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PREDICTION OF THE MOTIONS OF AN AUTONOMOUS SEMI-SUBMERSIBLE VEHICLE

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1 Introduction

This report summarises the work done by the University of Southampton on the Task 2 and 3 work packages following the meeting with Seaspeed Technology on 14th July.

At the 14th July meeting, it was decided to concentrate, initially, on the seakeeping performance of the vehicle and to look at resistance at a later stage. In order to address the problem of seakeeping a series of systematic variations was decided upon. For a given basis vessel (L, D, S, ∇) the motion characteristics would be calculated for a range of wavelengths and speeds. The effect of varying the centre of gravity, waterplane area, submergence and roll and pitch moments of inertia would then be considered. These variations would then be repeated for changes in diameter and length.

In order to calculate the motions characteristics of the vehicle a three-dimensional potential flow analysis has been adopted. This method represents the wetted surface of the vessel with quadrilateral panels which contain, at their centre, a pulsating source of unknown strength. The strength of the source is determined from the application of boundary conditions [1, 2]. This type of analysis has been applied successfully to the investigation of seakeeping characteristics of conventional ships, as well as multihulls such as SWATHS[3], catamarans[4] and trimarans[5]. Further research on the prediction of motion RAOs at high speeds is ongoing with the objective being to account for nonlinearities arising from the boundary conditions (i.e. various types of translating, pulsating source distribution), in particular at high forward speeds and viscous effects. The latter is very important in predicting the roll amplitude at resonance. No attempt was made to adjust the (potential flow) damping for roll motion, to account for viscous effects.

2 Numerical Modelling

In order to allow the dimensions of the vehicle to be changed readily, the process of creating the wetted surface idealisation was automated as far as possible. In creating the wetted surface idealisation the proportions of the conceptual arrangement (page 18, SEASENSE PROPOSAL, Sept. 1996) were adhered to. Dimensions were taken for the Survey/Military application as outlined in Technical Memo. S1. The forward and aft ends of the vehicle were treated as ellipsoids, the centre as a cylinder. The keel was modelled as tapering towards the bulb in the fore and aft directions. At this stage no appendages were included in the model. The bulb on the keel was not included as its hydrodynamic influence was judged to be very small compared with the rest of the body. The extra computational effort incurred by modelling it could not be justified. Care was taken throughout the modelling process to use panels with aspect ratios close to unity. This has been found to be important in past applications of the theory [5]. The waterline shape has been modelled very simply, tapering at its fore and aft ends and, if the panel length is sufficiently small, having a parallel mid-body.

The idealisation adopted initially has 344 panels, of which 240 are on the main body. This gives an adequate description of the hull without using an excessive number of panels on the wetted surface. The displacement generated by such an idealisation was within 3% of the displacement calculated analytically. A more refined idealisation having 624 panels (464 on the main body) has also been tried in order to determine the effect of improving the modelling of the hull. These two wetted surface idealisations are shown in figures 1 and 2.

3 Analytical Predictions

The characteristics of the basis vessel have been evaluated in regular head seas with wavelength (λ) varying between 14.0 metres and 1500 metres. This represents a variation in wave period (T) of 3 seconds to 31 seconds. This range is more than adequate for realistic sea states. Wave frequencies and lengths corresponding to different wave periods are given in table 1. All heave responses illustrated are plotted as a Response Amplitude Operator, that is; Heave Amplitude (m)/Wave Amplitude(m).

Pitch and Roll are plotted as; Motion Angle(rad)/ Equivalent Wave Slope, ka (rad). The effects of varying the Centre of Gravity vertically, the speed of the vehicle, submergence of the main body, waterplane area, pitch and roll moments of inertia, as well as the length and diameter of the vehicle have been considered. It was impossible to test every single combination of the above; however, over 200 variations have been tested and it is felt this gives a good indication of the effects of changing the main paramaters affecting the motions of the vehicle. For selected important configurations the RMS response of the vehicle has been calculated using an ITTC sea spectrum to give an idea as to how the vehicle will respond in a realistic sea state [6].

3.1 Centre of Gravity

The Centre of Gravity of the vehicle has been varied from -2.0m to -3.5m for the basis submergence of -2.0m ($-S$ to $-S - 1.50$m). Results for a mid-range speed of 12 knots are shown in figures 3 and 4 for heave and pitch in head seas and in figure 5 for roll in beam seas.

As can be seen the vehicle exhibits a large resonant response at a frequency around 0.5 rad/sec, i.e. a wave period of 14 seconds. This natural period decreases slightly as the VCG is moved down. For pitch the effect is similar to heave, with a decrease in the natural period as the VCG is moved down. Considering the response in a realistic sea-state, it is best to increase the natural period to wave periods having less energy. This will correspond to raising the centre of gravity as much as possible. In an ITTC sea spectrum of height=3.0m, T=10 seconds, the RMS response is 0.92m for the highest VCG and 1.62m for the lowest VCG.

The behaviour of roll is similar to heave and pitch, in that moving the VCG downwards results in a shorter natural period. The effect is, however, more marked for roll. The highest VCG position actually corresponds to a negative GM_T, so the longest achievable roll natural period is likely to be around 7 seconds.

All of these results are based on a constant pitch and roll radius of gyration.

3.2 Forward Speed

The effect of varying the speed of advance of the vehicle is shown in figures 6 and 7.

Only three speeds have been considered, namely 8 knots, 12 knots and 16 knots. The responses of the basis vessel have been computed at these speeds. In addition, for each speed, the VCG was altered in the same manner as described above. As one might expect, the natural frequency of the vehicle remains unchanged. However, the effect of forward speed means that this natural frequency is encountered in wavelengths of 342m, 386m and 428m for speeds of 8, 12 and 16 knots respectively. To illustrate this more clearly, the wave period corresponding to the heave natural period has been plotted as a function of forward speed (Fig. 8). Thus it can be seen that as the speed is varied from 0 knots to 20 knots the wave period that excites the heave natural period varies from 11.4 seconds to 16.1 seconds.

Although it is not clear from the graphs included, the effect of increasing the speed is to increase the magnitude of the resonant response. The forward speed effect means, however, that an increase in speed will result in less wave energy at this natural frequency. The increase in response with speed is not, therefore, expected to present a practical problem.

The effect of changing VCG is not shown here, but has been confirmed as identical to the 12 knot case discussed above.

3.2.1 Zero Forward Speed

To provide a direct comparison with the zero forward speed seakeeping tests on the SASS model, the response of the model in head seas was calculated. These results are shown in figures 9 and 10.

For these calculations the dimensions of the model were used, although the geometry will not be exactly correct due to the assumptions concerning shape adopted in section 2. The Centre of Gravity was varied to cover a range including that of the model as it stands ($\approx -S - 0.10$m).

From these figures it is clear that the heave natural frequency does not vary with the height of the Centre of Gravity, as it does with forward speed, but is at a frequency corresponding to a wave period of $\approx$ 6.0 seconds in all cases. The resonant response is also much lower at zero speed, as one might expect, although the data spacing in this frequency range may exaggerate the effect.

Although full RAOs for the model are not yet available, the observations on the model in regular waves do, in general, confirm these results.

3.3 Submergence

The third parameter varied is the submergence of the main body of the vehicle. Whilst this has been varied the depth of the keel has remained the same (i.e. the keel is still 2.0m below the main body centreline). For a speed of 12 knots submergences of $0.2L, 0.4L$ and $0.6L$ have been investigated. For each of these submergences the centre of gravity has been changed from -S to -S-1.5. Results for a basis VCG of -S-0.25m are given in figures 11,12 and 13.

As can be seen from these figures, the effect of changing the submergence is minimal for heave and pitch. The only point worth making is that the resonant response is increased as the main body approaches the surface. This effect is more marked in heave.

For roll, the effect of increasing the submergence of the main body is to increase the natural period of the vehicle. It would therefore appear as though an increase in submergence is be desirable.

3.4 Waterplane Area

To assess the effect of changing the waterplane area on the responses of the vehicle three different strut lengths have been tested, namely 0.75m, 1.25m and 1.50m. As the strut length was altered the breadth of the strut was also changed in order to keep the strut length/beam ratio constant. These changes are shown in figures 14 and 15.

As one would expect, the smaller the strut size, the higher the natural periods in heave and pitch of the vehicle. It also appears as though the resonant response is reduced as the strut size is reduced, however this may be due to the data spacing in this region. Since moving the natural period to a lower frequency is desirable, a smaller strut size is better. Calculating the RMS responses to an ITTC sea spectrum ($h_{\frac{1}{3}}$=3.0m, T=10secs) the strut length of 0.75m gives an RMS for heave of 0.27m as compared to 1.40m for a strut length of 1.50m. This is for the lowest (i.e. worst) VCG. Computing RMS values for intermediate strut lengths indicates that the real gain is between a strut length of 0.75m and 1.0m.

The effect of the strut size on roll is minimal, as one would expect given the small change in the breadth of the strut (from 0.15m to 0.3m).

3.5 Roll Moment of Inertia

The effects of changing the roll moment of inertia are shown in figure 16. Three values of k_{44} have been investigated, ranging from $0.5S$ to $1.0S$.

An increase in the moment of inertia will increase the natural period of the vehicle in roll.

3.6 Pitch Moment of Inertia

The effects of altering the pitch moment inertia are identical to those of altering the roll moment of inertia, i.e. an increase in the moment of inertia will result in an increase in the pitch natural period.

3.7 Diameter

The diameter of the main body has been varied from 1.0m to 0.7m and 0.4m. The results of this variation are shown in figures 17 and 18. Whilst the diameter was varied the strut length and breadth were not altered. Similarly the keel depth was not adjusted.

As the figures clearly show, the larger the diameter, the longer the natural period in both heave and pitch. This is as a result of increasing the mass of the vehicle, whilst the waterplane area and VCG remain unchanged. The response is, however, sharply 'tuned' to the wave period and a slight change in the dominant wave period in a sea state could alter the optimum configuration.

The effect of diameter on roll is illustrated in figure 19. As can be seen the effect is minimal.

3.8 Length

Three different lengths of the main body have been considered, L=2.0m, L=5.0m (the basis) and L=10.0m. These lengths correspond roughly to the different versions of the SASS being considered for different rôles. For each of these lengths three different diameters were tried, corresponding to the same L/D ratios as run for the basis (see above). Whilst the length was varied the strut length (and hence breadth) were also altered to maintain the strut length/vehicle length ratio as a constant. The keel length, breadth and depth remained unaltered. Results are shown in figures 20 and 21.

From the graphs it is clear that the longer the vehicle, the higher the heave and pitch natural periods. This is beneficial in a realistic sea state. For example; for the maximum diameter the RMS heave value is 1.348m for the smallest length and only 0.352m for the L=10.0m vehicle (ITTC spectrum, $h_{\frac{1}{3}} = 3.0m, T = 10s$). The RMS responses of the 3 versions of the SASS being considered are given in table 2 for representative sea states.

The effect of length on roll response (shown in fig. 22) appears to be similar to that of heave and pitch, in that an increase in length results in an increase in the natural period.

4 Conclusions

- A program to create an idealisation of the SASS vehicle, keeping initial proportions but allowing variation of parameters, has been developed. This appears to work well.
- Calculations over a realistic range of wavelengths have been undertaken for the basis Survey/Military version of the SASS in regular head and beam seas. Results indicate a relatively low response in heave and pitch.
- Variations in the vertical position of the Centre of Gravity indicate that the higher the VCG, the higher the natural period. This is true for heave, pitch and roll. This means a higher VCG is likely to give lower motions in a realistic sea state.
- Increasing the speed increases the magnitude of the resonant response. This is unlikely to be serious as the frequency of encounter effect moves the resonant response to wavelengths with less energy.
- Increasing the submergence of the main body has little effect on heave and pitch. However, the natural period in roll is increased with increasing submergence. This is likely to prove beneficial in a realistic sea state.
- Decreasing the waterplane area increases the natural period in heave and pitch. There is little effect on roll. This increase is quite marked and could prove beneficial in a realistic sea state.
- Increasing the roll and pitch radii of gyration increases the natural periods of those modes. This could be of benefit for both motions.

- Increases in diameter (for a fixed length) increase the natural periods of heave and pitch response. This increase could, again, be beneficial.
- Increasing the length of the vehicle increases the natural periods of heave and pitch. This increase is large and could therefore be very helpful in reducing the response of the vehicle.

5 Recommendations

From the above it is clear that, if an increase in the natural periods of all motions is sought, the vehicle should be as long as possible, as wide as possible, with as small a waterplane area as possible. The main body should be as deeply submerged as practicable and the VCG as high as possible whilst maintaining stability. It is likely that the vehicle will require a control mechanism for both pitch and roll, as if the resonant response is excited it will be large. If this control system can be applied to the heave motion as well it will obviously be of benefit.

