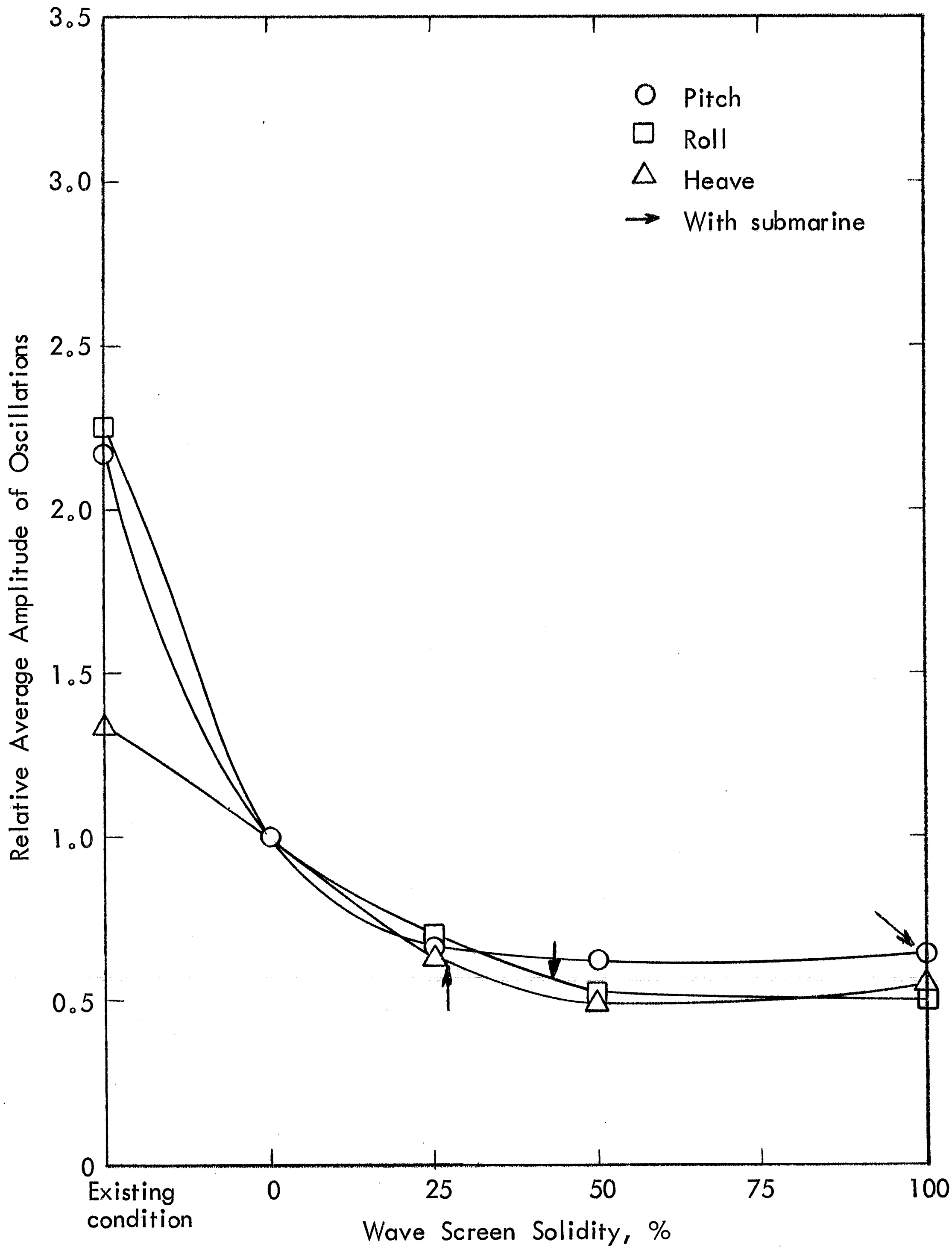

Fig. 26 - Overall effectiveness of wave screens in reducing APL oscillations

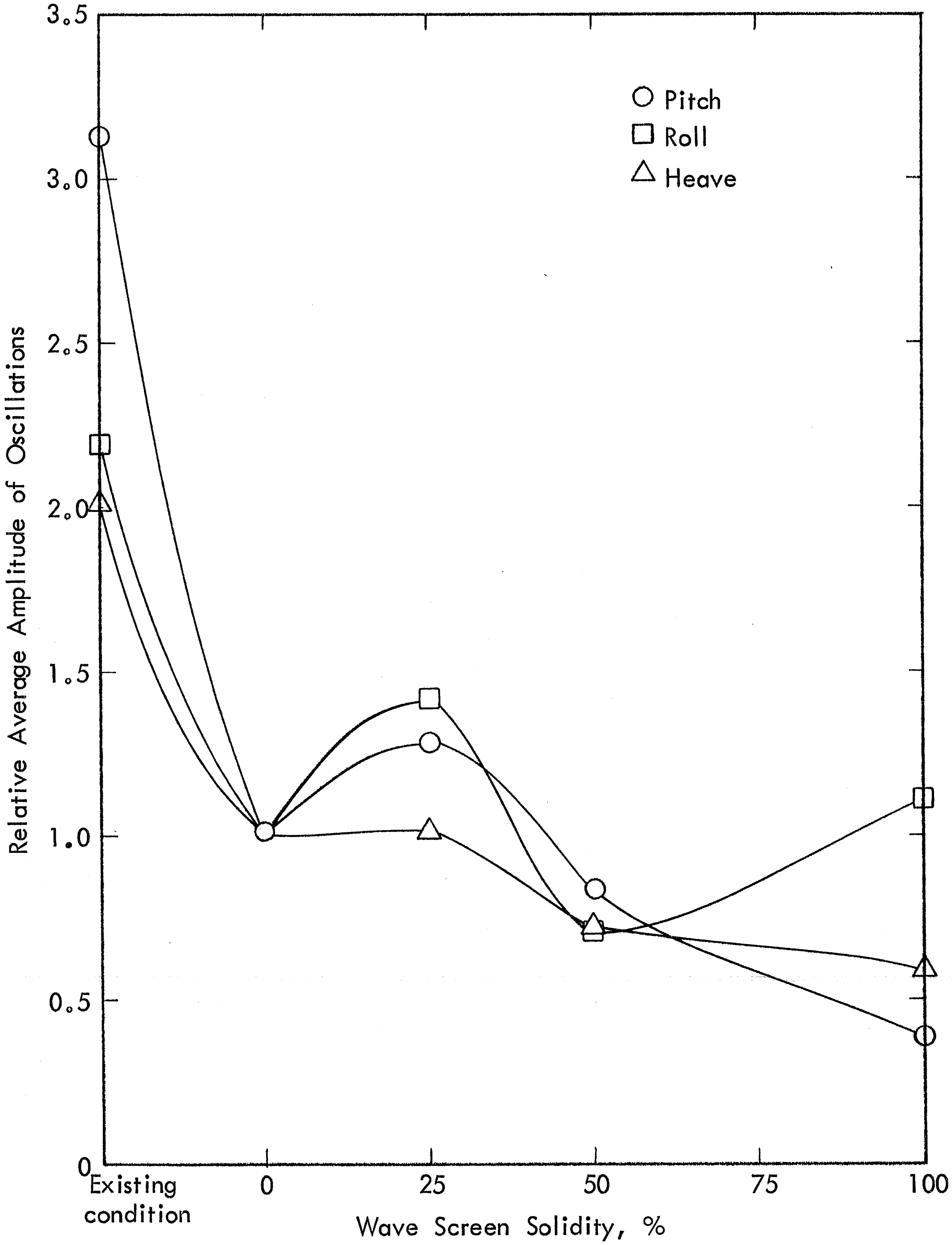

