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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/8894981
Technical Report (National Research Council of Canada. Institute for Ocean Technology); no. TR-2005-11, 2005

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DOCUMENTATION PAGE

REPORT NUMBER TR-2005-11	**NRC REPORT NUMBER**	**DATE** November 2005

REPORT SECURITY CLASSIFICATION Unclassified	**DISTRIBUTION** Unlimited

TITLE

MOTION RESPONSE OF A FULL-SCALE LIFE RAFT IN LABORATORY TOW EXPERIMENTS

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PUBLICATION

SPONSORING AGENCY(S)

Institute for Ocean Technology, National Research Council, St. John’s, NL

IOT PROJECT NUMBER 2064	**NRC FILE NUMBER**

KEY WORDS	**PAGES**	**FIGS.**	**TABLES**
Inflatable life rafts, full-scale, waves	iv, 64, App. A-D	64	4

SUMMARY

Inflatable life rafts, introduced in World War II, are commonly used today on oil installations, merchant ships, cruise ships, ferries, military vessels and small vessels as evacuation systems. Large passenger ship, such as ferries, are typically equipped with standby vessels to tow the life rafts to safety, away from hazards such as fires, explosions, collisions and sinking vessels.

While operators find the compact and lightweight features of life rafts attractive, these features also make them less stable in waves and wind. Rafts have very shallow draught and a large part of the base can break clear of the water when a steep wave passes underneath it, thereby decreasing stability. Large overturning moments can be generated on the windward side, which could overturn the raft. Drogues and water pockets are commonly used to counteract the overturning moment and to increase stability (Cole and Wills, 1981)

Several experiments have been conducted to study potential capsizing situations using full-scale and model life rafts.

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L.M. Mak, A. Simões Ré, A. Kuczora

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1.0 Introduction

Inflatable life rafts, introduced in World War II, are commonly used today on oil installations, merchant ships, cruise ships, ferries, military vessels and small vessels as evacuation systems. Large passenger ship, such as ferries, are typically equipped with standby vessels to tow the life rafts to safety, away from hazards such as fires, explosions, collisions and sinking vessels.

While operators find the compact and lightweight features of life rafts attractive, these features also make them less stable in waves and wind. Rafts have very shallow draught and a large part of the base can break clear of the water when a steep wave passes underneath it, thereby decreasing stability. Large overturning moments can be generated on the windward side, which could overturn the raft. Drogues and water pockets are commonly used to counteract the overturning moment and to increase stability (Cole and Wills, 1981)

Several experiments have been conducted to study potential capsizing situations using full-scale and model life rafts.

Bardarson (1983) undertook full-scale sea trials to study the weather endurance of life raft canopies and the stabilizing effect of sea anchors. They showed that the most important factor to increase life raft stability was the sea anchor. The Icelandic type sea anchor, with a small opening at the aft end and a bigger opening at the forward end, was shown to considerably increase life raft stability. They found water and wind penetrated through the closing device of traditional triangular and square shape raft entrance openings. Canopy failings usually originated at the corners of the triangular entrance openings. The use of circular entrance openings was shown to have better performance.

National Maritime Institute studied raft stability using theoretical models; model and full-scale liferafts; wind tunnel and tank tests as well as sea trials. Forman, E.J. (1983) conducted sea trials, which showed that a life raft would not capsize with a satisfactory sea anchor. Ballast pockets contributed to life raft stability but compared with a sea anchor, their stabilizing force was small, especially when the life raft was laden with occupants.

Cole and Wills (1981) compared different aspects of life raft designs on stability, including circular and rectangular hull shape, canopy shape, drogue, water pockets, loading and inflation pressure. They found waves with wavelength 2-5 times the raft dimension to be more destabilizing than longer waves of the same steepness. They also found the following conditions helped to increase raft stability: concave upwind and convex downwind canopy shape, drogue, water pockets, reduced hull and tube pressure, and crew on the upwind side.

Mckenna and Paulin (1997) conducted a series of experiments to document critical situations for capsize. The tests included calm water towed resistance experiments with conventional and series drogues (drogue made of a large number of small cones), calm water towing experiments with a full-scale 16-person and a 1:7 scale 20-person raft model, towing experiments in waves and drift tests with the 1:7 scale raft model.

In drogue tow resistance tests in calm water, they found resistance increased non-linearly with increased tow speed, Froude scaling could be used to scale conventional and series drogues, and series drogues were more stable than conventional drogues during tow.

In life raft tow resistance tests in calm water, they found resistance increased non-linearly with increased tow speed. The resistance increased with drogue deployment and increased raft loading. Raft did not move significantly from side-to-side. At high tow speed, the bow of the raft tended to submerge but this was reduced somewhat with drogue deployment. Longer drogue lead length resulted in more resistance especially at high tow speeds. Larger wind forces were transmitted to the raft when the canopy was oriented perpendicular to the wind than when the canopy was oriented parallel to the wind.

For the drift test, they reported that drogue deployment significantly reduced drift rate. Capsizing in breaking waves occurred only when the drogue was not deployed.

In 1:7 scaled life raft model tow tests in waves, they found the series drogue was most effective in suppressing surge motion but became less effective as the number of occupants increased. Pitch amplitudes of 20 degrees and yaw amplitudes of 40 degrees were reported for both conventional and series drogues. Yaw amplitudes were most significant with drogue deployment. Life raft capsizing only occurred when no drogue was deployed. They found capsizing to be more likely in the presence of wind, large pitch and large surge motions.

Hardiman and Harris (1996) investigated raft stability by using a 1:7 scale model of a 20-person life raft to assess the effects of wind speed, wave height, wave steepness, personnel loading, personnel distribution, wave loading, free surface, drogue deployment, ballast pockets and canopy. They concluded that drogues were essential for the survivability of life rafts and a series drogue was more effective than a single cone drogue. They also concluded from the accelerations measured that occupants could be seriously injured in extreme seas.

Current IMO regulations require life rafts to be towed in calm water only. Data on life raft towing performance in waves and wind is very limited. However, it can be seen from the previous studies that both environmental variables and life raft variables have effects on raft stability. Therefore, it is important to assess the raft towing performance in waves and wind. This can help to assess the effects of different variables on raft towing in realistic ocean environments, in which the life rafts must operate. Such information would be beneficial to marine operators, rescuers, life raft designers and training providers.

As there is little information on full-scale life raft towing in a controlled environment with waves and wind, where the effects of different variables on raft towing can be investigated, the current project addressed some of the existing knowledge gaps.

2.0 Project Objectives and Scope

The overall objectives of the experimental study to tow a 16-person full-scale life raft are to identify how life raft and occupant motion as well as tow force varies with different environmental conditions and raft configurations. Environmental variables included regular waves with different frequencies but constant wave slope (1:15) and irregular waves. Raft variables included ballast type (manikins versus ballast bags), drogue versus no drogue, floor inflated versus floor not inflated, and even versus uneven weight distribution. All the experiments were conducted with a 16-person full-scale life raft. The specific experimental objectives are listed below:

<u>Raft tow tests in calm water</u>

1. Assess the effects of ballast type, drogue deployment, floor inflation and weight distribution on raft tow force and raft tow stability along its tow direction, for various tow speeds.

<u>Raft tow tests in waves</u>

1. Determine and compare raft tow force, surge, heave and pitch response amplitude operators (RAOs) in regular and irregular waves. Assess if irregular waves can be used as a cost effective means to determine raft response with a high degree of confidence.

2. Assess the effect of tow speed on raft motion RAO and tow force.

3. Assess the effect of ballast type, floor inflation, drogue deployment and weight distribution on mean tow force, tow force variation and stability along the tow direction.

4. Assess the effect of drogue deployment, floor inflation and weight distribution on life raft surge, heave and pitch motion.

5. Compare the life raft motion with the occupant motion, and assess the effect of drogue deployment, floor inflation and weight distribution.