It should be stressed that the actual resonant magnitudes may be substantially altered from those calculated by viscous effects. This is especially true of roll and, to a lesser extent, pitch. In the case of roll it is possible that the resonant frequencies will also be altered substantially.

It is believed that the trends predicted will remain valid.

References

[1] R.B. Inglis and W.G. Price. A three-dimensional ship motion theory: Calculation of wave loading and response with forward speed. *Trans. RINA*, 124:183–192, 1982.

[2] R.B. Inglis and W.G. Price. The influence of speed dependent boundary conditions in three dimensional ship motion problems. *International Shipbuilding Progress*, 28(318):22–29, 1981.

[3] R.E.D. Bishop, W.G. Price, and Y.S. Wu. A general linear hydroelasticity theory of floating structures moving in a seaway. *Philosophical Transactions of the Royal Society*, Series A, 316:375–426, 1986.

[4] D.A. Hudson, P. Temarel, and W.G. Price. Seakeeping of high speed displacement craft. In *FAST '95: Proceedings of the Third International Conference on Fast Sea Transportation*, volume 2, pages 877–892, Lübeck-Travemünde, Germany, 1995.

[5] P. Temarel and D.A. Hudson. Prediction of heave, pitch and roll motions for three trimaran models. Ship Science Report 95, University of Southampton, 1996.

[6] E.V. Lewis, editor. *Principles of Naval Architecture*, volume 3, chapter Motions in Waves. SNAME, 1989.

Table 1: Wave Frequency and Wavelength for Different Wave Periods

Wave Period (secs)	Wave Frequency (Hz)	Wavelength (m)
3	0.333	14.047
5	0.200	39.019
10	0.100	156.078
15	0.067	351.175
20	0.050	624.311
25	0.040	975.486
30	0.033	1404.699

Table 2: Response of Different Versions of SASS Vehicle at 12 Knots

SASS Version:	Coastal	Survey	Offshore
Length (m)	2.0	5.0	10.0
Sig. Wave Height (m)	1.0	3.0	5.0
Wave Period (s)	8.0	10.0	12.0
RMS Heave (m)	0.451	1.105	1.477
RMS Pitch (m)	2.706	1.000	3.794

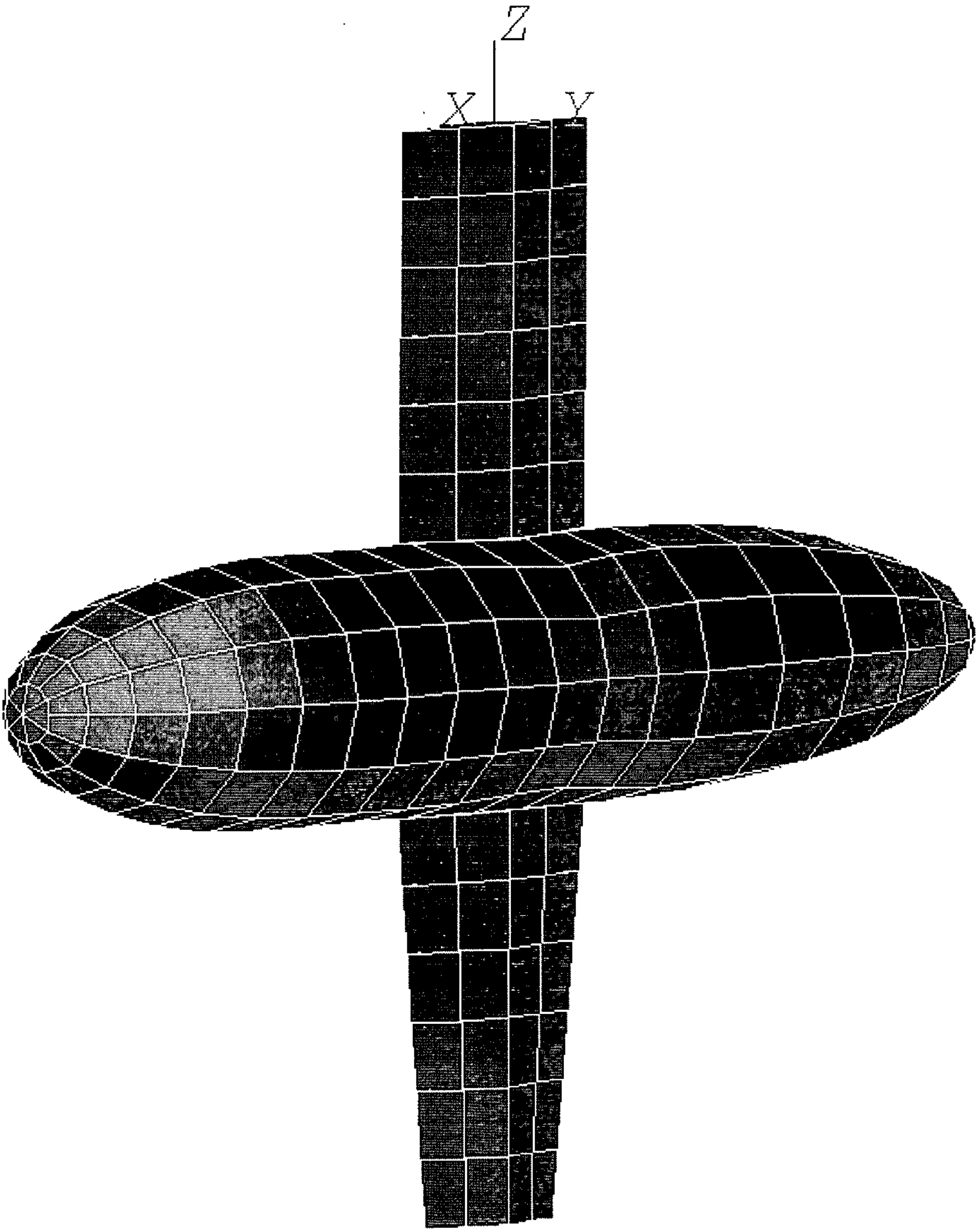

Figure 1: Wetted Surface Idealisation (344 panels)

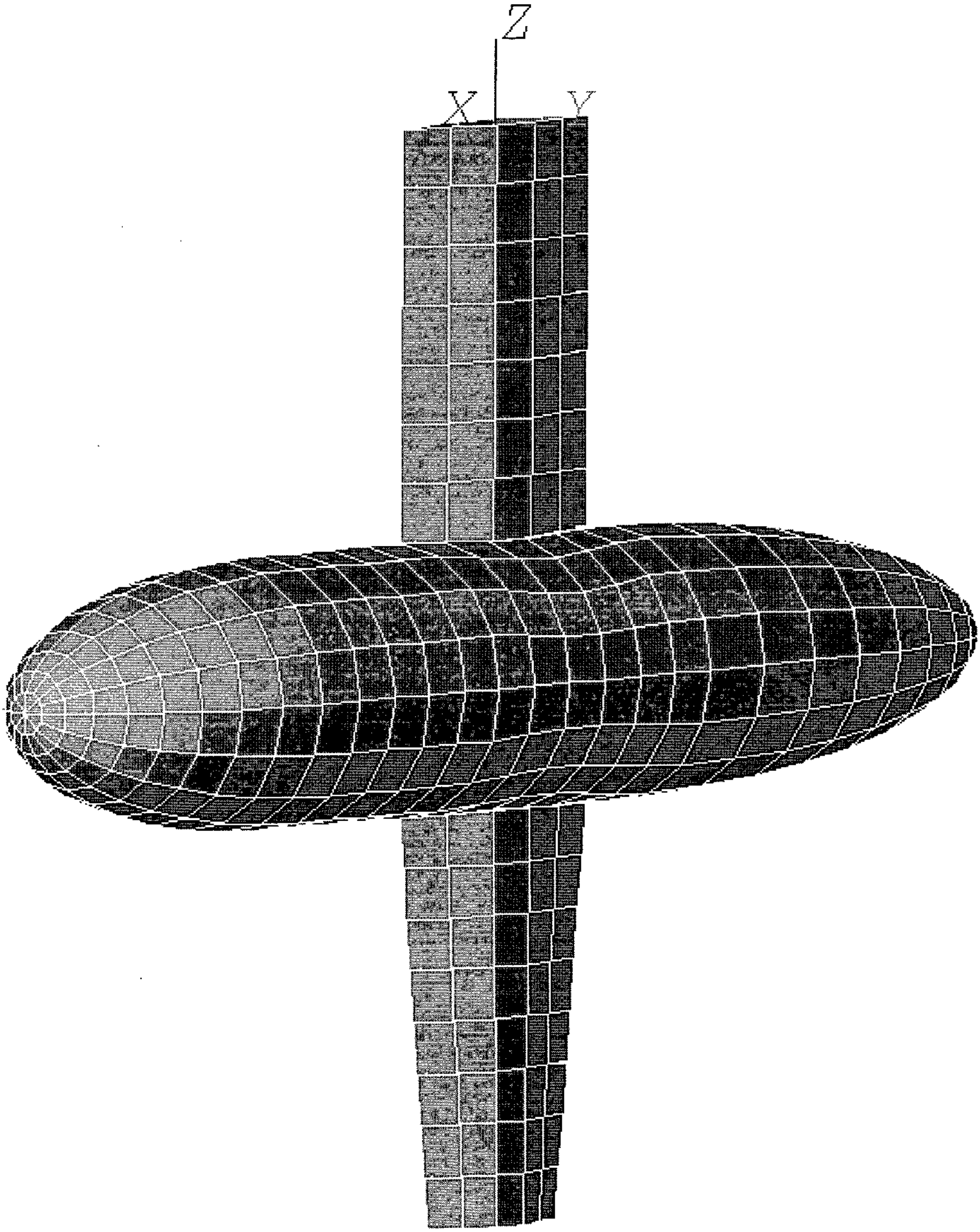

Figure 2: Wetted Surface Idealisation (624 panels)

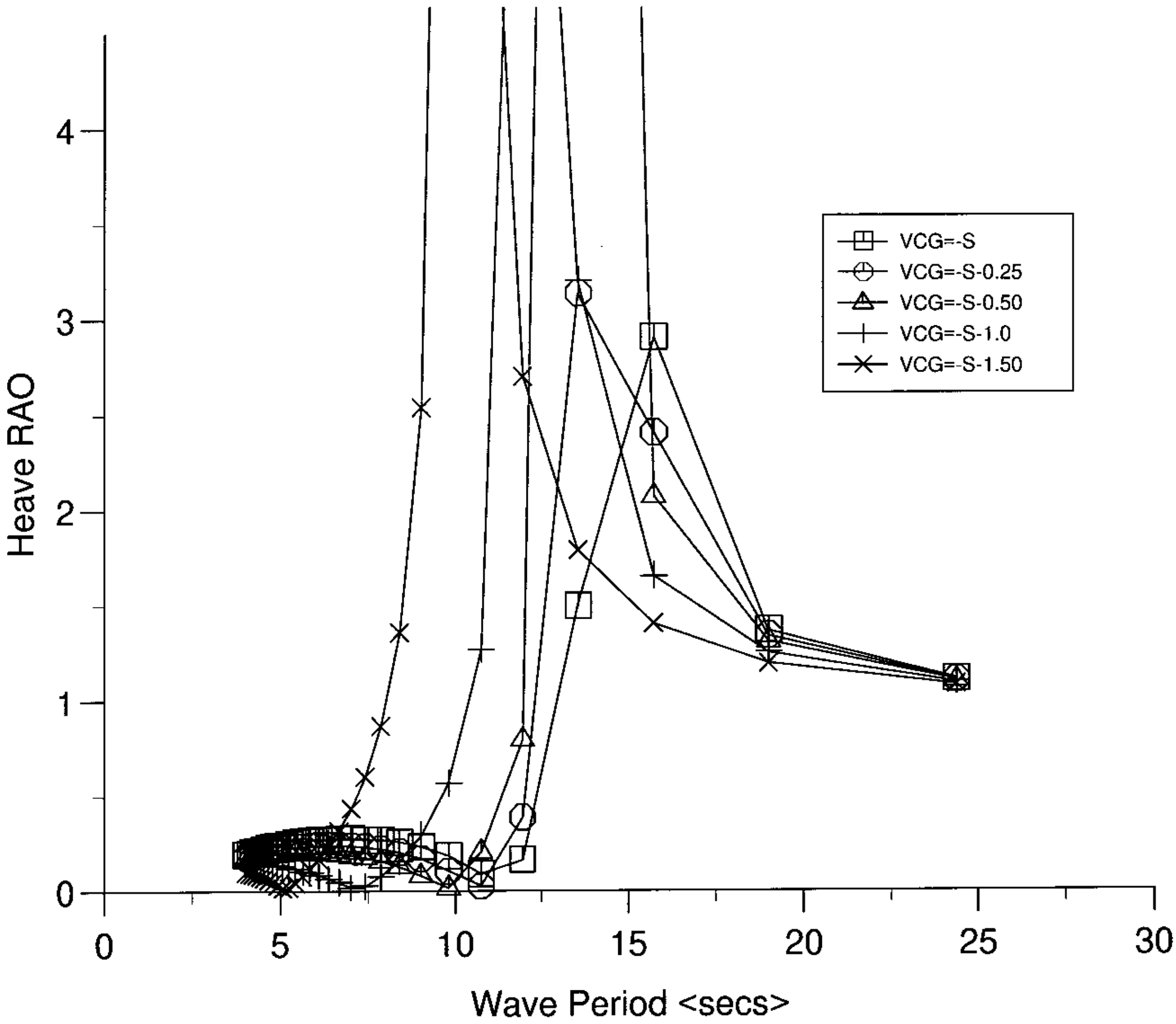

Figure 3: Heave RAO for L=5.0m, U=12Kts, S/L=0.4, varying VCG.