Fig. 27 - Overall effectiveness of wave screens in reducing YRBM oscillations

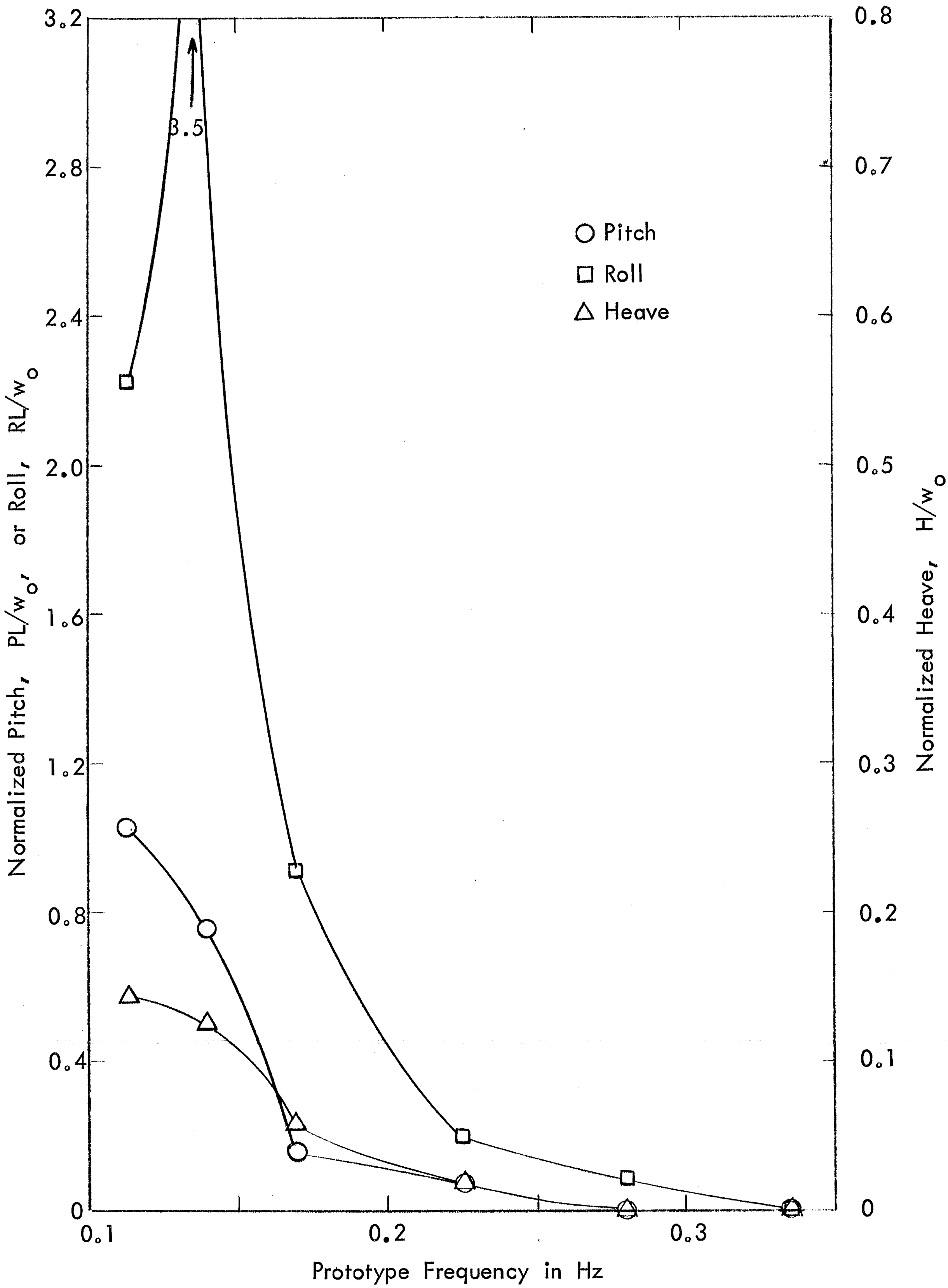

Fig. 28 - Single APL moored parallel to wall with pier and 100 per cent wave screens in place