6. Assess whether the raft motion will cause motion sickness to its occupants.

7. Assess whether the raft motion will cause injury to its occupants.

The experimental tow tests were conducted using a typical SOLAS approved commercially available 16-person life raft. The tests were conducted in uni-directional regular and irregular waves without wind. Wind effects will be addressed in the model-scale experiments to be reported at a later date. A carriage was used to tow the life raft, which is similar to towing the life raft with a large vessel rather than a small vessel (e.g. a fast rescue craft or a lifeboat).

3.0 Test Program and Test Setup

3.1 Test Facility

The test program was conducted in the Tow Tank at the Institute for Ocean Technology. The Tow Tank is 200 m long, 12 m wide and 7 m deep. A dual-flap wavemaker at one end of the tank is capable of generating regular and irregular uni-directional waves. For regular waves, the maximum wave height is 1 m. For irregular waves, the maximum significant wave height is 0.5 m. The operating frequencies range from 0.1 Hz to 1.8 Hz. A parabolic beach at the opposite end of the tank is used for wave absorption. The tank is equipped with a towing carriage, which has a maximum speed of 10 m/s. Fans and water jets can also be installed to simulate wind and surface currents. The Tow Tank is equipped with a VMS and Windows based distributed client/server data acquisition system.

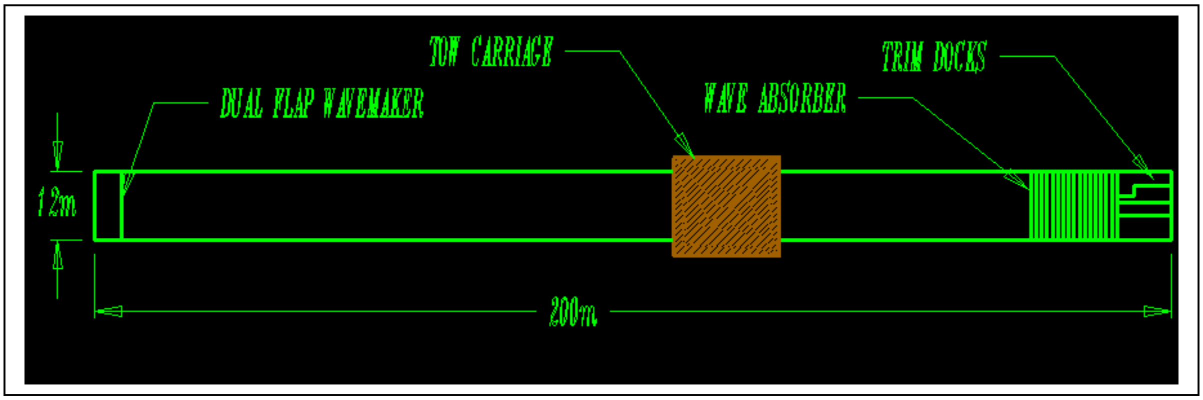


Figure 3.1 Tow Tank

3.2 Life Raft

A typical SOLAS approved commercially available 16-person life raft was purchased and used throughout the test program. The life raft used has two separate inflatable floatation tubes, a lower and an upper floatation tube. The upper floatation tube is connected to the canopy arch inflation chamber. The floatation tubes are made of heavy butyl rubber. The raft has 8 sides, arranged in a symmetric octagon. Each side of the raft is 1.33 m in length. The raft is 3.21 m wide. It has one boarding platform and two entrances. The manufacturer suggested tow point used in the experiment is adjacent to the entrance without the boarding platform. The drogue attachment point is at the opposite side of the raft, adjacent to the boarding platform. The inflated raft empty weighs 52.5 kg.

Figure 3.2 16-person life raft

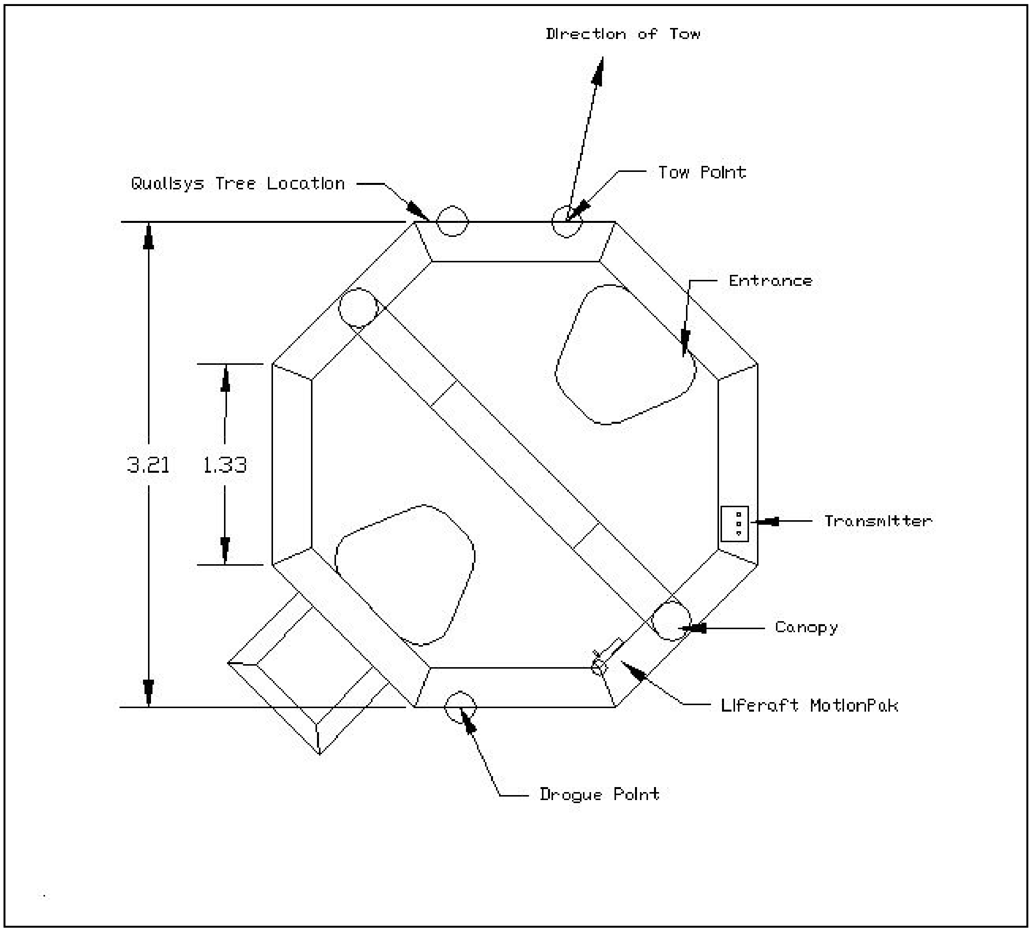


Figure 3.3 16-person life raft dimensions and layout (All dimensions in meters)

3.3 Drogue

The conventional drogue and painter used in the test program came with the life raft. The drogue is constructed of lightweight fabric. Its overall dimensions are shown in the figure below.

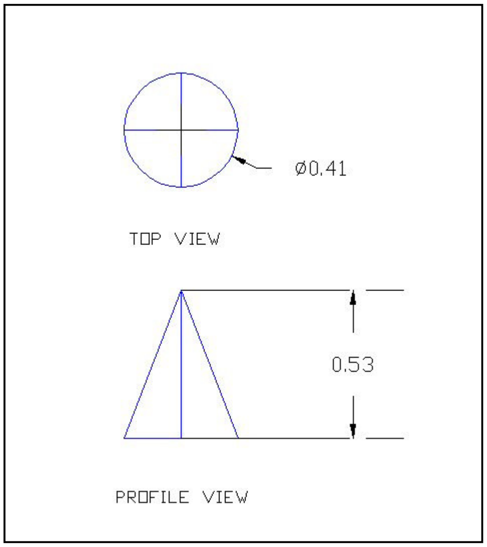
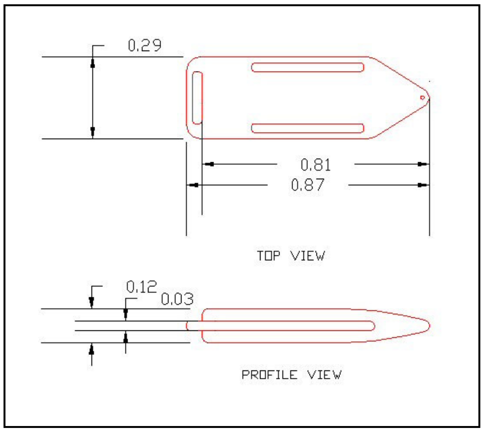


Figure 3.5 Conventional Drogue

Figure 3.4 Conventional drogue (All dimensions in meters)

3.4 Float

At low tow speeds, the drogue tends to sink deep underneath the water surface during tow. As the tow tank has limited water depth, 7m, there is the danger that the drogue would drag along the tank floor. To prevent this from occurring, a float was attached to the drogue line to keep it from submerging to the tank floor. The float and its overall dimensions are shown below.