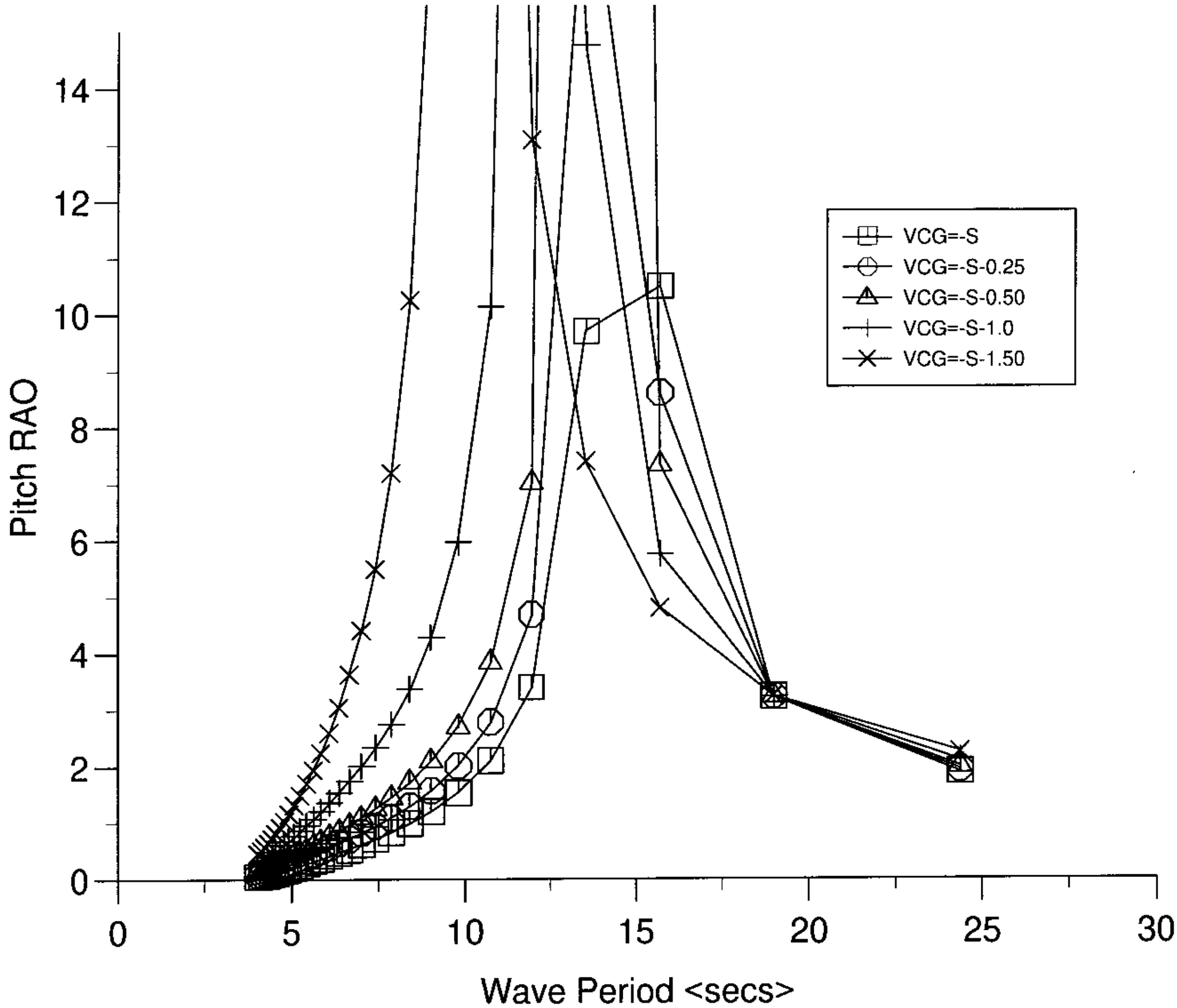

Figure 4: Pitch RAO for L=5.0m, U=12Kts, S/L=0.4, varying VCG.

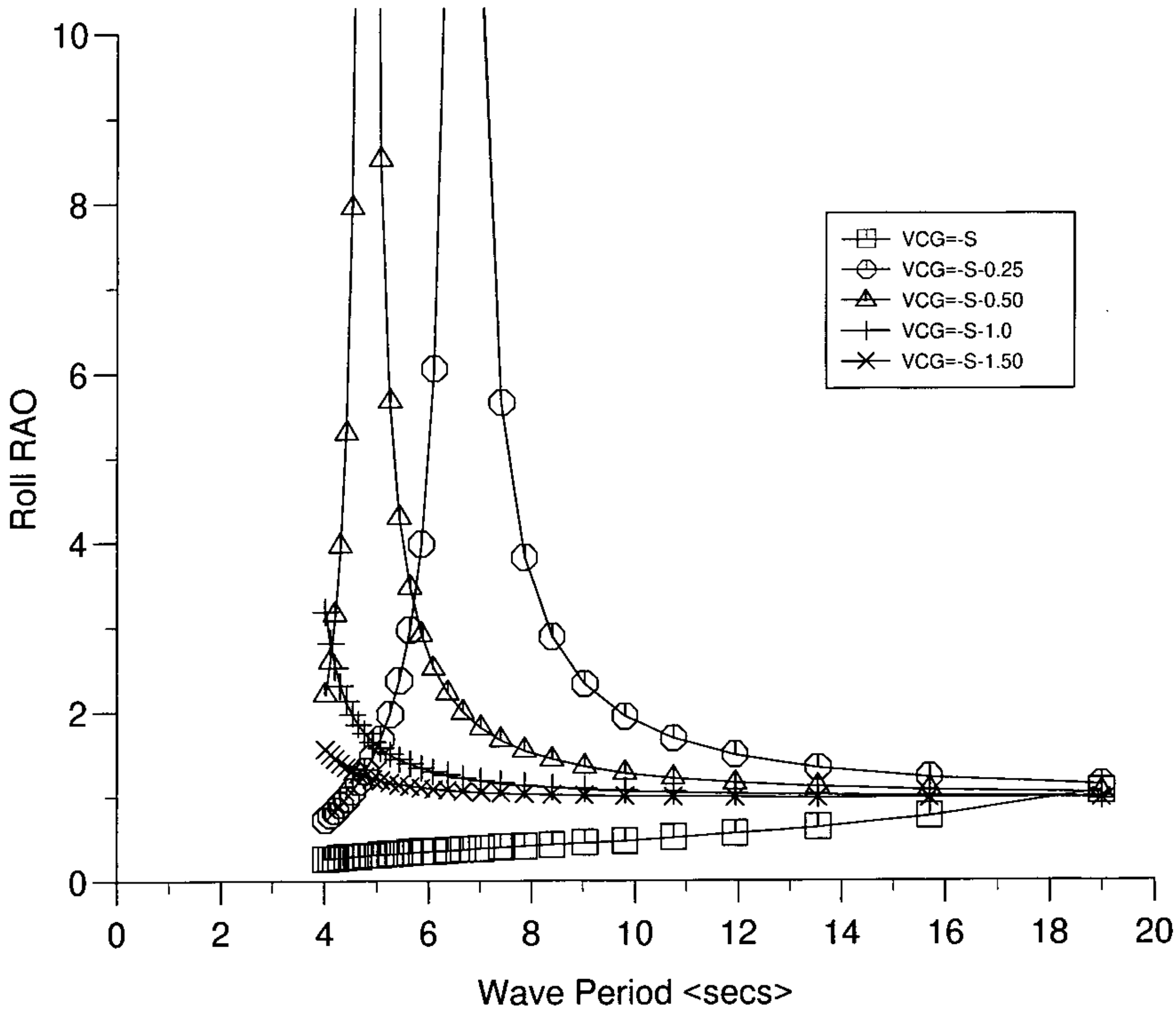

Figure 5: Roll RAO for L=5.0m, U=12Kts, S/L=0.4, varying VCG.

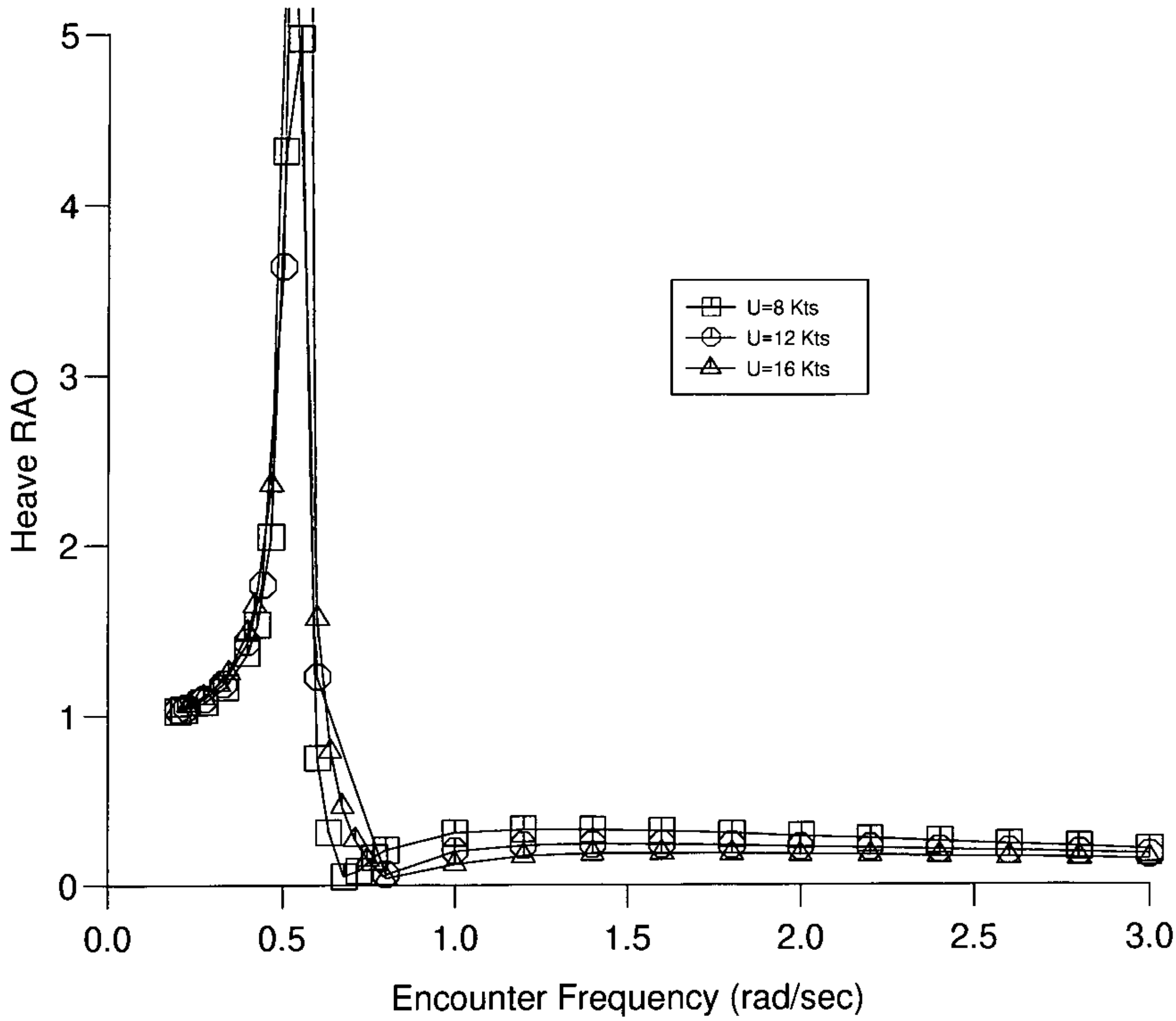

Figure 6: Heave RAO for L=5.0m, VCG=-2.5m, S/L=0.4, varying U.