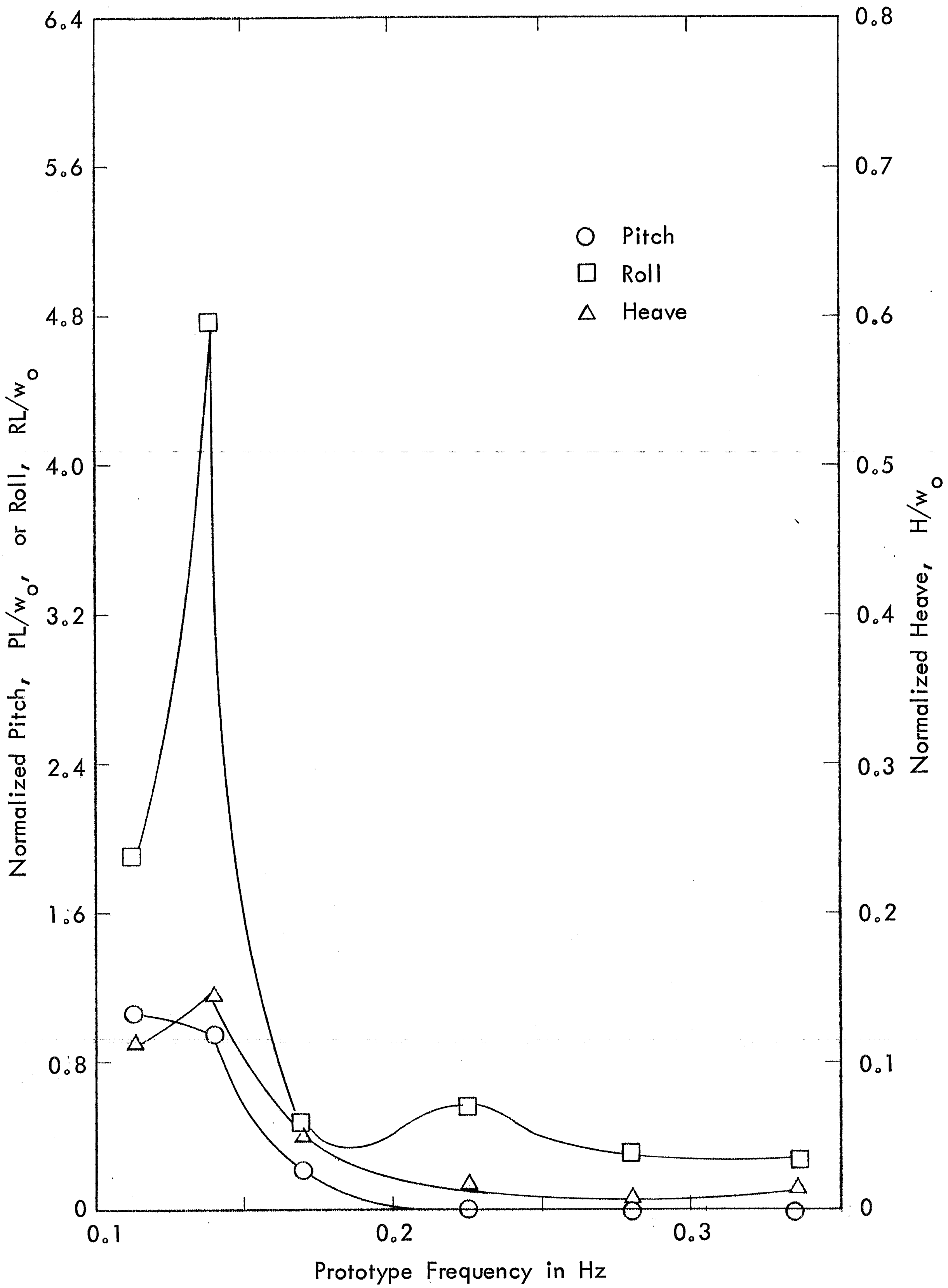

Fig. 29 - Single APL moored normal to pier with 100 per cent wave screens in place

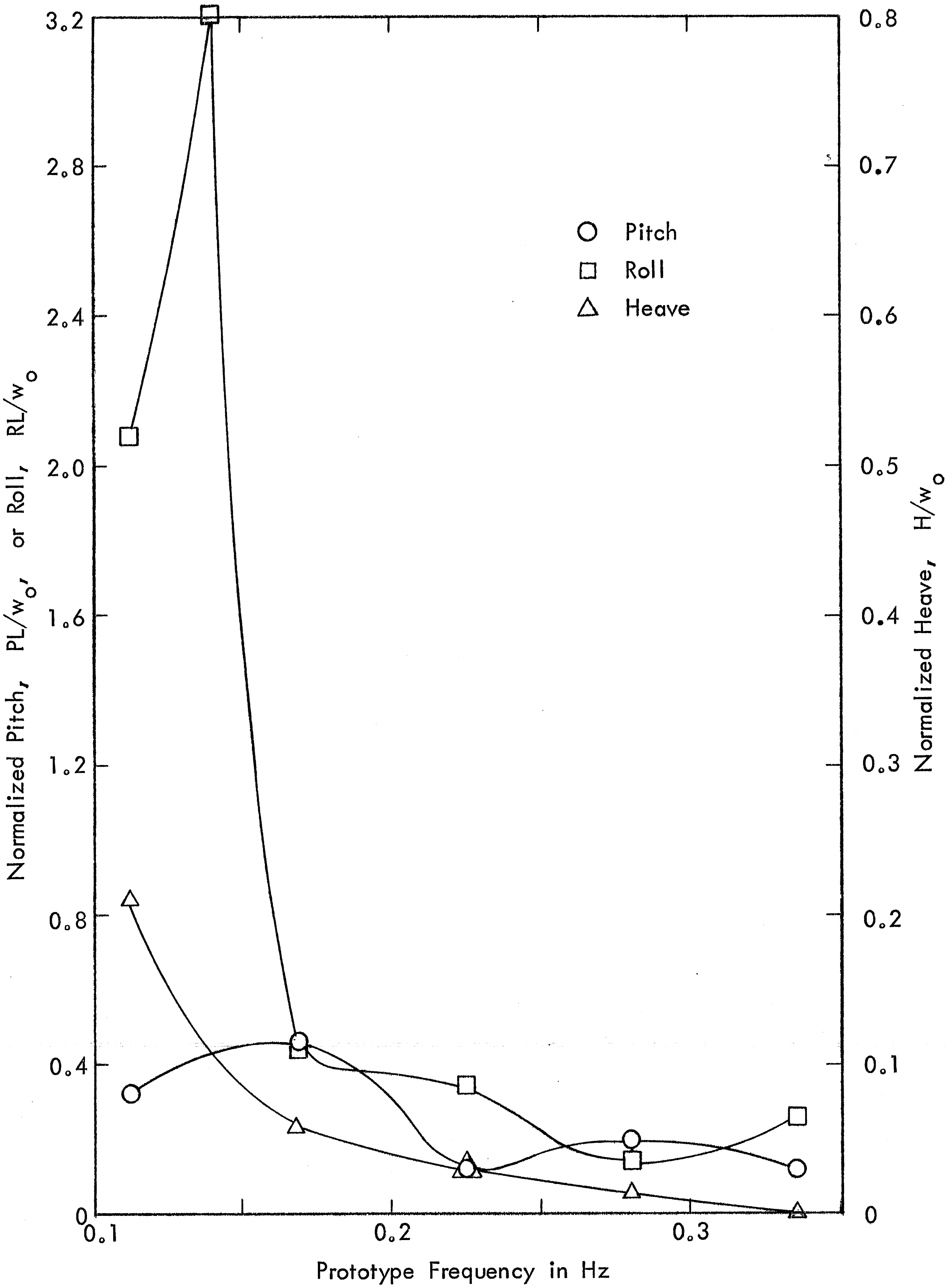

Fig. 30 - Single APL moored parallel to pier with 100 per cent wave screens in place