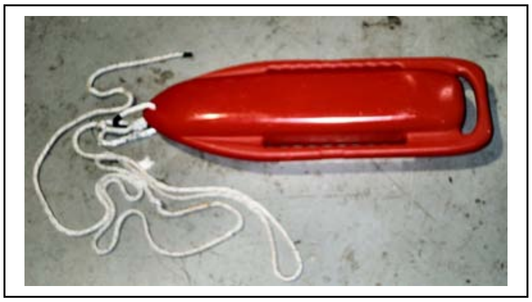


Figure 3.7 Float

Figure 3.6 Float (All dimensions in meters)

3.5 Test Setup

The test setup is shown in Figures 3.8 and 3.9.

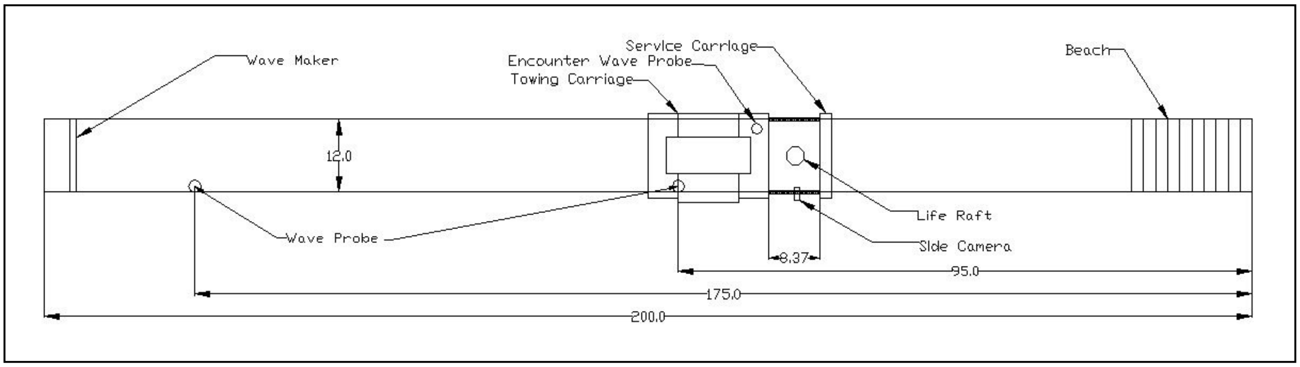


Figure 3.8 Test Setup Drawing (All dimensions in meters)

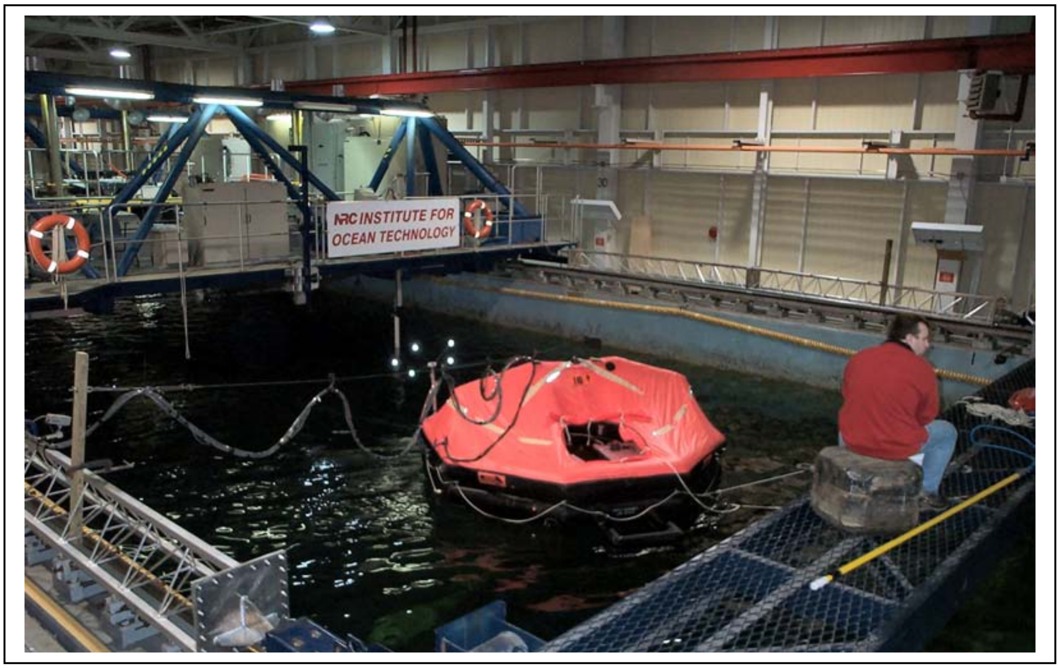


Figure 3.9 Test Setup Picture

For the tests, the towing carriage (left of Figure 3.9) was connected to the service carriage (bottom right of Figure 3.9) via two aluminum truss-like structures (bottom left and middle right of Figure 3.9), which allowed the two carriages to move as a unit.

There were two stationary wave probes at 95 m and 175 m locations respectively. The encounter wave probe was installed on the towing carriage and moved with it during the tow tests.

The life raft was set up in between the towing carriage and the service carriage. During the experiments, the towing carriage towed the life raft into the waves, from the beach end of the tank to the wave maker end of the tank. A 21-meter long towline extending from the tow carriage was used for towing. After each experiment, the towing carriage moved back to the start position for the next run. A tagline on the service carriage was used to tow the life raft back. The average wait time in between runs was 10 minutes. The tagline was slacked off during the experiment, so it did not influence the life raft motion. The electrical cables were overhung using an umbilical cord, so they did not influence the life raft motion. A side camera was installed on the aluminum frame in between the carriages to record the raft motions.

4.0 Instrumentation

4.1 Data Acquisition

Two data acquisition systems were used in this test program – one system was used to acquire signals from the raft and another system was used to acquire signals on the tow carriage. In the raft, the signals were collected by a PIC (Programmable Integrated Circuit) acquisition system, which in turn was connected to a radio transmitter. The acquired signals were transmitted to the carriage wirelessly. On the carriage, all the signals from both acquisition systems were acquired by GDAC (GEDAP Data Acquisition and Control) client-server acquisition system.

The following table shows the signals collected on the raft.

Signal	Instrumentation	Sample Rate
Manikin surge, sway and heave accelerations (-3 g to 3 g). Yaw, pitch and roll rates (-75 deg/s to 75 deg/s)	MotionPak II 6 degree-of-freedom motion sensor	50 Hz
Raft surge, sway and heave accelerations (-3 g to 3 g). Yaw, pitch and roll rates (-75 deg/s to 75 deg/s)	MotionPak II 6 degree-of-freedom motion sensor	50 Hz

The following table shows the signals collected on the carriage.