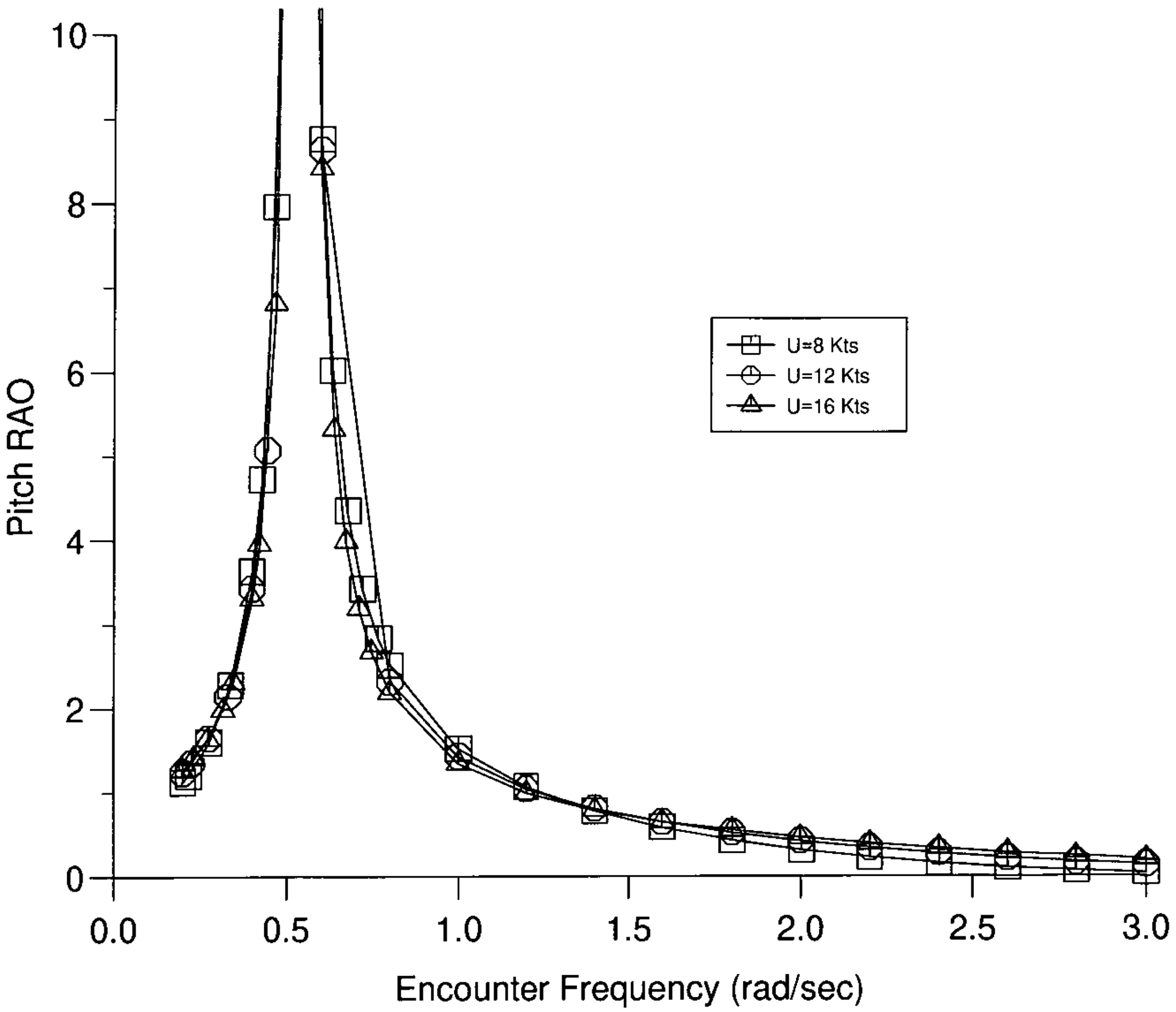

Figure 7: Pitch RAO for L=5.0m, VCG=-2.5m, S/L=0.4, varying U.