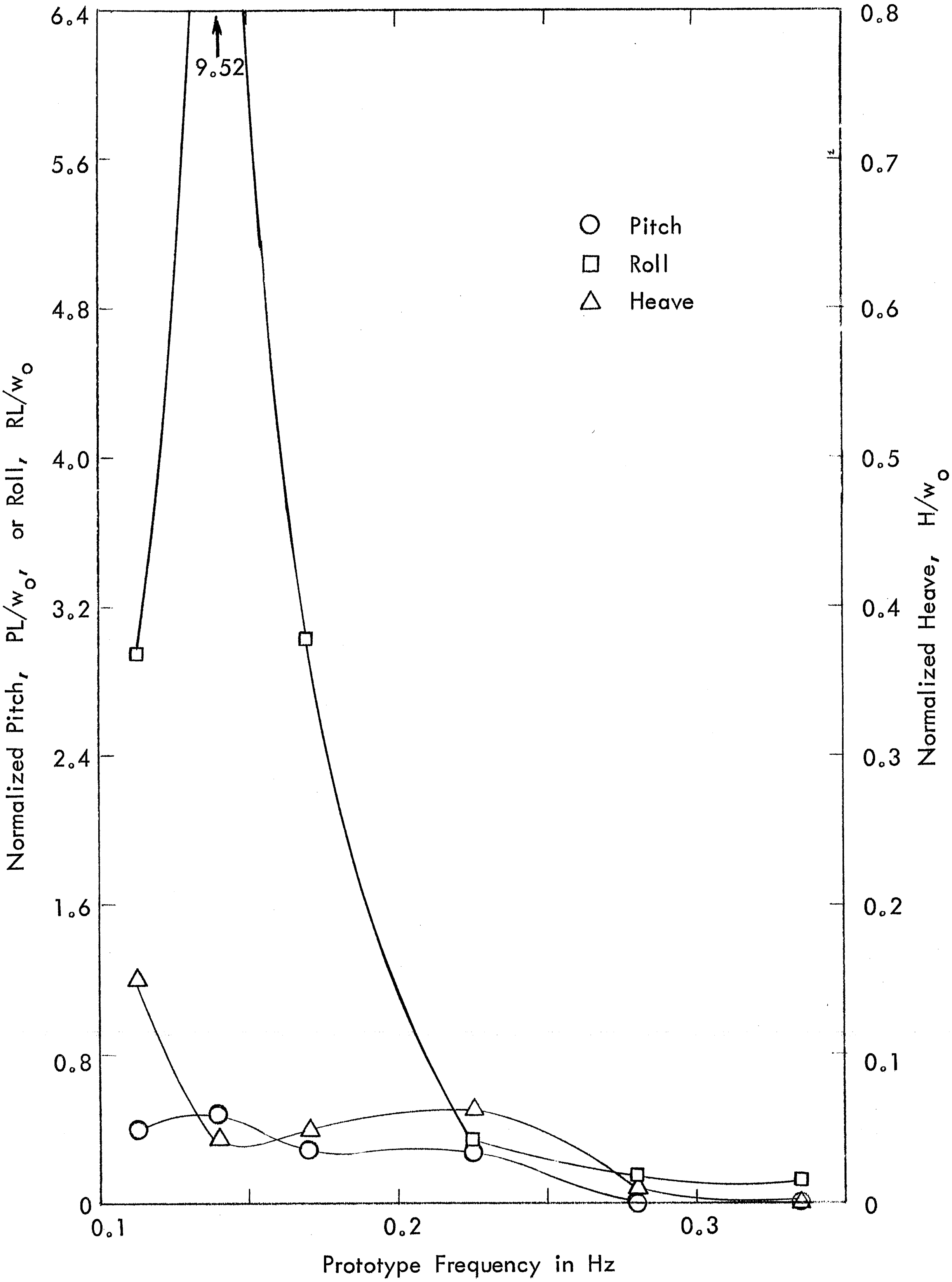

Fig. 31 - Single APL moored normal to pier with 50 per cent wave screens in place

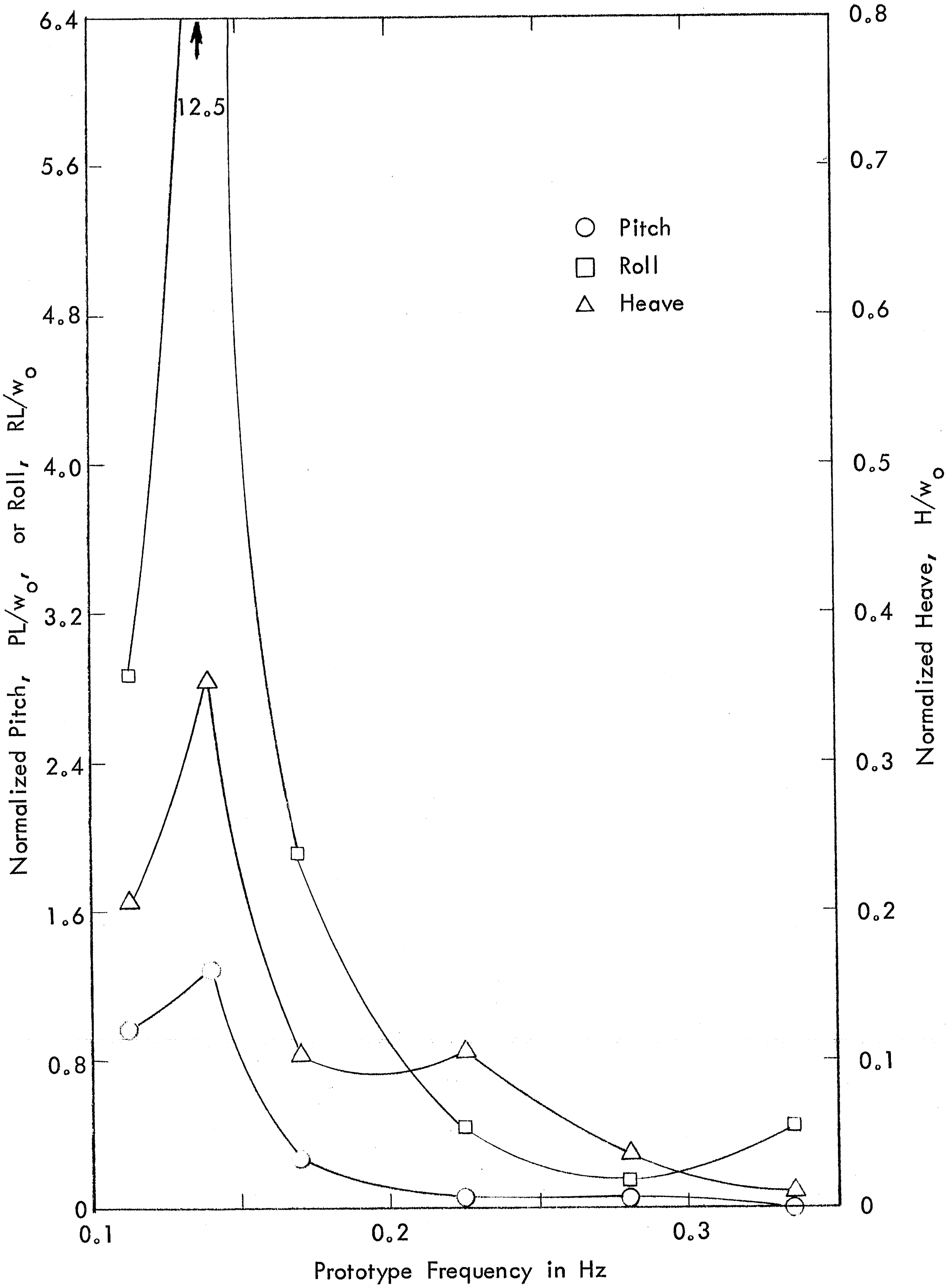

Fig. 32 - Single APL moored parallel to wall with pier and 50 per cent wave screens in place