Signal	Instrumentation	Sample Rate
Carriage position		50 Hz
Carriage speed		50 Hz
Encounter wave probe		50 Hz
Upstream wave probe		50 Hz
Midstream wave probe		50 Hz
Tow force	Load cell	50 Hz
Tow force in x, y and z directions	3 component load cells	50 Hz
Tow angle	Yo-yo pot	50 Hz
Drogue Force	Load cell	50 Hz
Raft surge, sway and heave displacements. Yaw, pitch and roll angles.	Qualisys optical tracking system	50 Hz
Raft lower floatation tube pressure	Pressure sensor	50 Hz
Raft upper floatation tube pressure	Pressure sensor	50 Hz
Raft canopy pressure	Pressure sensor	50 Hz

4.2 Co-ordinate Systems

For analysis, the Qualisys optical tracking system, the life raft MotionPak and the manikin MotionPak use a right-hand co-ordinate system. The positive x-axis is defined as parallel to the tow direction, down the tank, towards the wave maker. The y-axis is defined as positive, 90 degrees counter-clockwise from the positive x-axis. The z-axis is defined as positive pointing up.

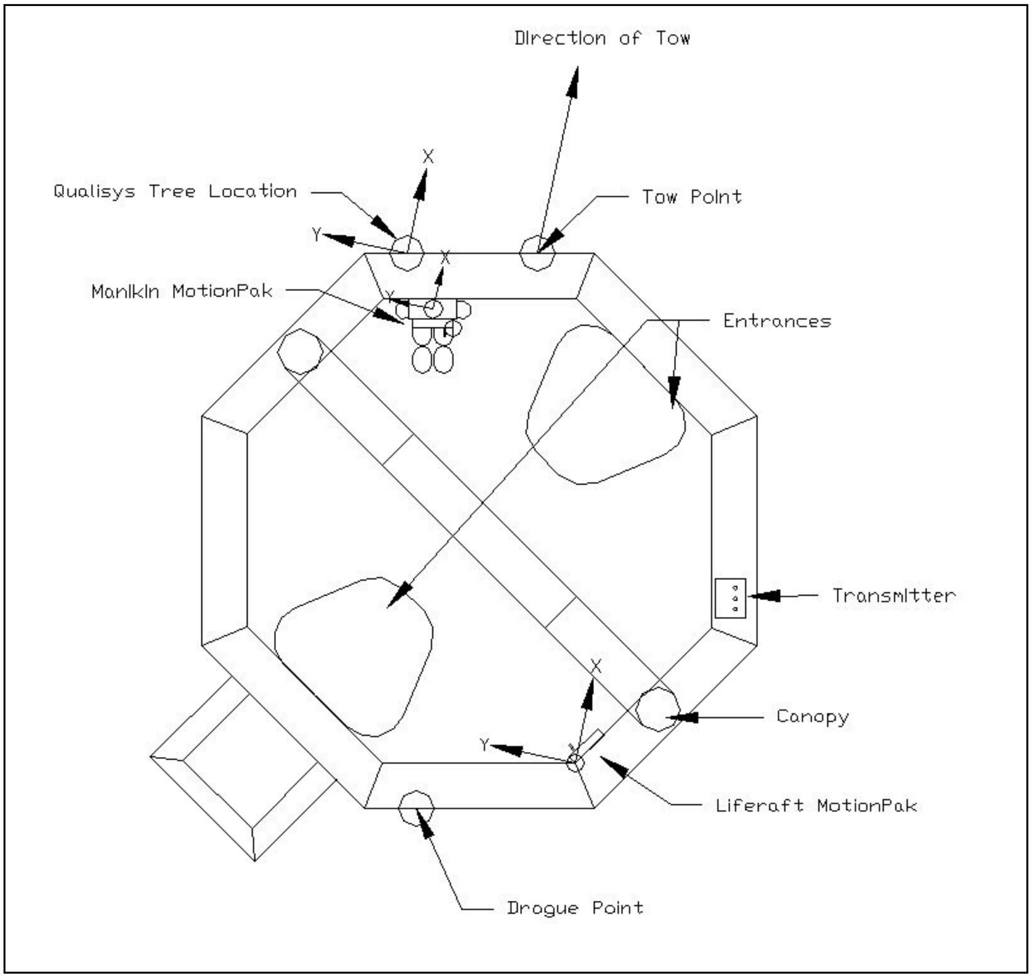


Figure 4.1 Co-ordinate Systems

5.0 Test Program

The test program was divided into the following phases –

1. Tow tests in calm water to determine the resistance of the life raft with and without the drogue and the float.

2. Tow tests in regular and irregular waves to determine the added resistance in waves.

   For regular waves, the wave frequencies varied from 0.36 Hz to 0.88 Hz. The ratio of wave height to wavelength was maintained at 1:15 for all frequencies.

   For irregular wave, a Jonswap spectrum with the following parameters was used.
   Significant wave height = 0.5 m
   Spectrum peak frequency = 0.392 Hz
   Phillip Alpha constant = 0.081
   Gamma = 1.0
   Repeat period = 120 seconds

   The irregular wave was chosen to correspond with human subject tests, which were used to assess human performance in carrying out various raft management tasks inside the life raft. The wave is roughly equivalent to sea state 1 with no wind. The following figure shows the irregular wave spectrum. Most of the wave energy, 90%, is concentrated between 0.3 and 0.7 Hz. Between 0.3 and 0.5 Hz, 75% of the wave energy is concentrated around the peak of the spectrum.

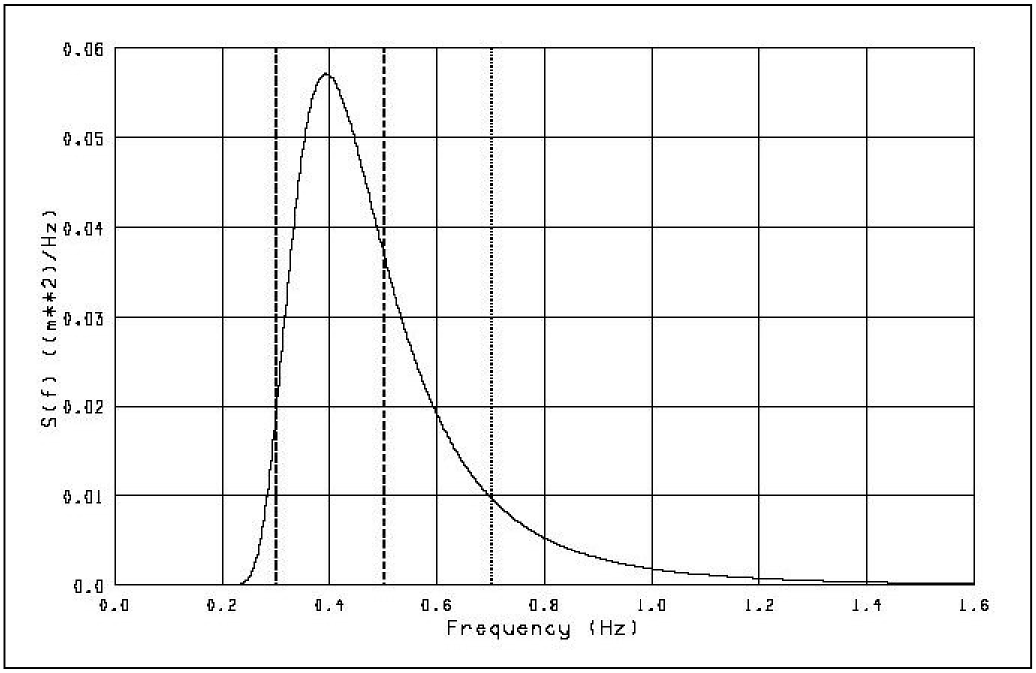


Figure 5.1 Irregular wave spectrum

Originally, the intent was to conduct an extensive series of tests on all combinations of test variables – tow speed, weight distribution, floor inflation, drogue deployment and ballast type. Due to very limited tank time (four 12-hour days), the test matrix was reduced strategically.

The test matrix in calm water, regular and irregular waves are shown below. In each phase, the life raft was towed at varies speeds, ranging from 1 knot to 3 knots (or 0.52 m/s to 1.55 m/s). The effects of tow speed, weight distribution, floor inflation, drogue deployment and ballast type on life raft motion, manikin motion and tow force were assessed.