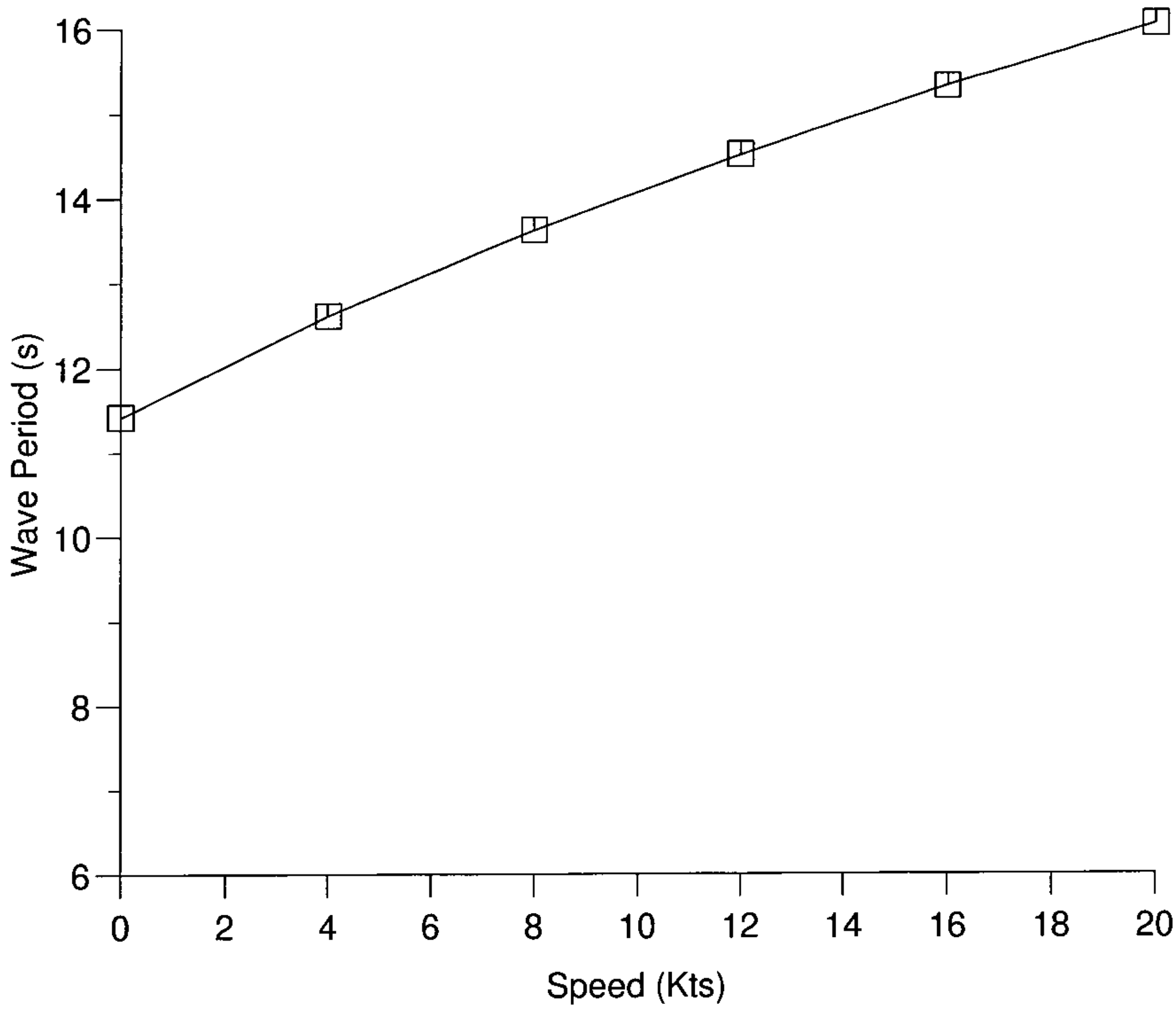

Figure 8: Wave Period Exciting Heave Natural Period vs Speed

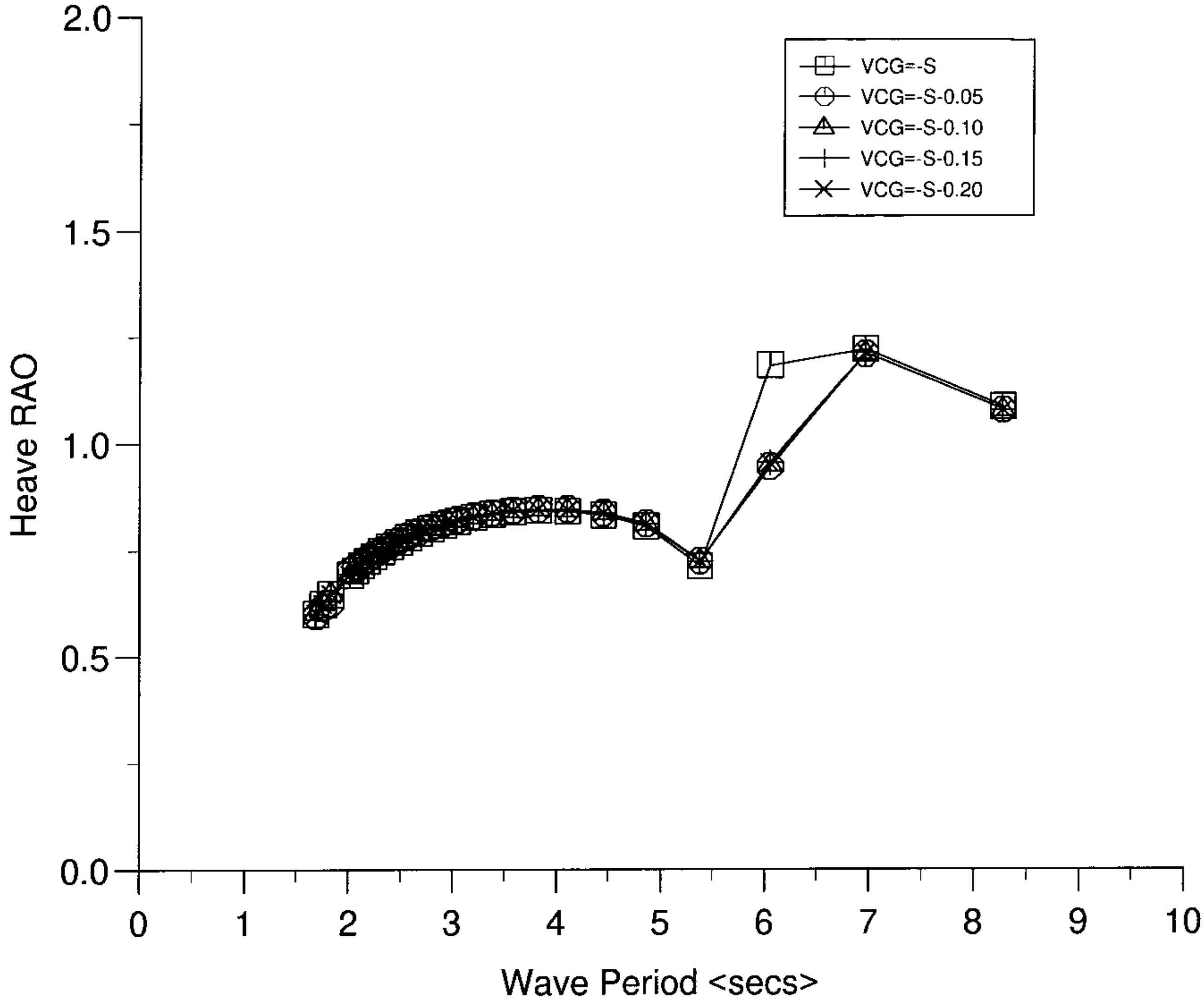

Figure 9: Heave RAO for L=0.75m, S/L=0.4, U=0.0m/s

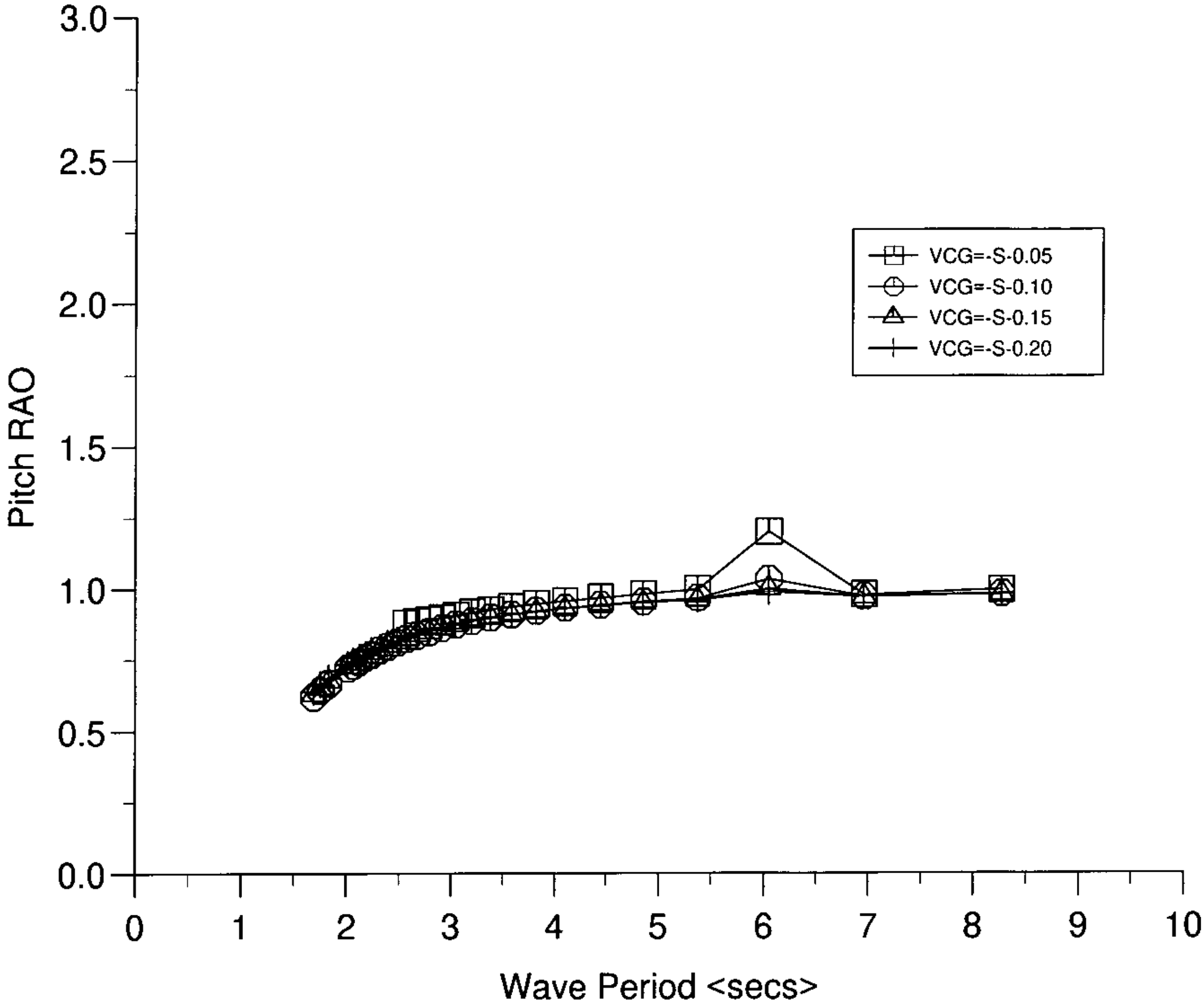

Figure 10: Heave RAO for L=0.75m, S/L=0.4, U=0.0m/s

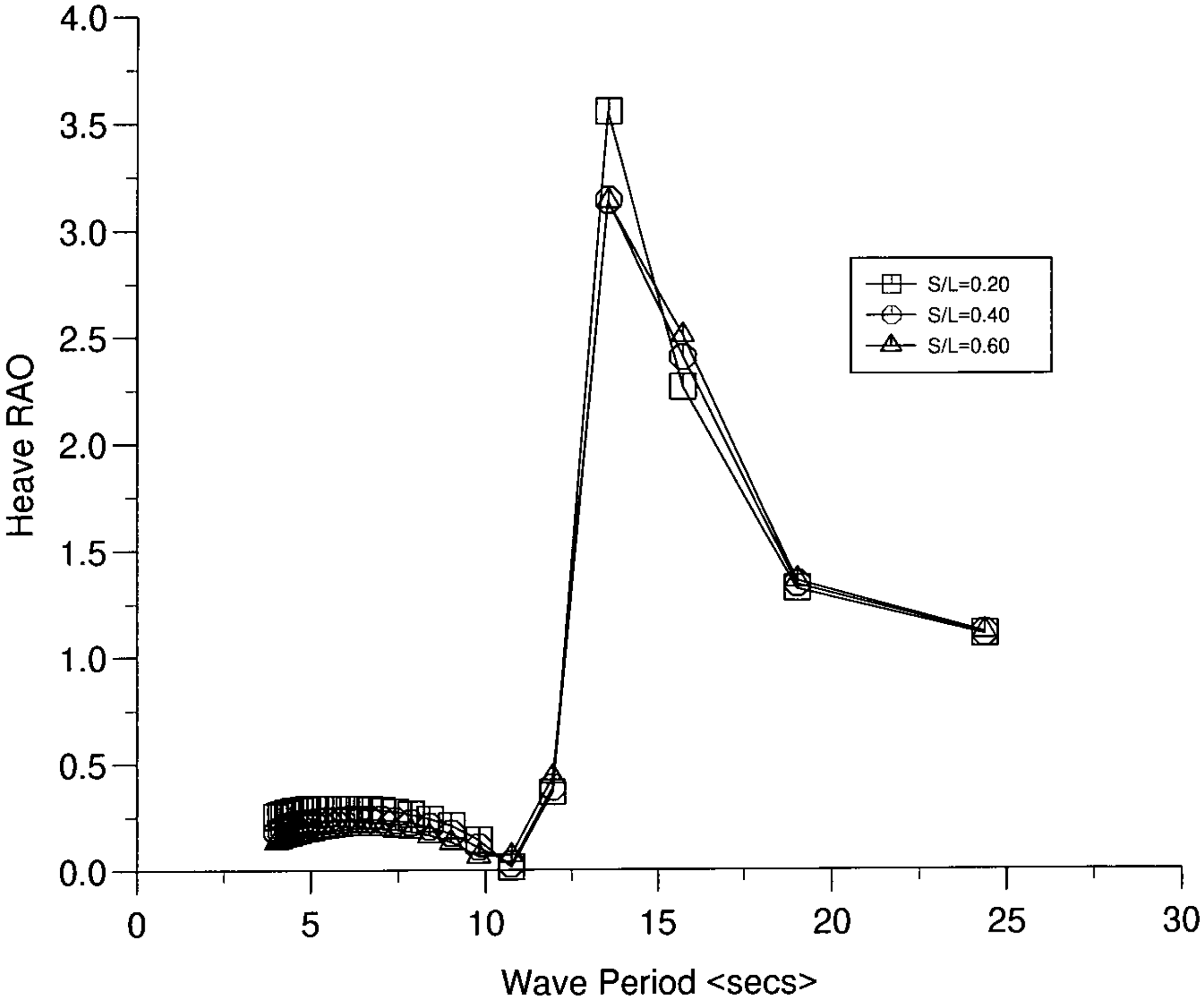

Figure 11: Heave RAO for L=5.0m, VCG=-S-0.25m, U=12kts, varying S.

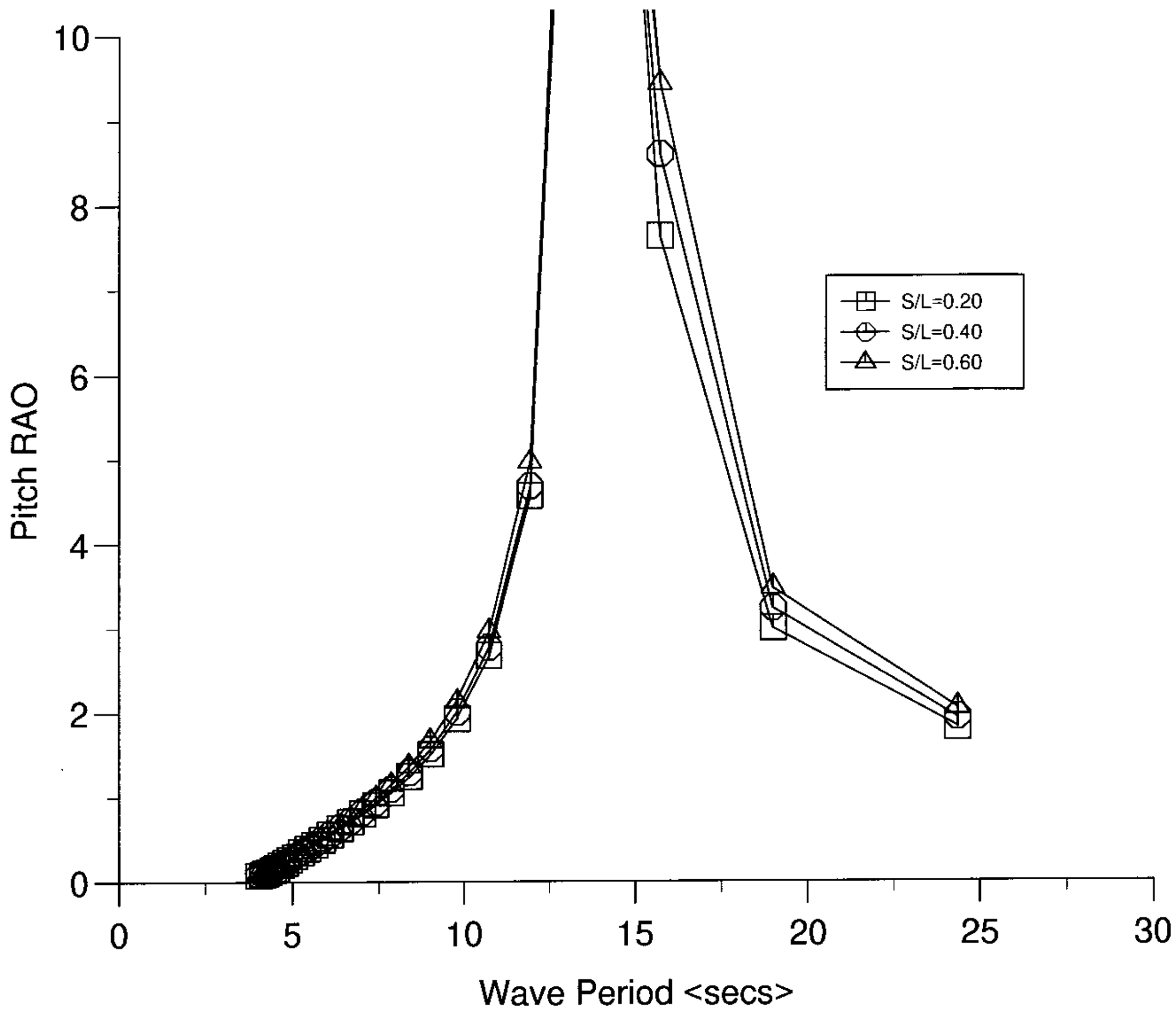

Figure 12: Pitch RAO for L=5.0m, VCG=-S-0.25m, U=12kts, varying S.