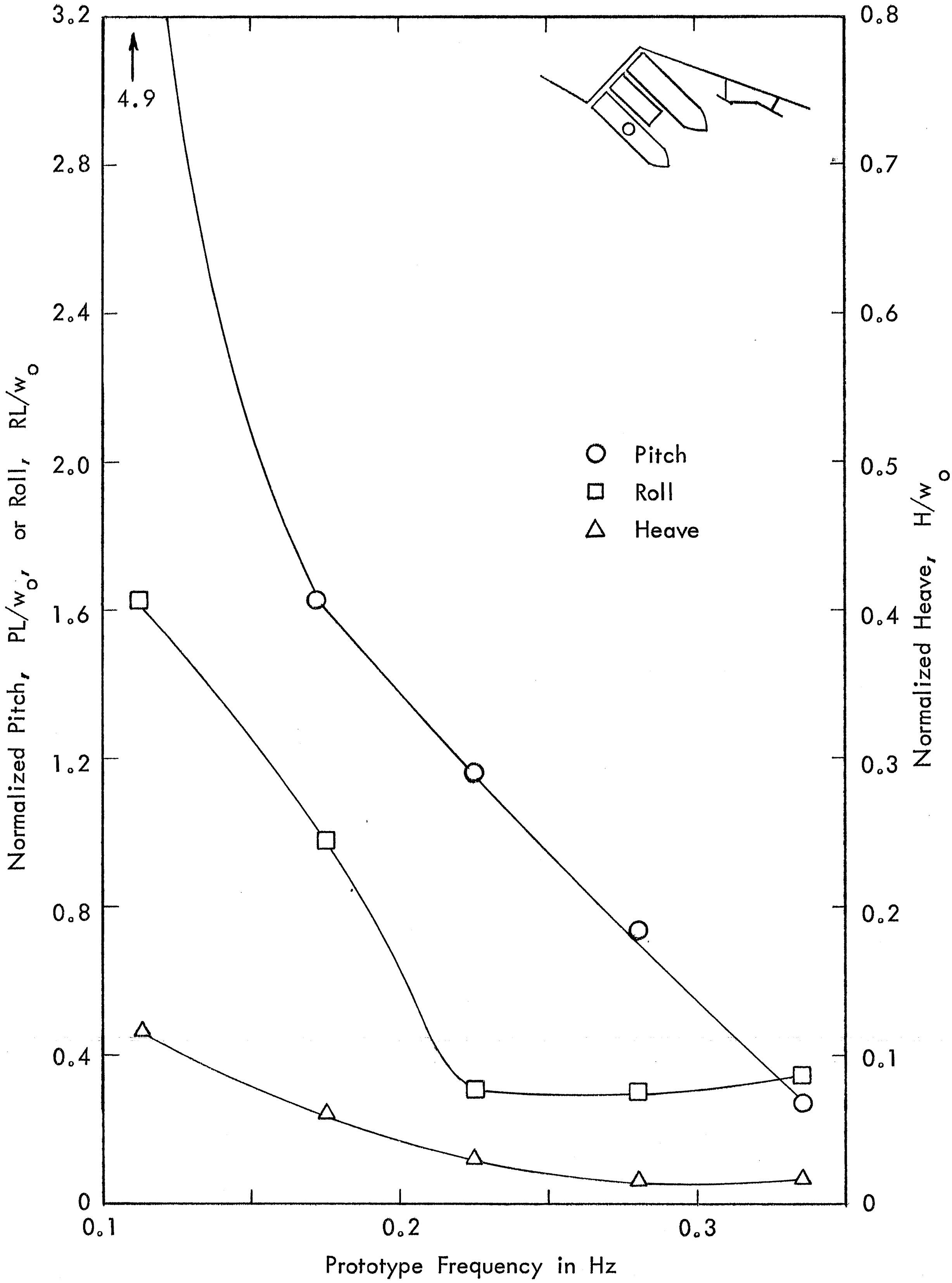

Fig. 33 - Oscillation of APL when moored with other APL and YRBM - YRBM at center