				Calm Water		Regular Waves		Irregular Waves	
Case	Weight Distribution	Floor Inflation	Drogue	Ballast Type					
				Manikins	Bags	Manikins	Bags	Manikins	Bags
A	Even	Inflated	Drogue	Y	Y	Y		Y	Y
B	Even	Inflated	No drogue		Y		Y		Y
C	Even	Not inflated	No drogue		Y		Y		Y
D	Uneven	Inflated	No drogue		Y		Y		Y
E	Uneven	Not inflated	Drogue	Y	Y	Y	Y	Y	Y
F	Uneven	Not inflated	No drogue	Y	Y		Y	Y	Y

Table 5.1 Tow test matrix in calm water, regular and irregular waves

In all test conditions, a manikin with a MotionPak was placed in the front of the raft, near the tow point. The raft MotionPak was placed at the aft of the raft (see Figure 4.1).

For even weight distribution with ballast bags, five 200-litre water ballast bags were used. The layout of the ballast bags is shown in Figures 5.2 and 5.3. Four ballast bags were placed at the circumference of the raft and one ballast bag was placed at the center of the raft. The four ballast bags at the circumference were fully filled with water, while the one in the center was half filled. The total ballast weight was about 900 kg, evenly distributed in the raft. The ballast weight corresponded to twelve 75 kg persons sitting in the raft (75% of full complement).

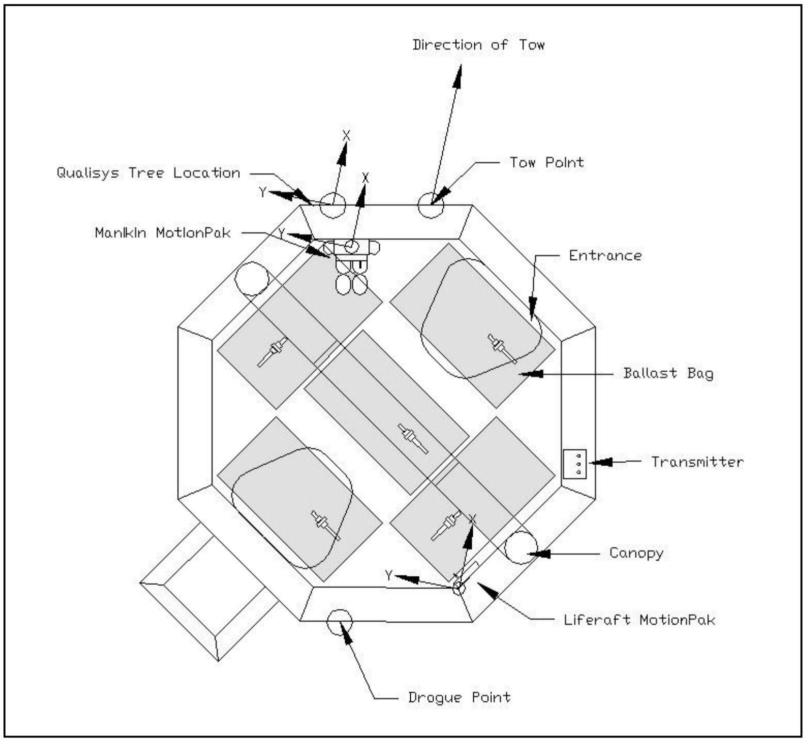


Figure 5.2 Layout of water ballast bags (even weight distribution)

Figure 5.3 Life raft with water ballast bags (even weight distribution)

For even weight distribution with manikins, twelve manikins were used as shown in Figures 5.4 and 5.5. Eleven manikins were filled with water for ballast and one manikin was equipped with MotionPak. Each ballast manikin weighed about 75 kg. The twelve manikins were evenly distributed around the circumference of the raft. The ballast condition was approximately equivalent to the condition for even weight distribution with ballast bags.

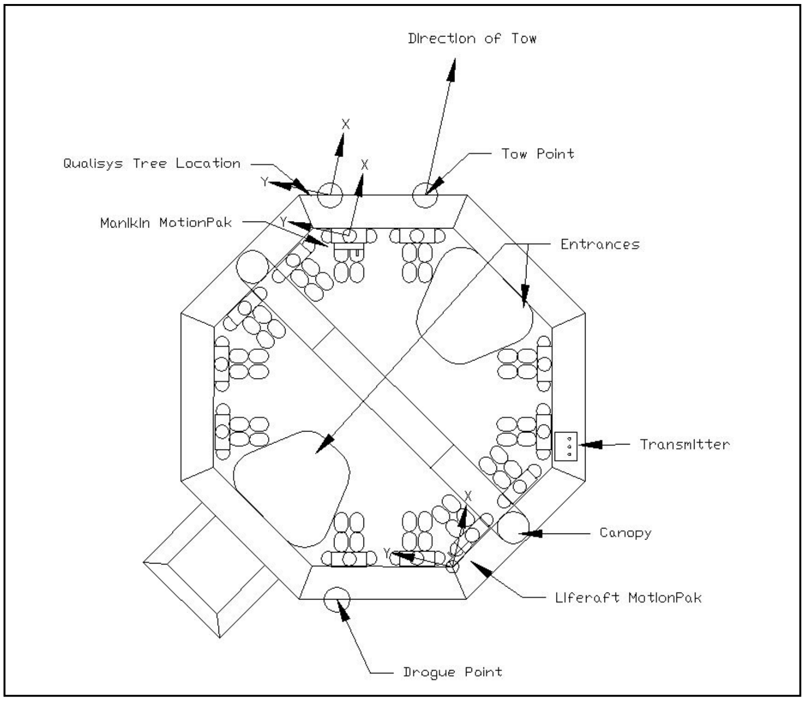


Figure 5.4 Layout of manikins (even weight distribution)

Figure 5.5 Life raft with manikins (even weight distribution)

For uneven weight distribution with water ballast bags, five 200-litre water ballast bags were used. The layout of the ballast bags is shown in Figure 5.6. Three ballast bags were placed at the circumference of the raft as before. An additional ballast bag was placed at the aft of the raft. These ballast bags were fully filled with water, so there was more weight at the aft of the raft than at the front. The center ballast bag was half filled and was folded, so there was more weight on the port side of the raft than the starboard side. The total ballast weight was about 900 kg. The ballast weight corresponded to twelve 75 kg persons sitting in the raft.

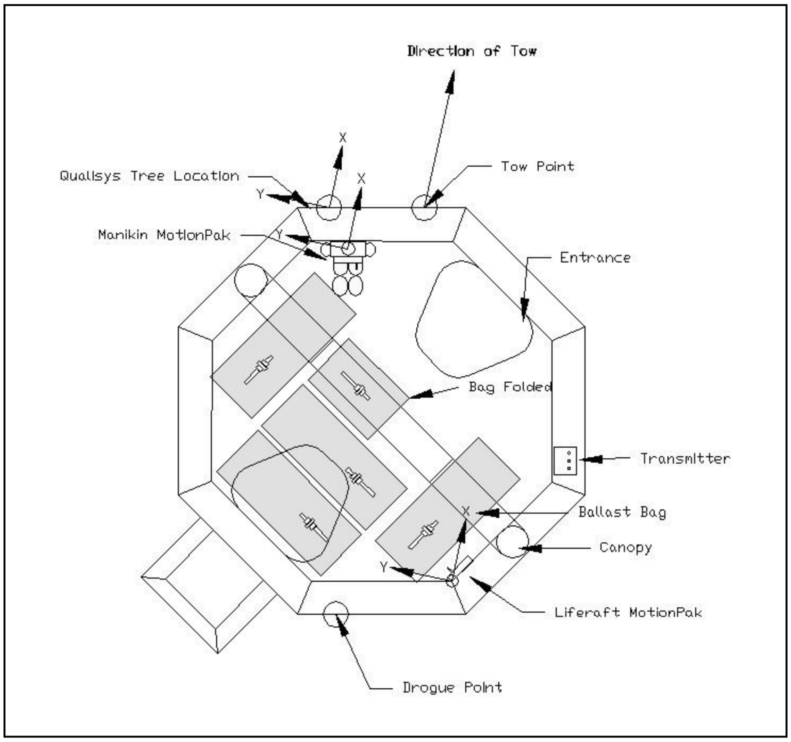


Figure 5.6 Layout of water ballast bags (uneven weight distribution)

For uneven weight distribution with manikins, twelve manikins were used. The positions of the manikins are shown in Figure 5.7. Eleven manikins were filled with water for ballast and one manikin was equipped with MotionPak. The manikins were positioned such that there was more weight at the aft of the raft and at the port side. The ballast condition was approximately equivalent to the condition for uneven weight distribution with ballast bags.