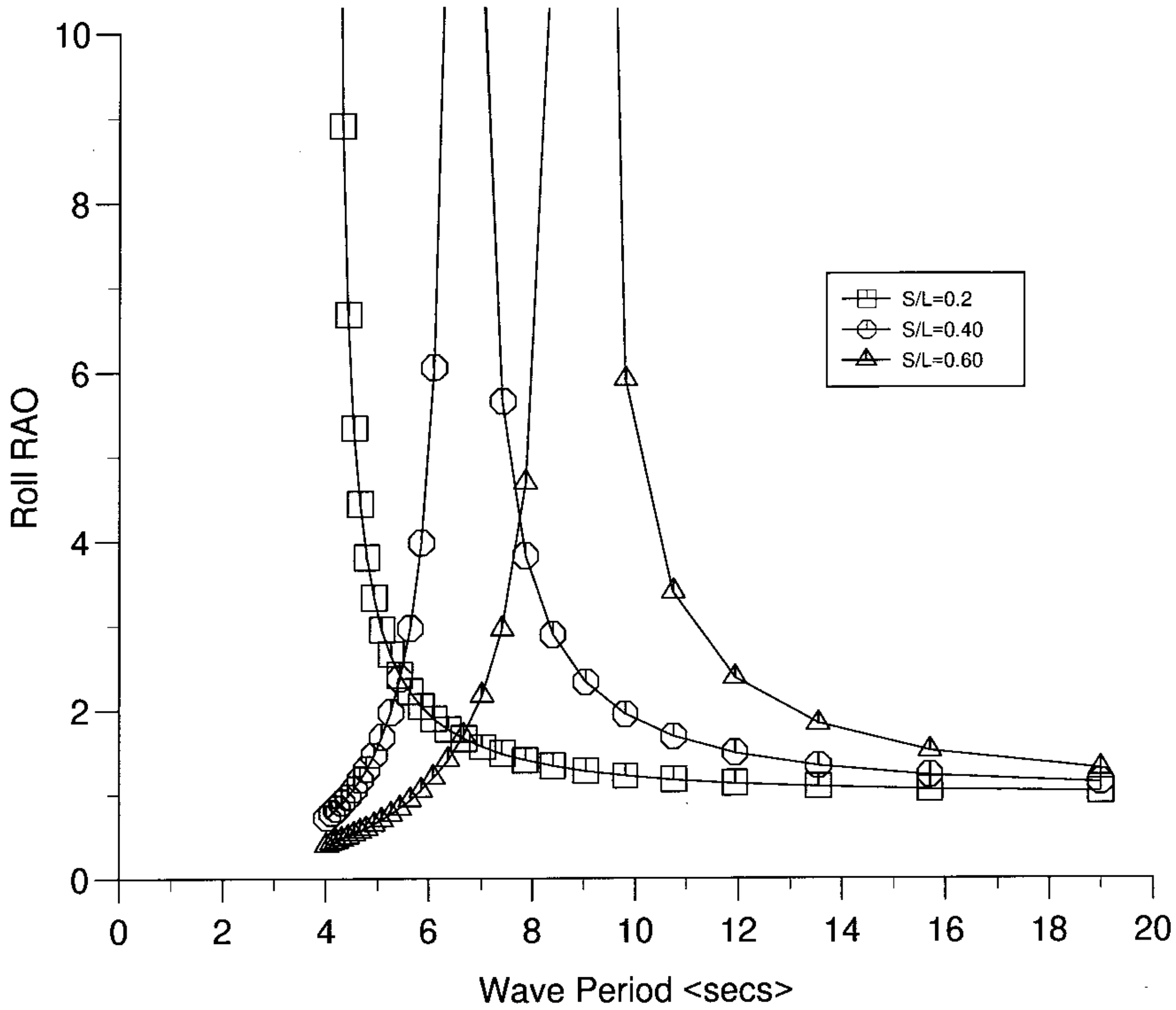

Figure 13: Roll RAO for L=5.0m, VCG=-S-0.25m, U=12kts, varying S.

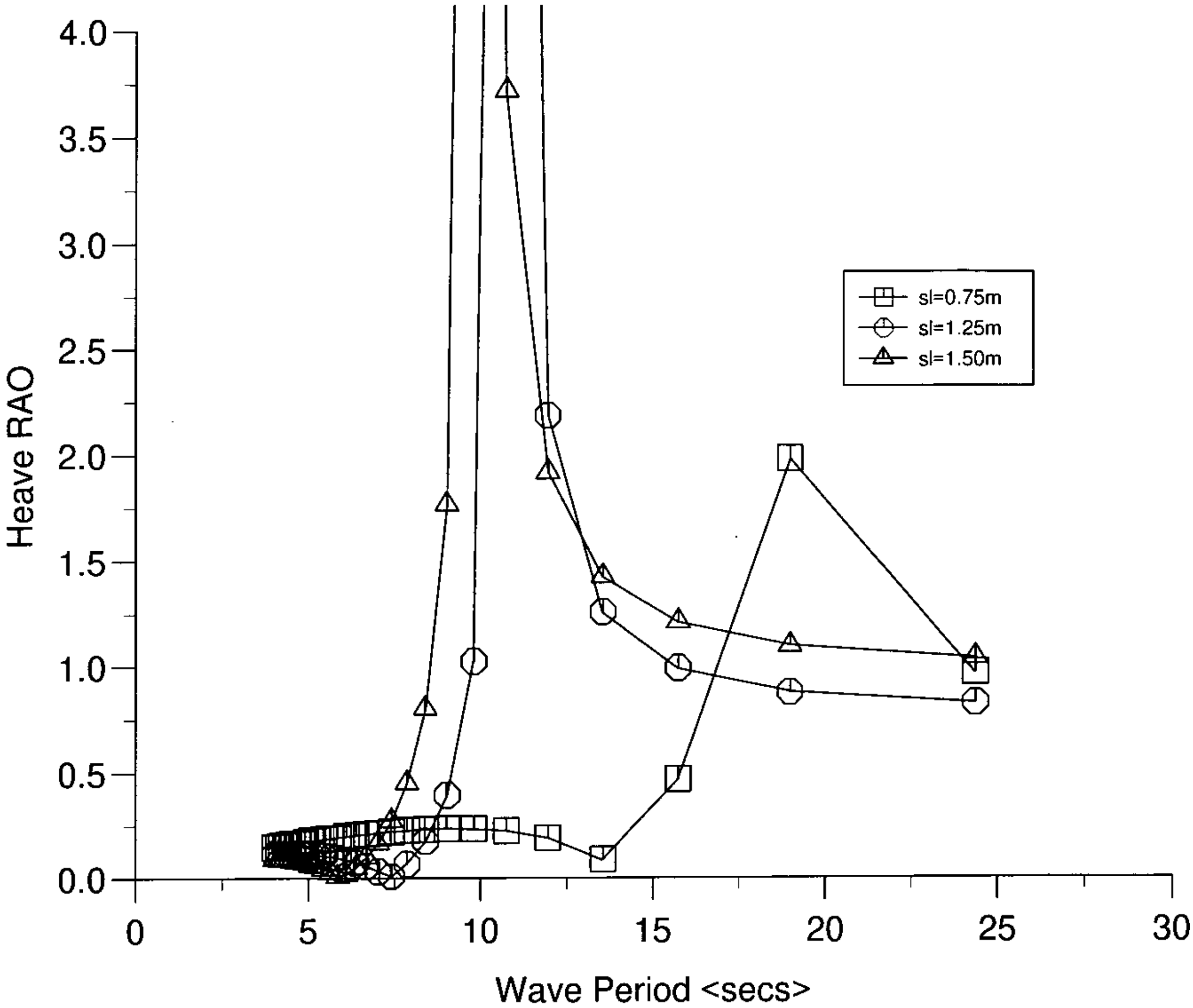

Figure 14: Heave RAO for L=5.0m, VCG=-S-0.25m, U=12kts, S/L=0.4, varying strut length.

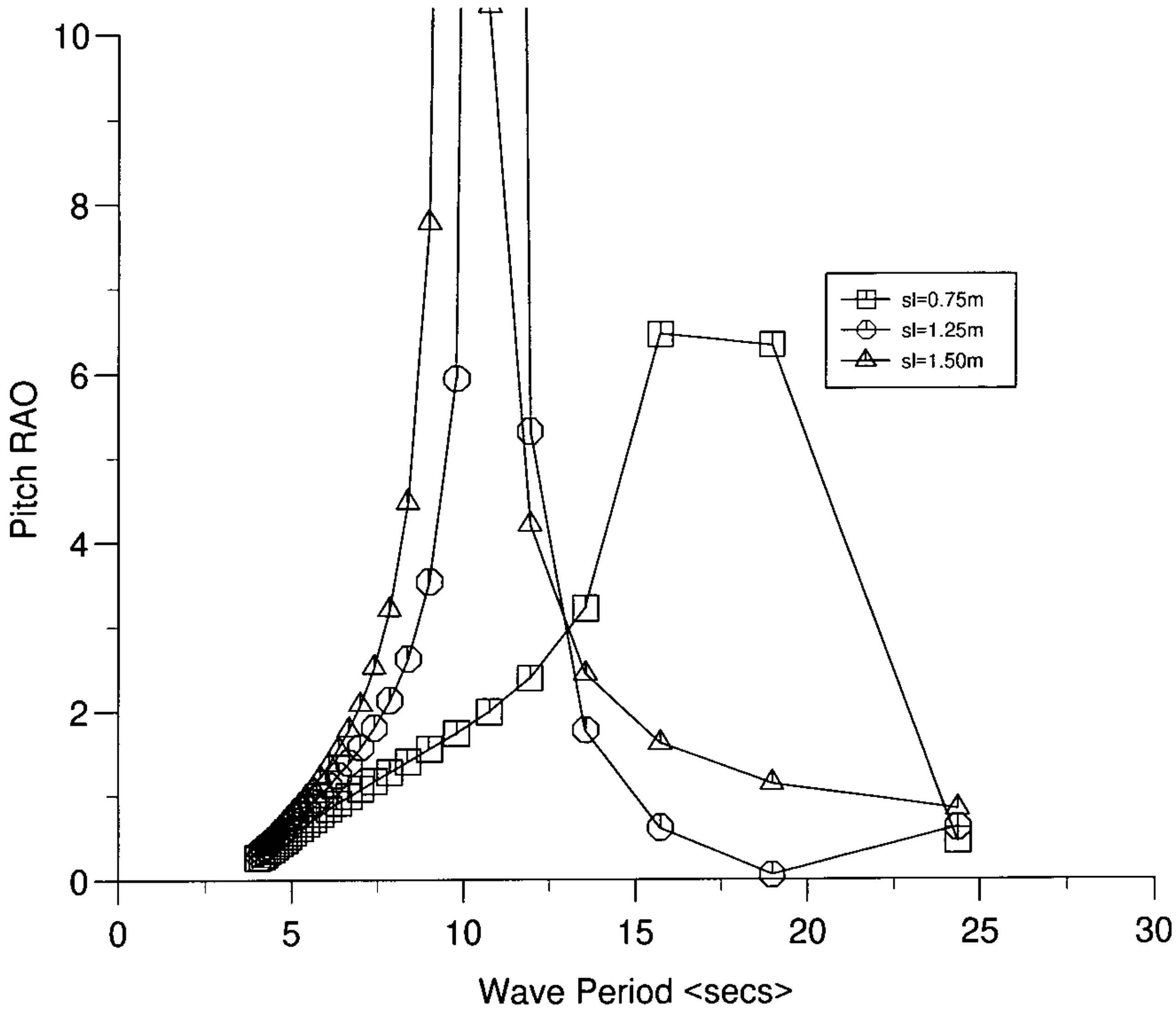

Figure 15: Pitch RAO for L=5.0m, VCG=-S-0.25m, U=12kts, S/L=0.4, varying strut length.

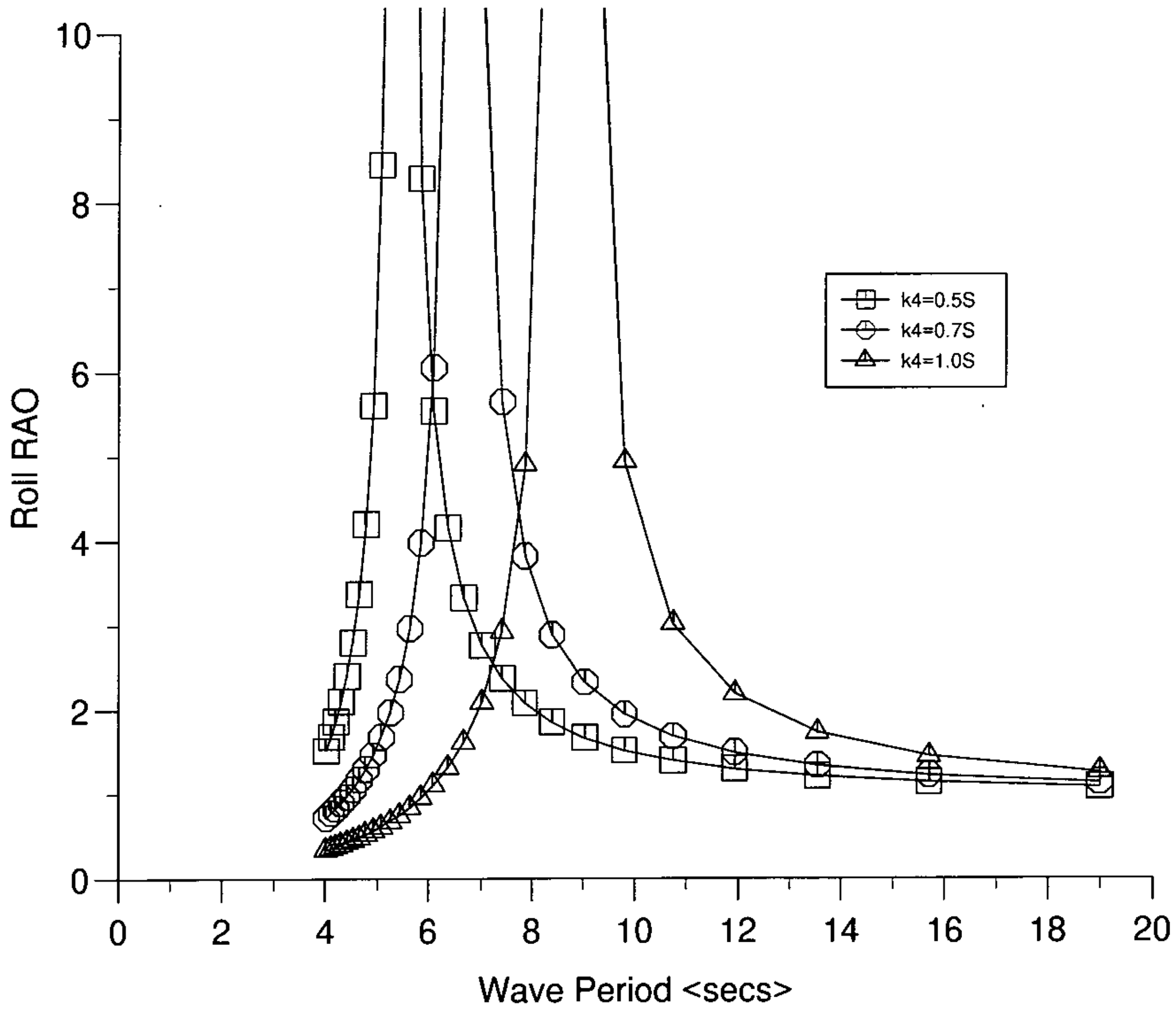

Figure 16: Roll RAO for L=5.0m, VCG=-S-0.25m, U=12kts, S/L=0.40, varying k_{44}.