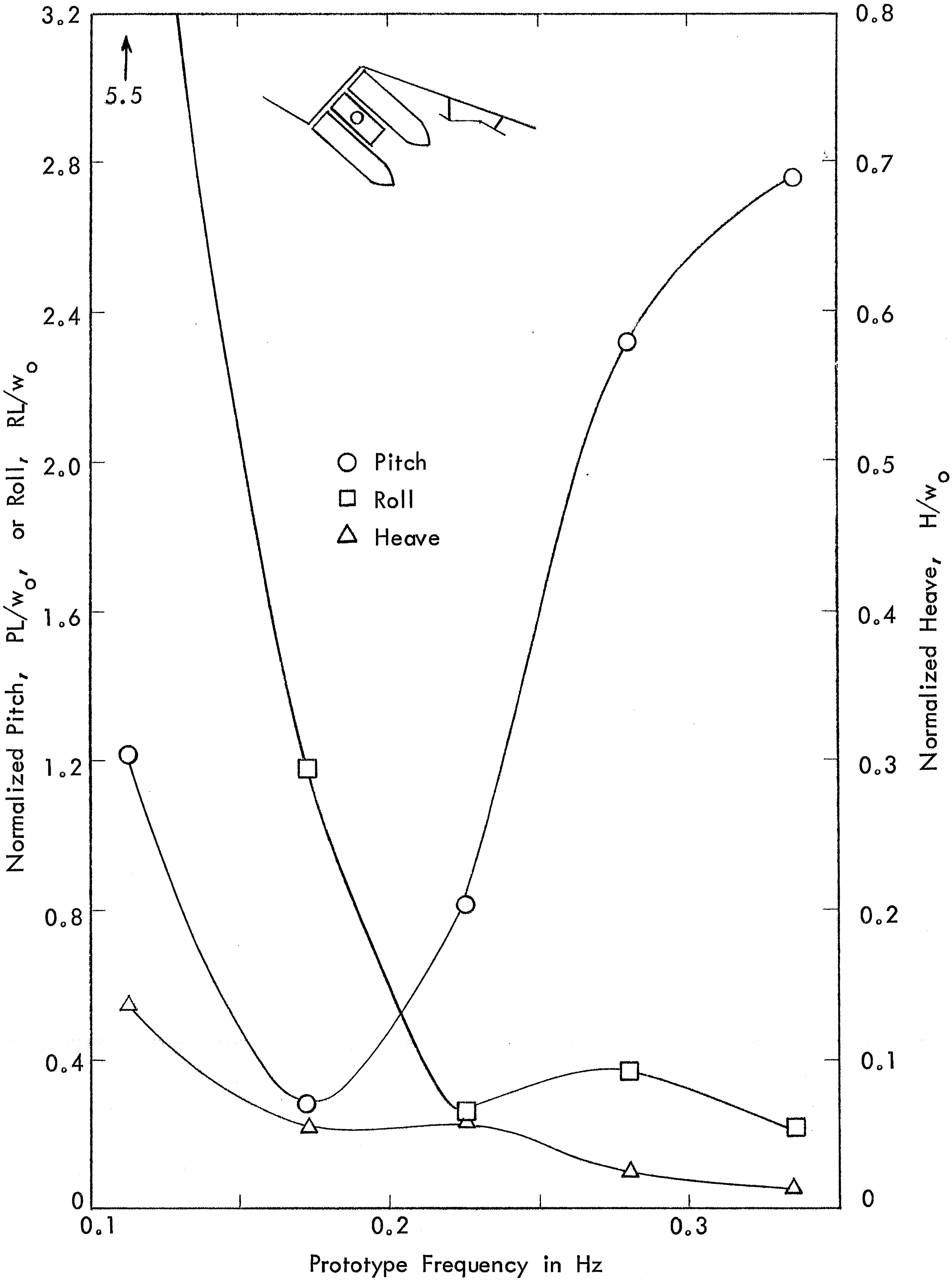

Fig. 34 - Oscillation of YRBM when moored with two APL's - YRBM at center

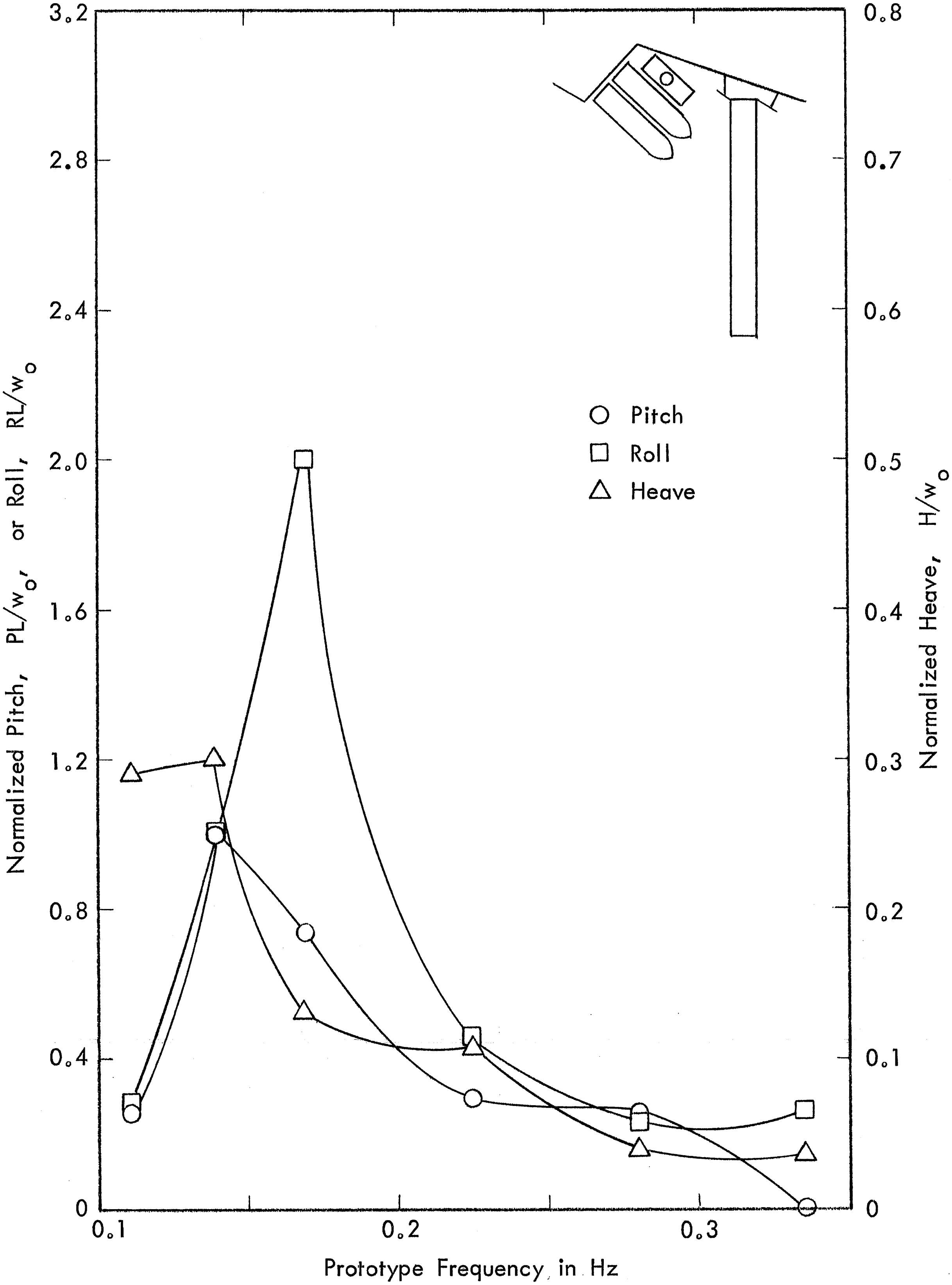

Fig. 35 - Oscillation of YRBM when moored with two APL's - YRBM at corner, pier in place