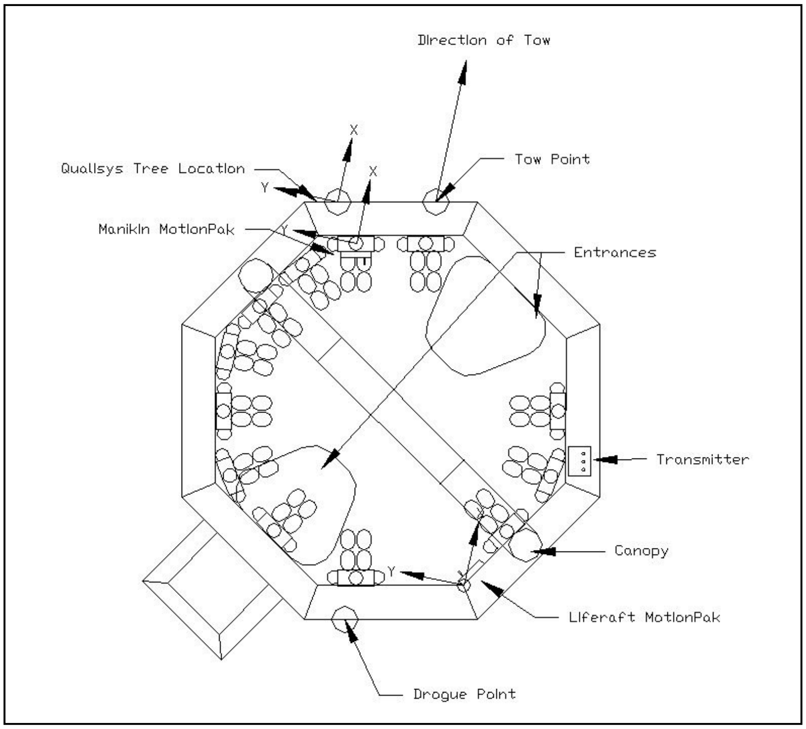


Figure 5.7 Layout of manikins (uneven weight distribution)

6.0 Results and Discussions

All speed results presented in this section are in imperial knots.

6.1 Calm Water

6.1.1 Effect of manikin ballast and water bag ballast on tow force for different test conditions

Figures 6.1 and 6.2 show the comparison between manikin ballast and water bag ballast on tow force in the following cases respectively.

Case E (Uneven weight distribution, Floor not inflated, Drogue)
Case F (Uneven weight distribution, Floor not inflated, No Drogue)

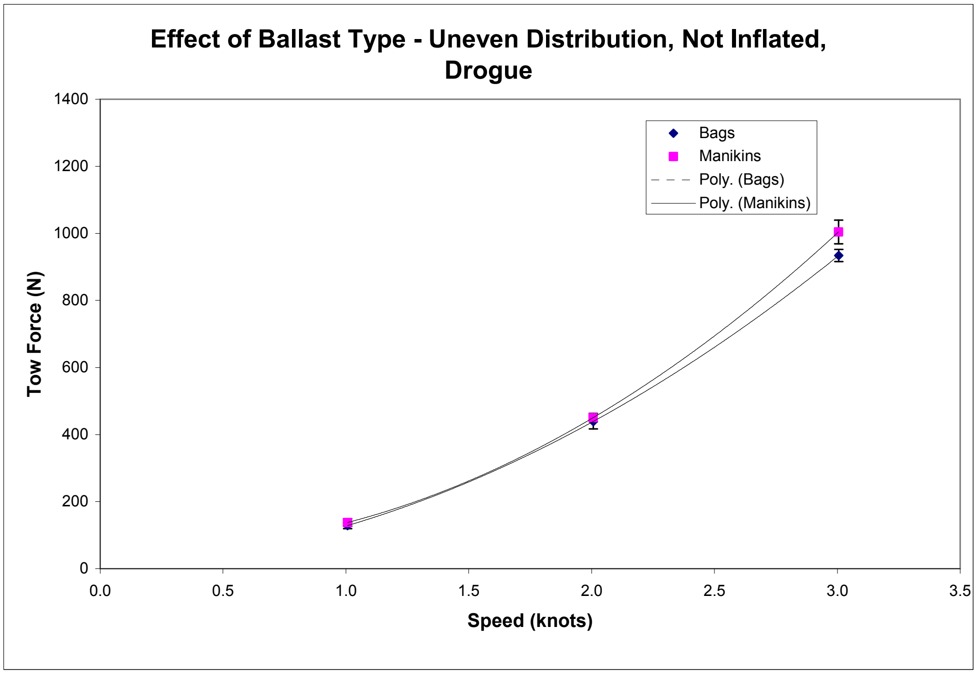


Figure 6.1 Effect of ballast type – Case E (Uneven weight distribution, floor not inflated, drogue)

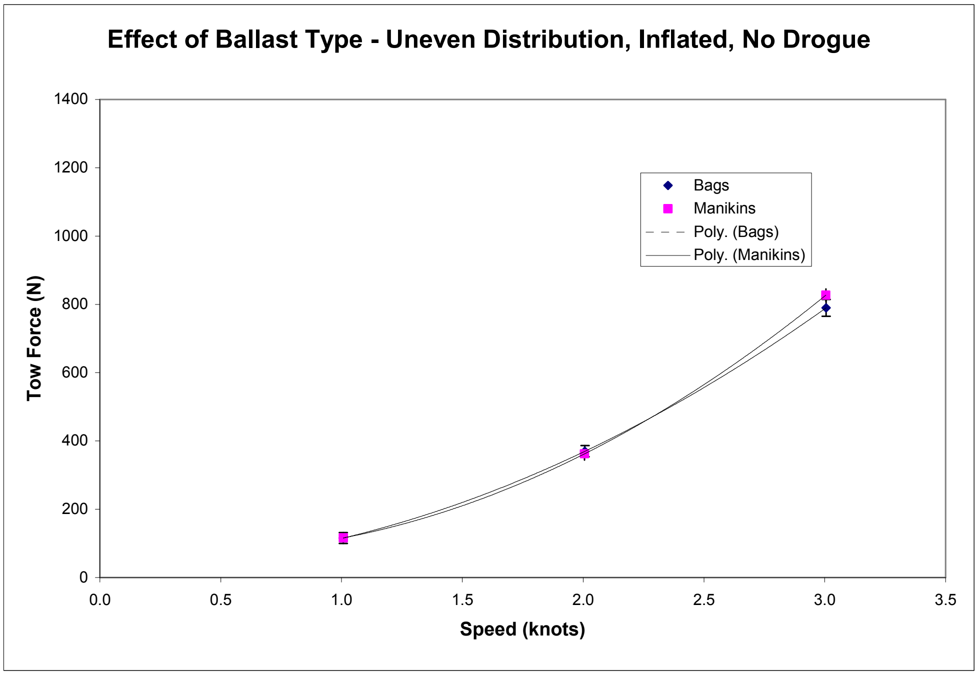


Figure 6.2 Effect of ballast type – Case F (Uneven weight distribution, floor inflated, no drogue)

Below 2 knots, there was little difference in tow force between manikin ballast and water bag ballast.

Above 2 knots, in both Case E and Case F, manikin ballast resulted in higher tow force than water bag ballast. The difference in tow force with manikin ballast and water bag ballast increased with tow speed. The effect was more pronounced for Case E, with drogue. At 3 knots, the tow forces with manikin ballast were approximately 70 N and 37 N higher than that with water bag ballast, in Case E and Case F respectively.