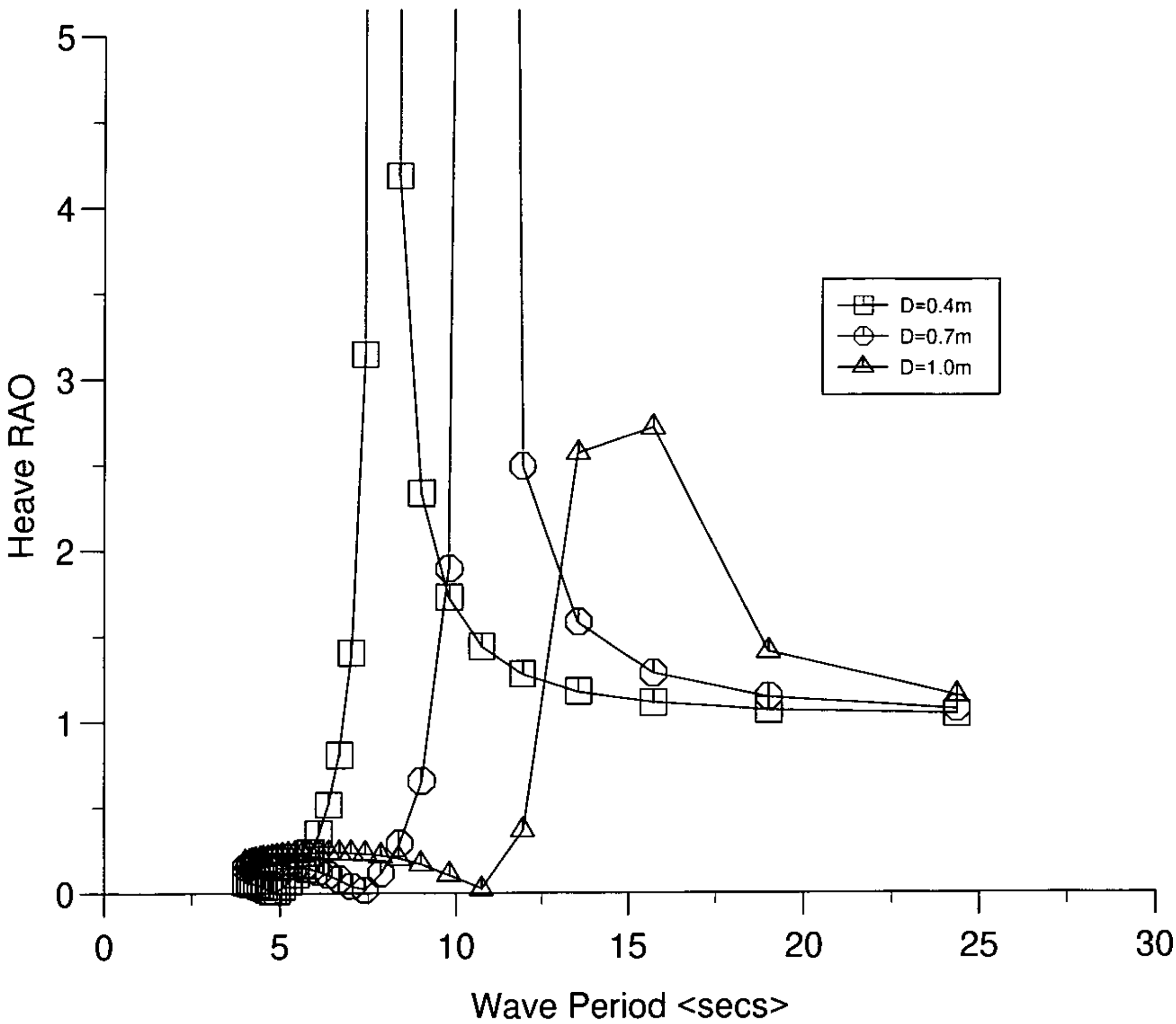

Figure 17: Heave RAO for L=5.0m, VCG=-S-0.25m, U=12kts, S/L=0.40, varying diameter.

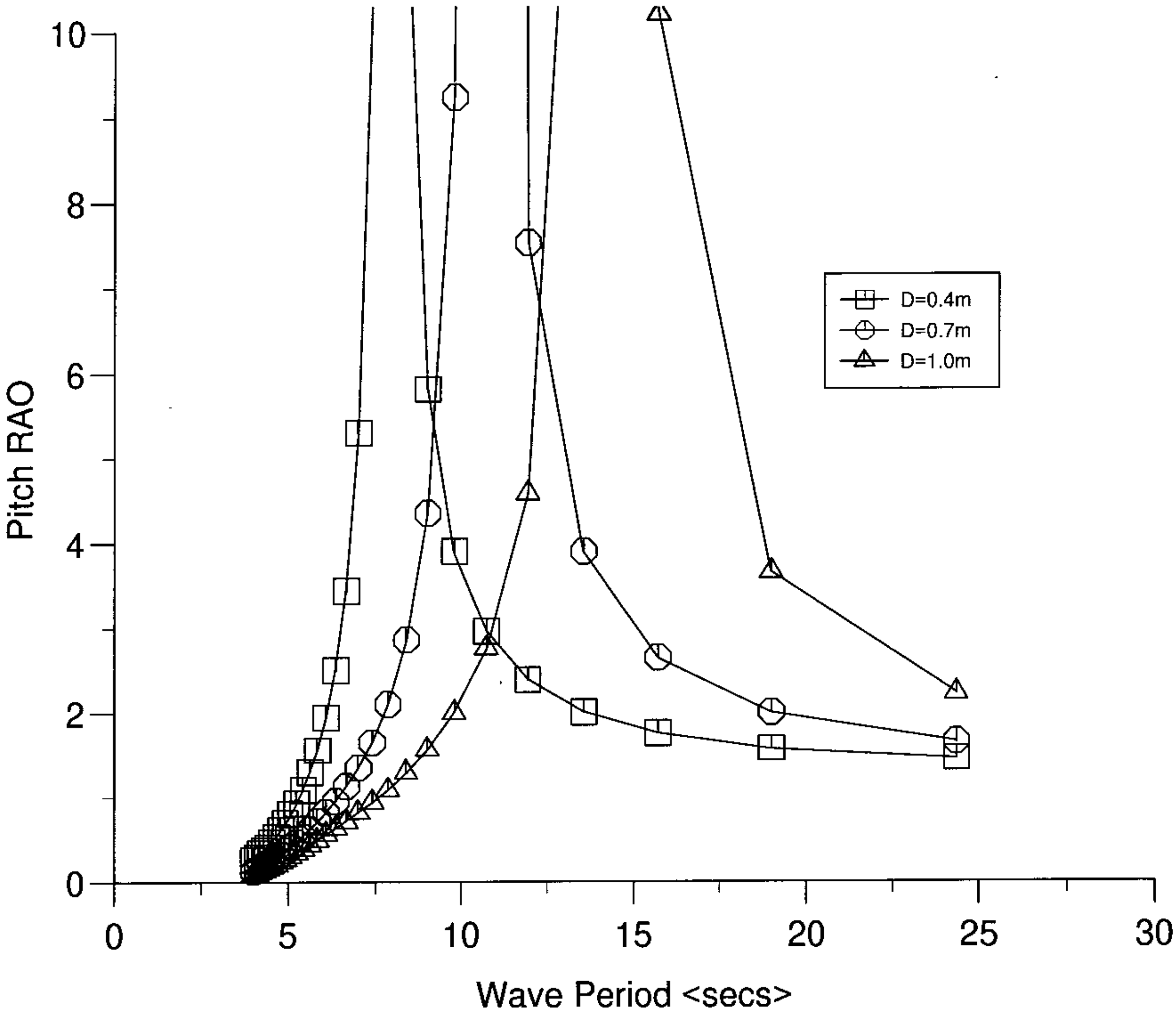

Figure 18: Pitch RAO for L=5.0m, VCG=-S-0.25m, U=12kts, S/L=0.40, varying diameter.

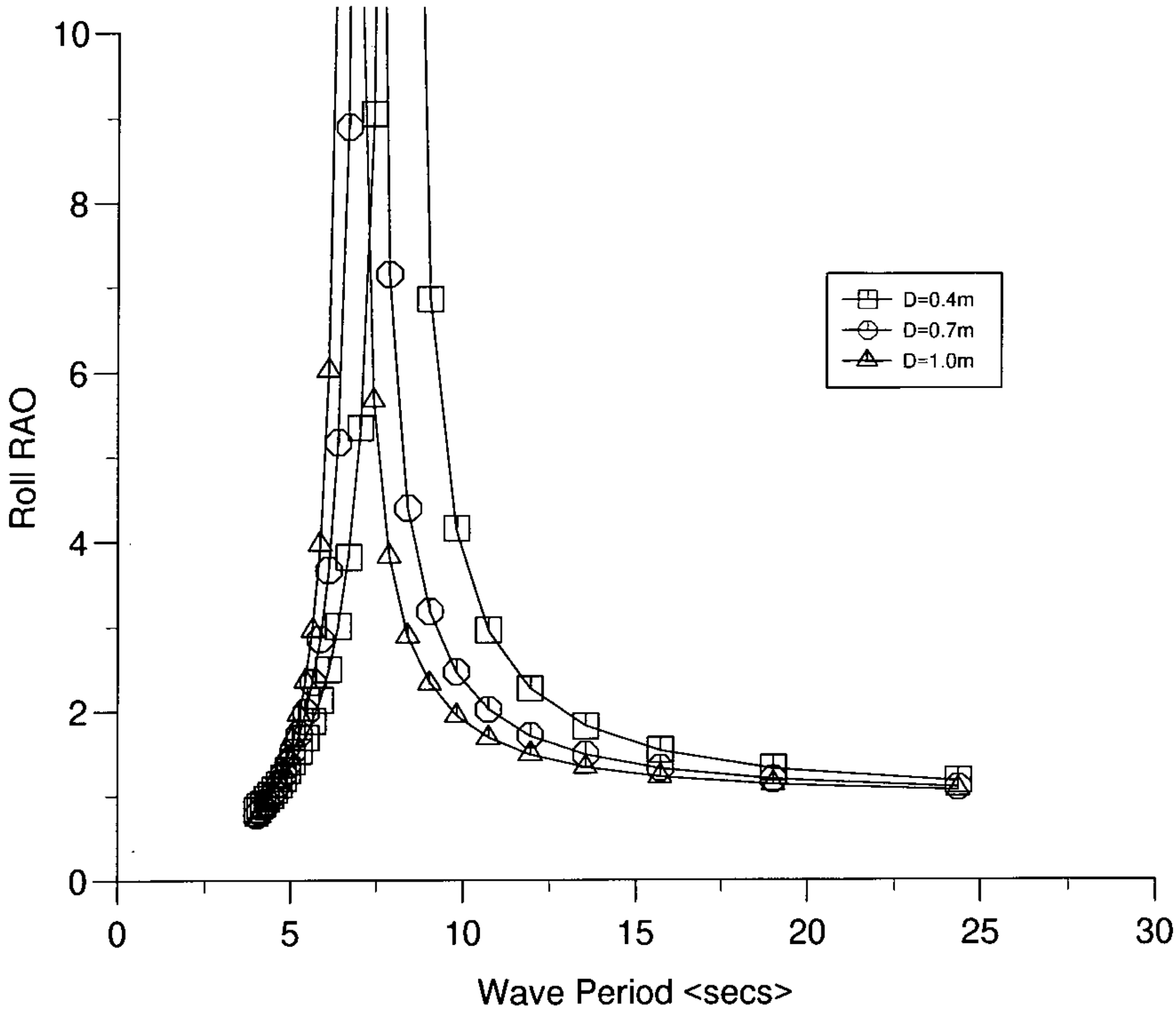

Figure 19: Roll RAO for L=5.0m, VCG=-S-0.25m, U=12kts, S/L=0.40, varying diameter.