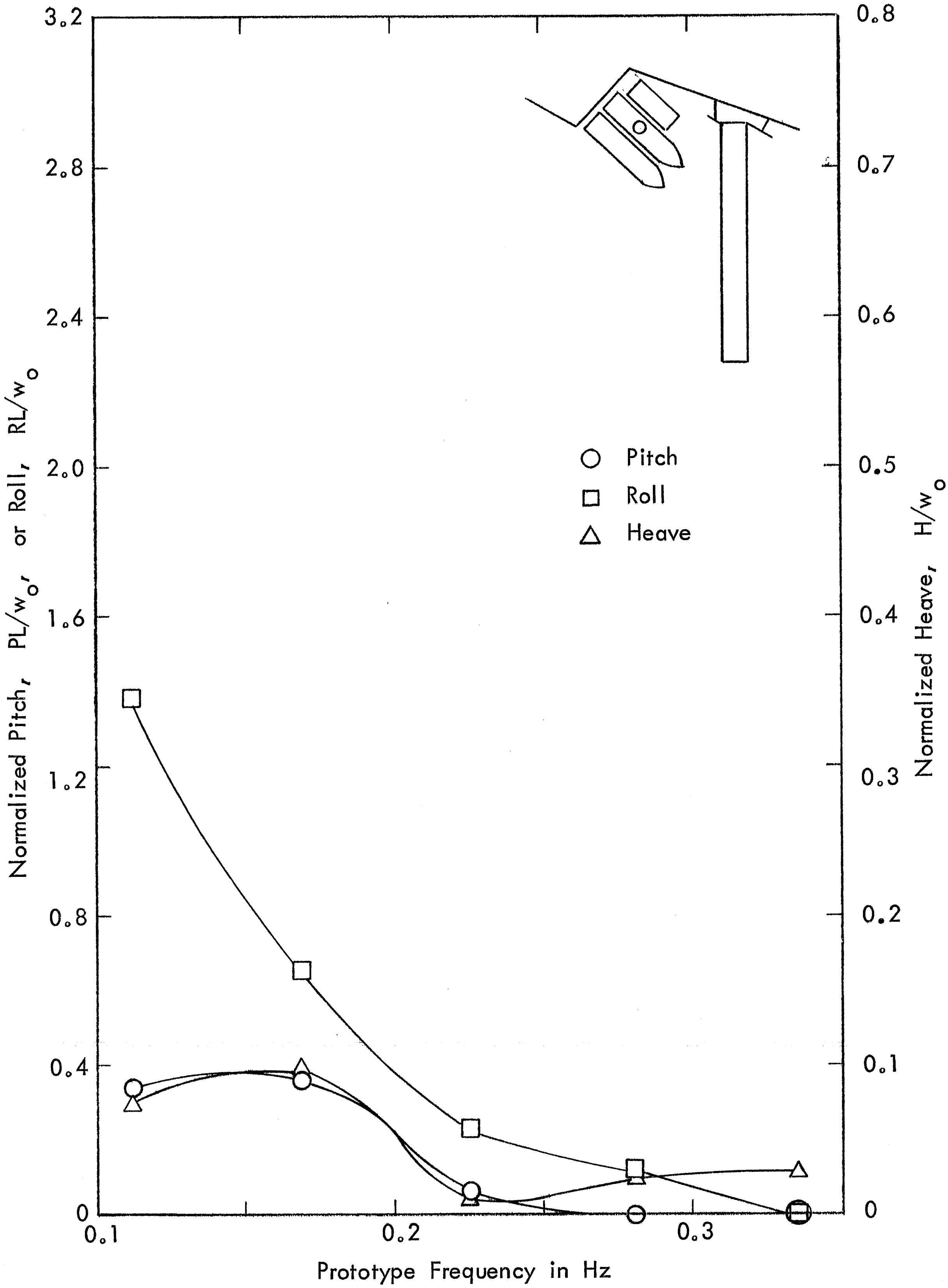

Fig. 36 - Oscillation of APL when moored with other APL and YRBM - with 100 per cent wave screens in place

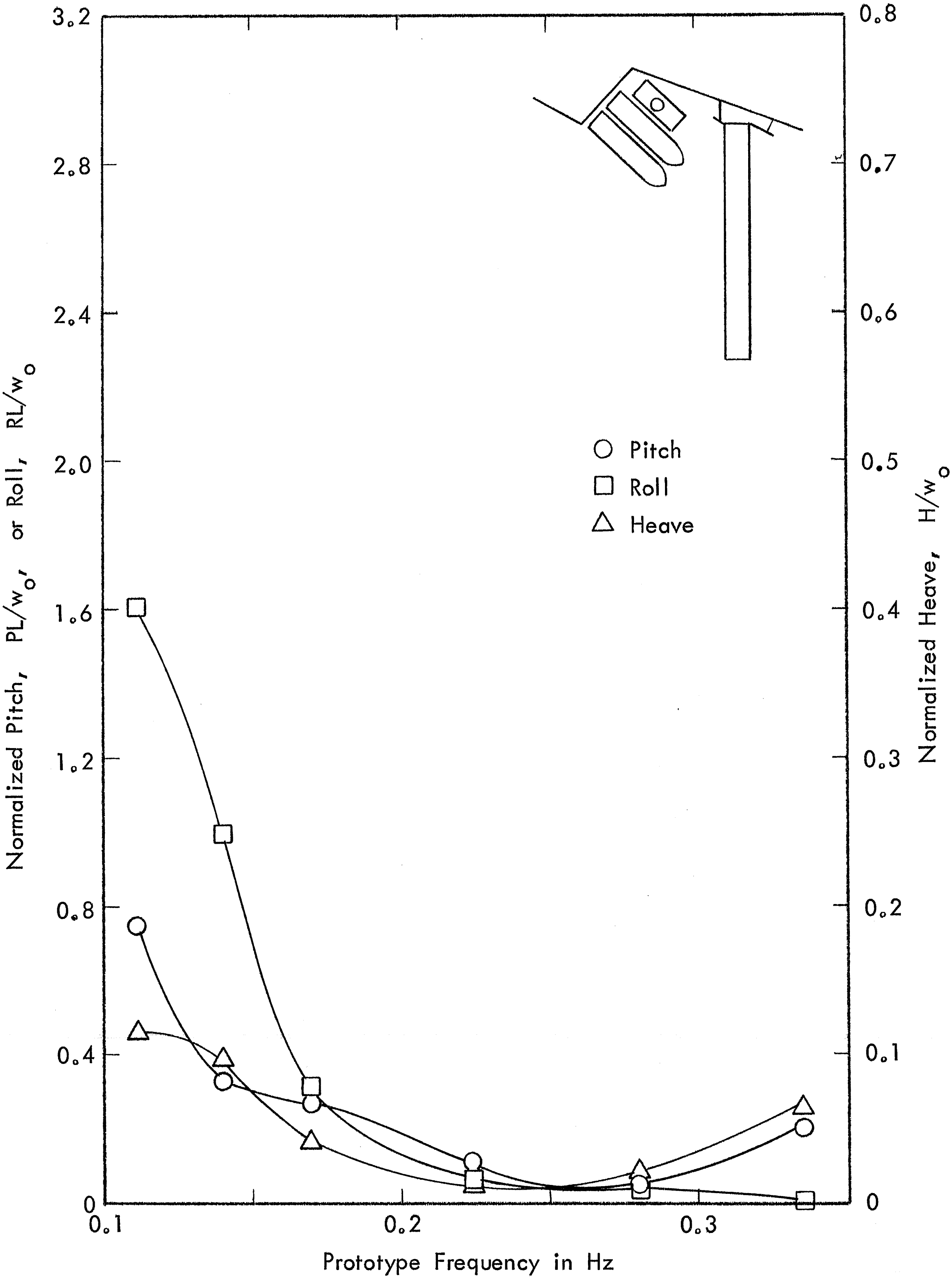

Fig. 37 - Oscillation of YRBM when moored with two APL's - with 100 per cent wave screens in place