6.1.2 Effect of conventional drogue on tow force

Figure 6.3 shows the direct drogue force measured from the load cell in Case E. Figure 6.4 shows the effect of conventional drogue on tow force, comparing Case E with Case F.

Case E (Uneven weight distribution, Floor not inflated, Drogue)
Case F (Uneven weight distribution, Floor not inflated, No Drogue)

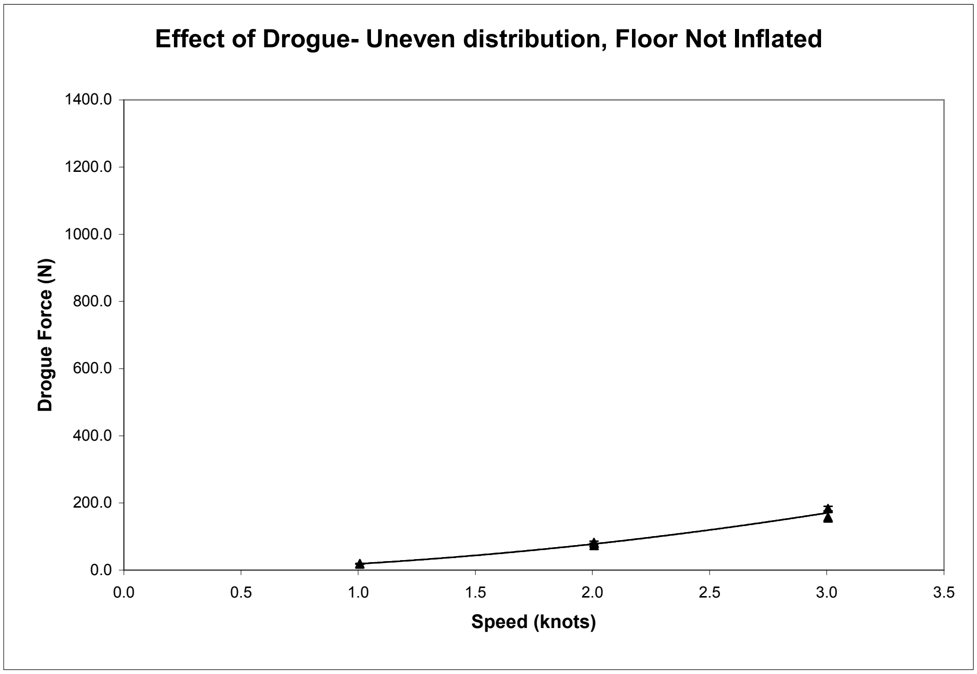


Figure 6.3 Effect of drogue – Case E (Uneven weight distribution, Floor not inflated)

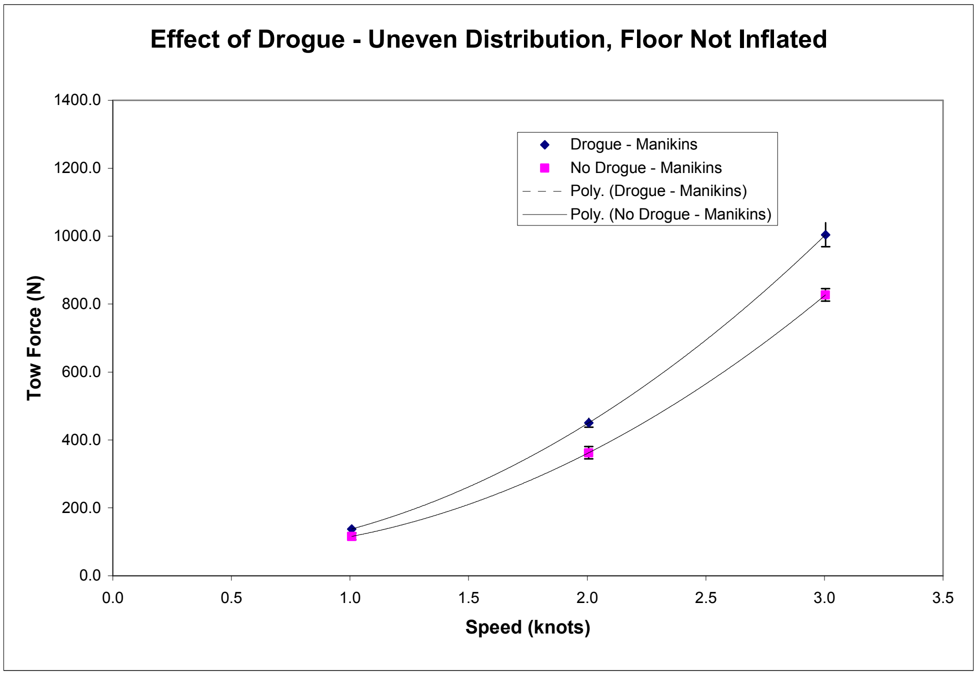


Figure 6.4 Effect of drogue – Case E versus Case F (Uneven weight distribution, Floor not inflated)

In Figure 6.4, it was observed that drogue deployment resulted in higher tow force. The difference in tow force with and without drogue increased with tow speed. This was expected as drogue deployment increased drag. At 3 knots, the tow force with drogue deployment was approximately 175 N higher than that without drogue. This agreed well with the force measured from the drogue load cell in Figure 6.3.

6.1.3 Effect of floor inflation on tow force

Figures 6.5 and 6.6 show the effect of floor inflation on tow force for the following case comparisons respectively.

Case B (Even weight distribution; Floor inflated; No drogue) versus
Case C (Even weight distribution; Floor not inflated; No drogue)

And

Case D (Uneven weight distribution; Floor inflated; No drogue) versus
Case F (Uneven weight distribution; Floor not inflated; No drogue)

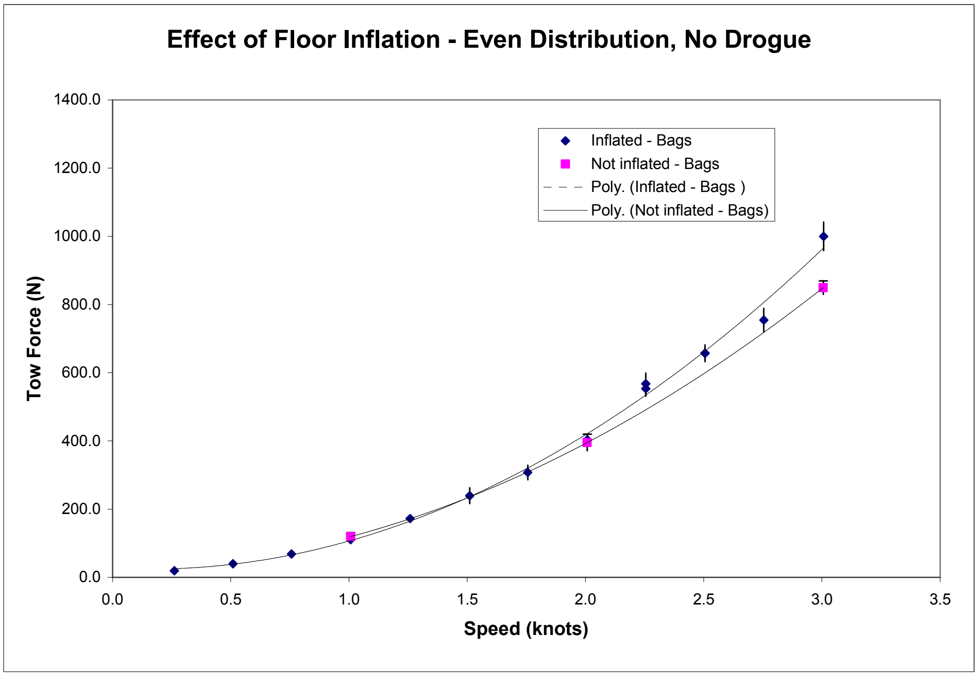


Figure 6.5 Effect of Floor Inflation – Case B versus Case C (Even weight distribution, No Drogue)