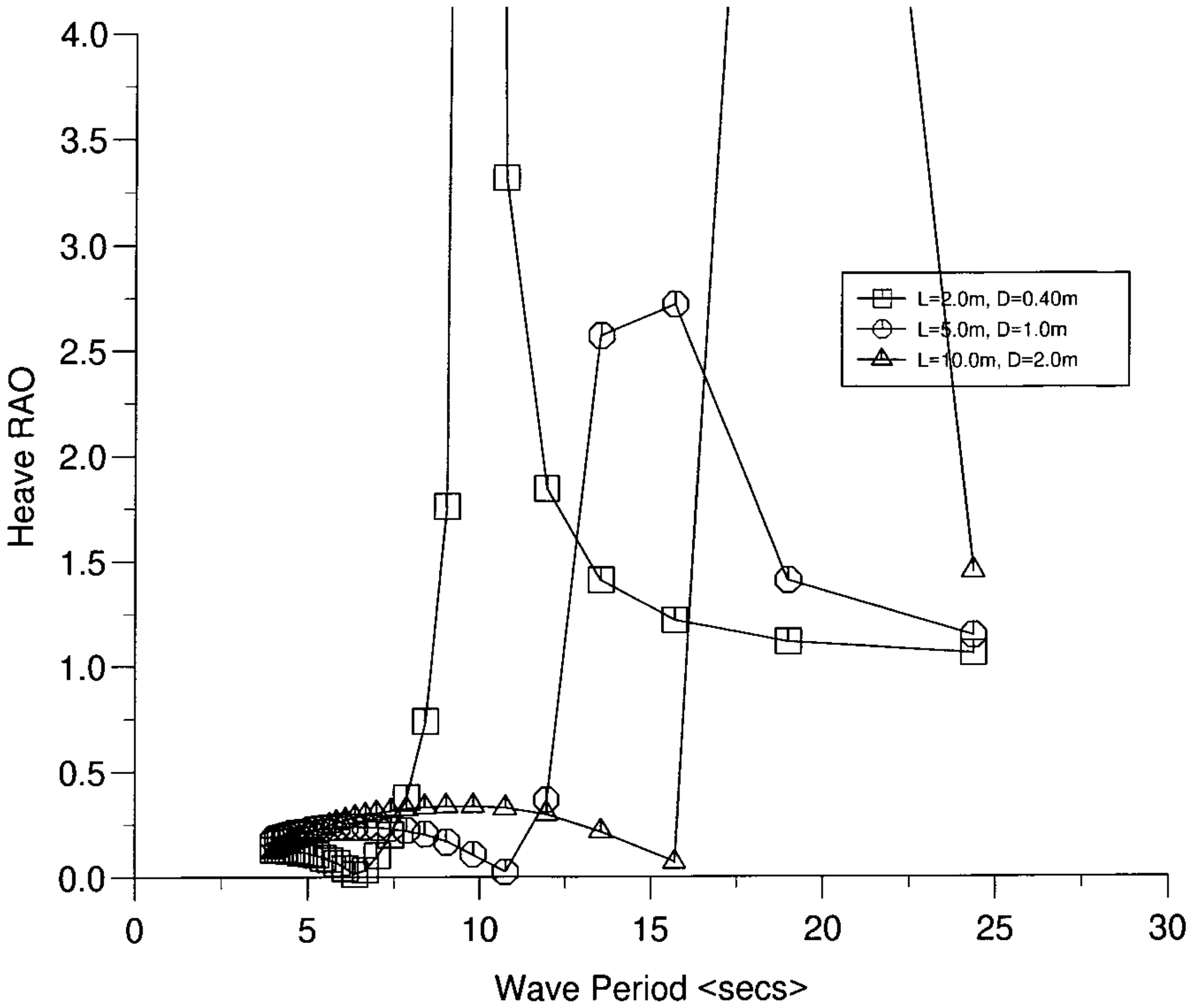

Figure 20: Heave RAO for Varying Length (max. D.), VCG=-S-0.25m, U=12kts, S/L=0.40.

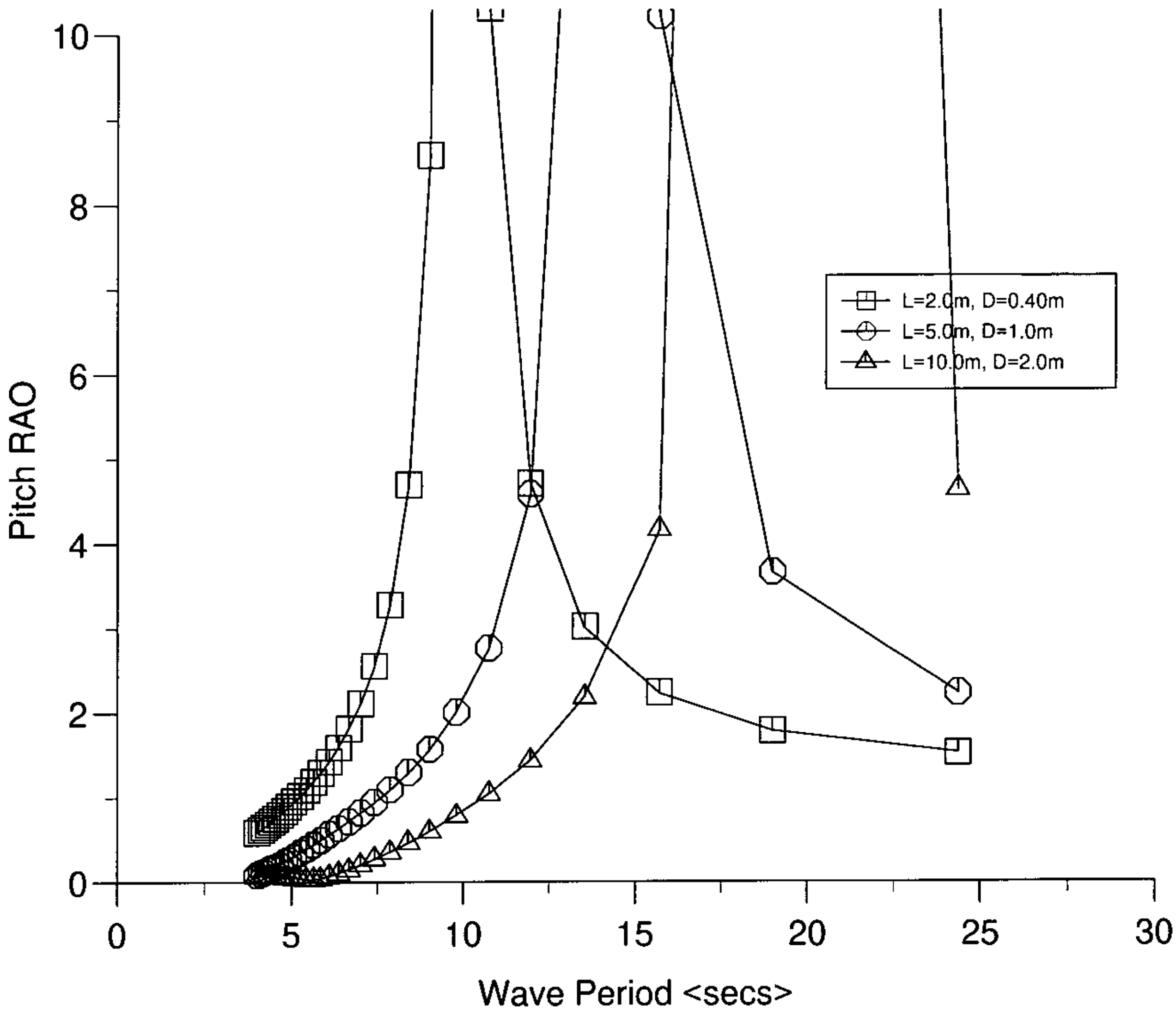

Figure 21: Pitch RAO for Varying Length (max. D.), VCG=-S-0.25m, U=12kts, S/L=0.40.

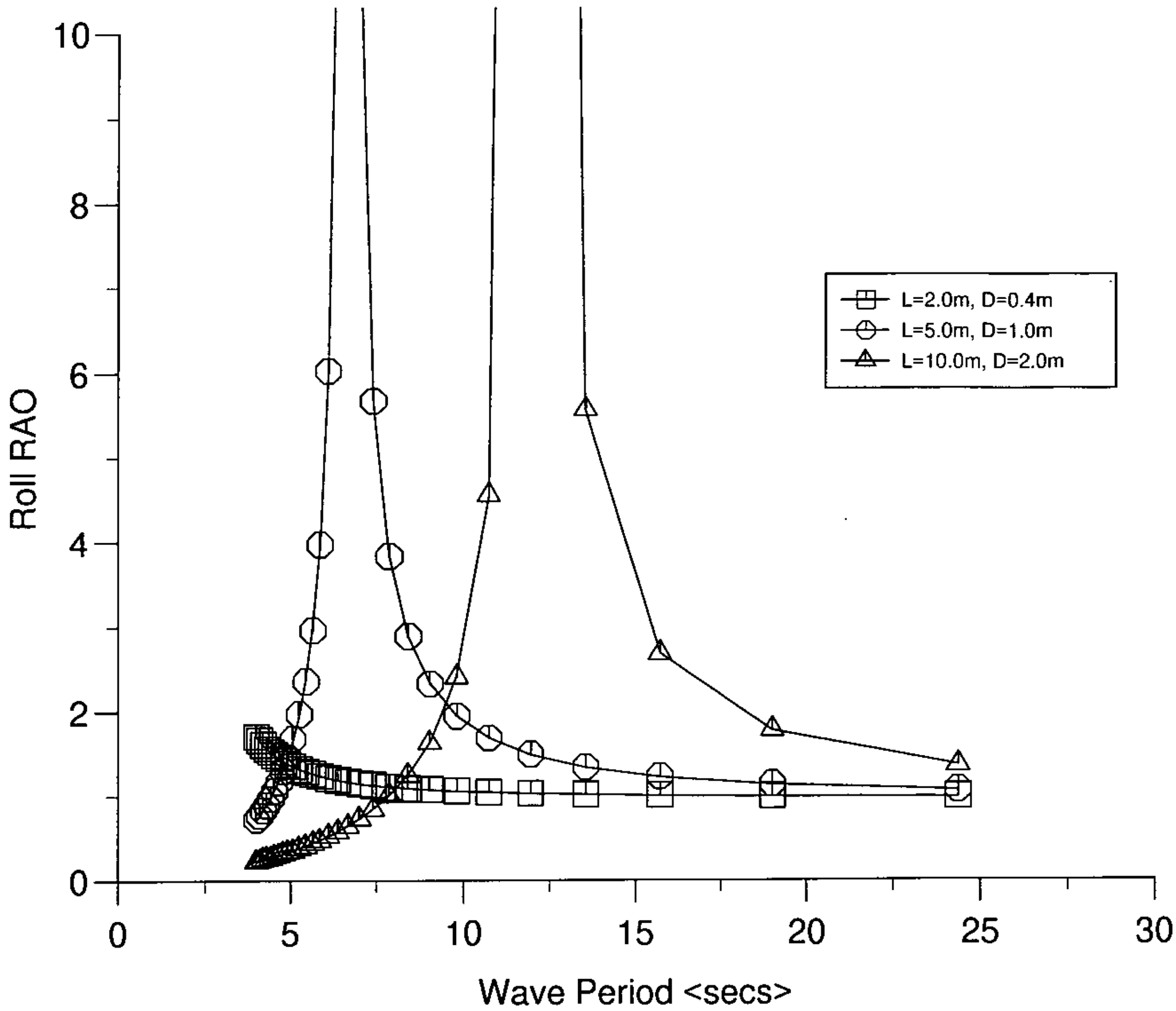

Figure 22: Roll RAO for Varying Length (max. D.), VCG=-S-0.25m, U=12kts, S/L=0.40.