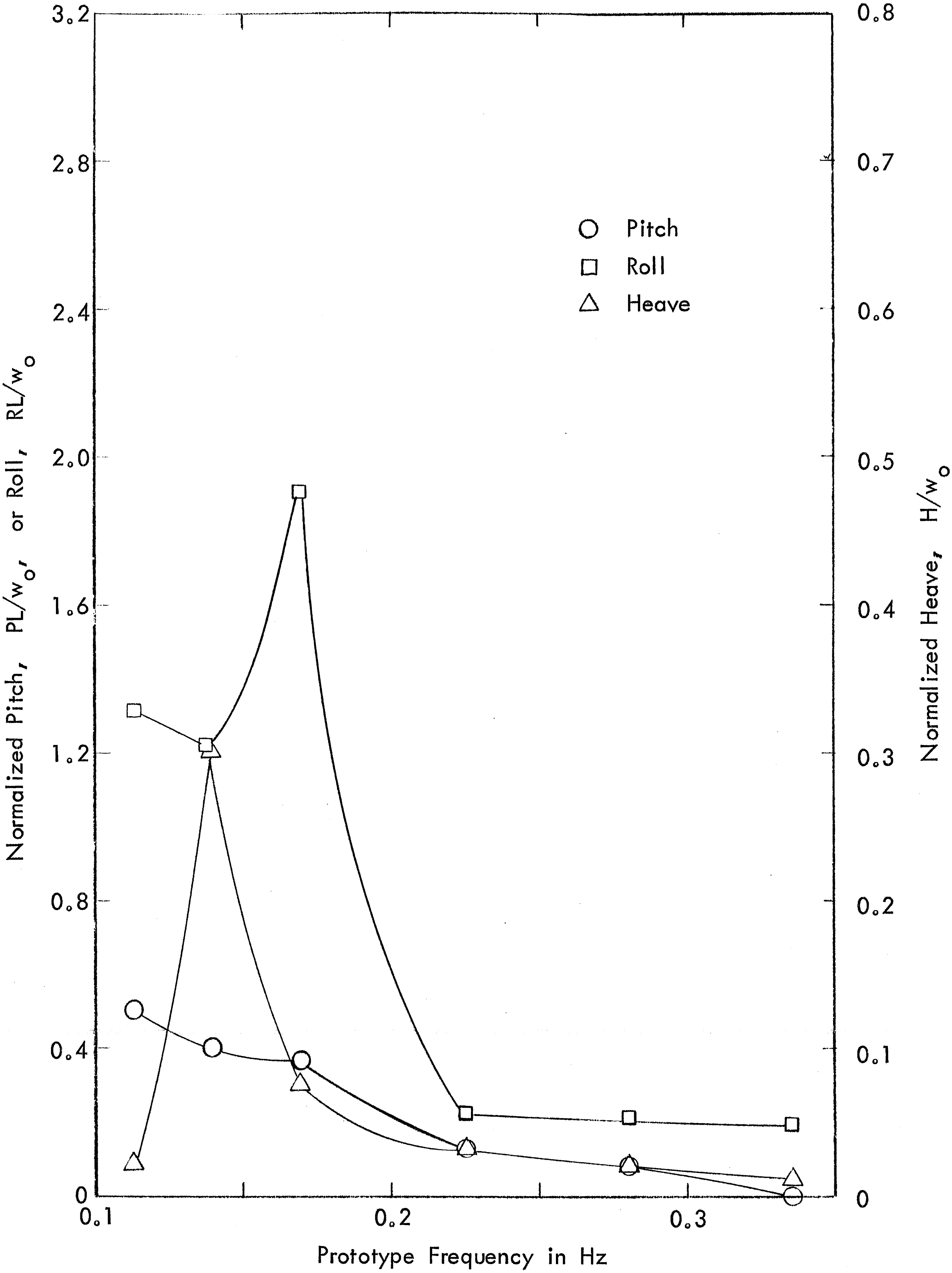

Fig. 38 - Single APL moored normal to wall with submarine on north side of pier

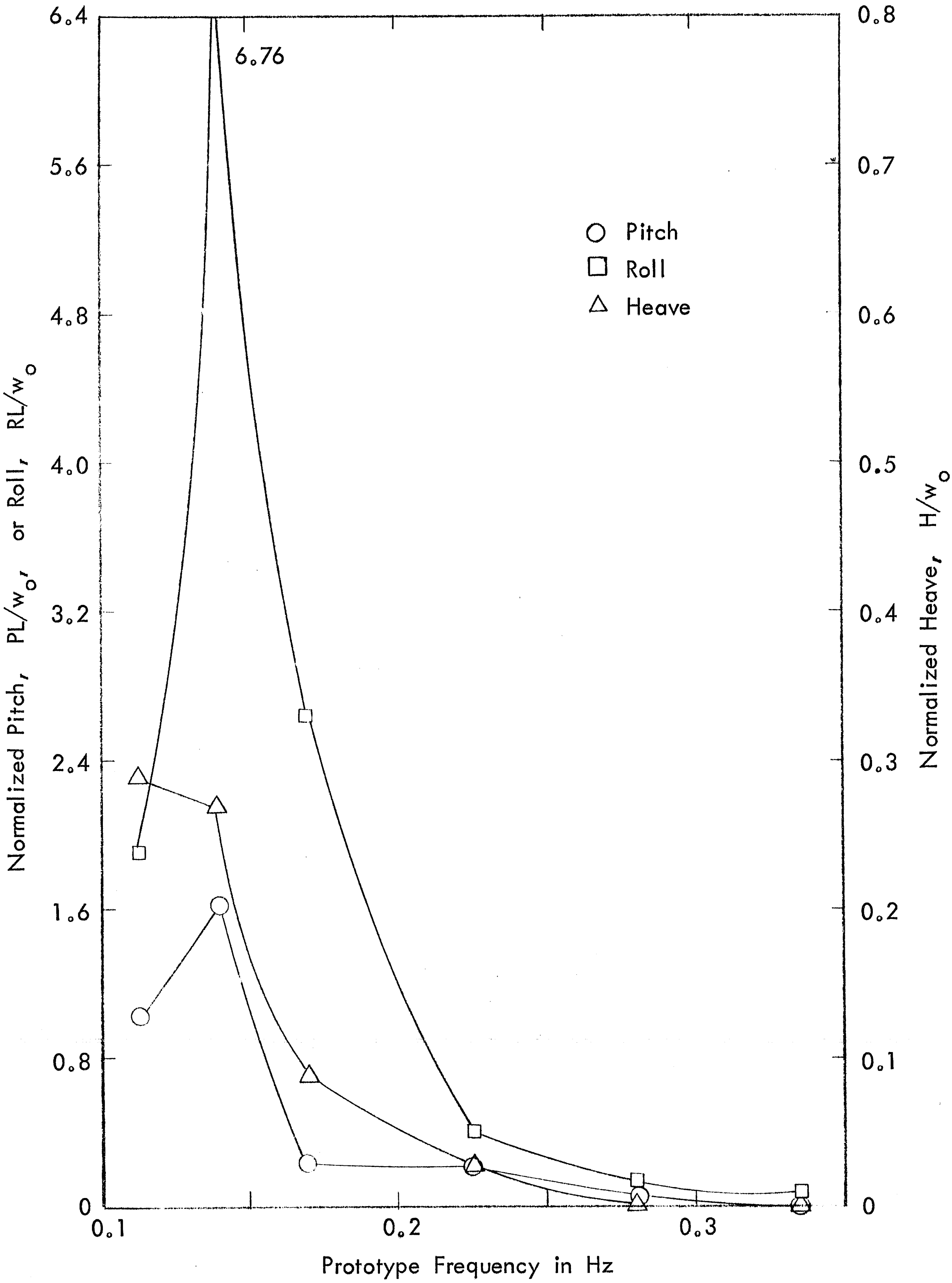

Fig. 39 - Oscillation of APL when moored parallel to wall with submarine at north side of pier