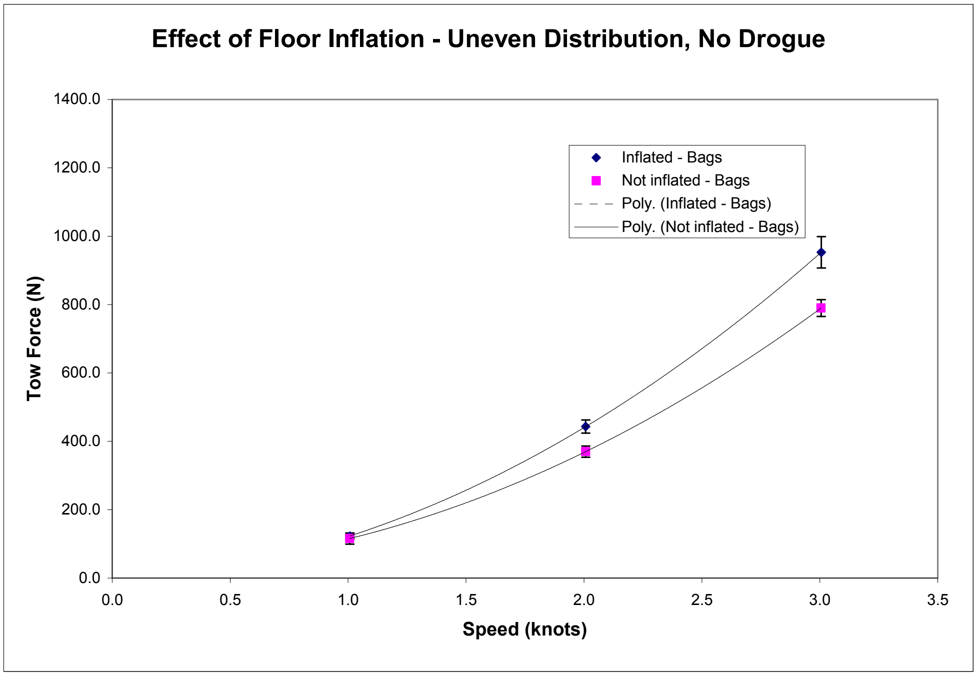


Figure 6.6 Effect of Floor Inflation – Case D versus Case F (Uneven weight distribution, No Drogue)

In both comparisons, tow load was higher with floor inflated than with floor not inflated. At 3 knots, with even weight distribution, the tow force with floor inflated was 150 N higher. With uneven weight distribution, the tow force with floor inflated was 163 N higher. The difference in tow force with floor inflated and floor not inflated increased with tow speed. The raft was more rigid with floor inflated. When being towed, a rigid raft may have less compliance. Therefore, increased tow force is observed.

6.1.4 Effect of weight distribution on tow force

Figures 6.7 and 6.8 show the effect of weight distribution on tow force for the following case comparisons respectively.

Case B (Even weight distribution; Floor inflated; No drogue) versus
Case D (Uneven weight distribution; Floor inflated; No drogue)

And

Case C (Even weight distribution; Floor not inflated; No drogue) versus
Case F (Uneven weight distribution; Floor not inflated; No drogue)

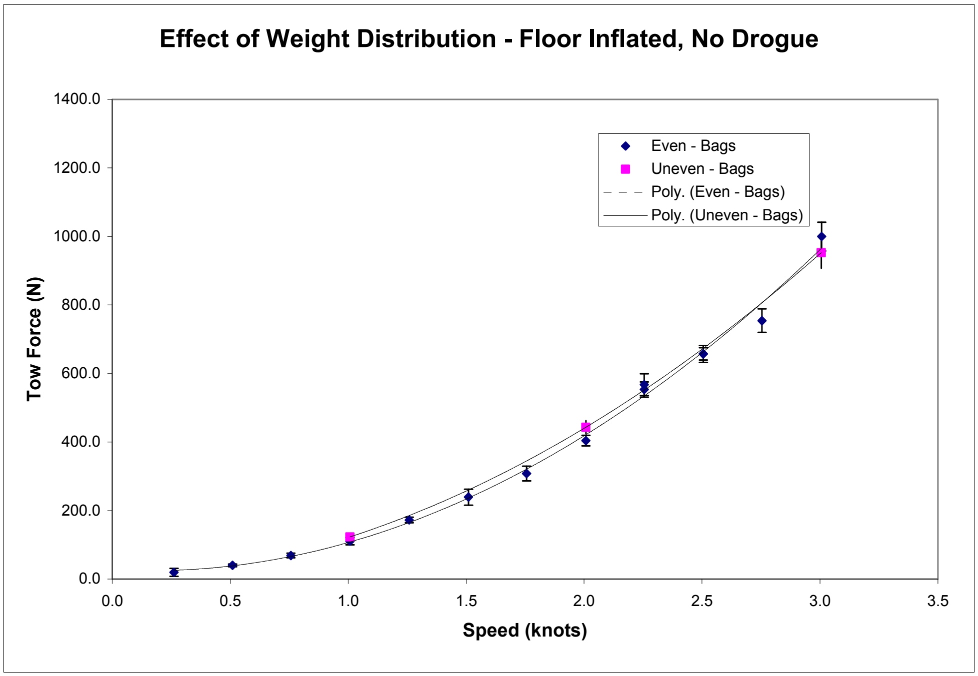


Figure 6.7 Effect of weight distribution - Case B versus Case D (Floor inflated, No drogue)

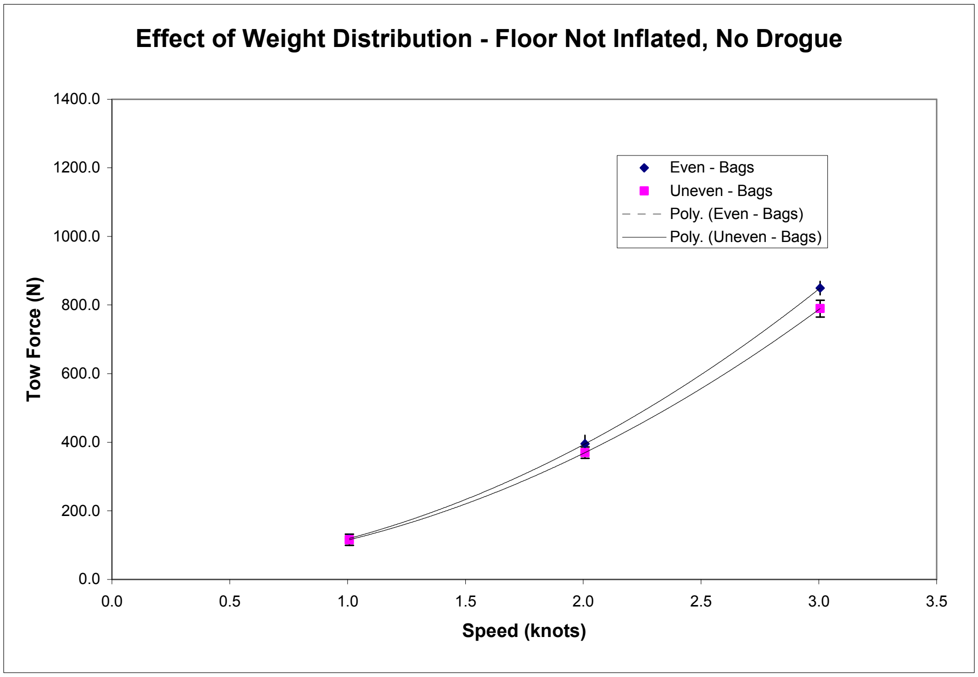


Figure 6.8 Effect of weight distribution – Case C versus Case F (Floor not inflated, No drogue)

In Figure 6.7, at 3 knots with floor inflated, the tow force with even weight distribution is about 60 N higher than with uneven distribution. In Figure 6.8, with floor not inflated, the tow force with even weight distribution is about 50 N more than with uneven distribution

However, in Figure 6.7, with floor inflated, the trend line shows no apparent difference in tow force between even and uneven weight distribution, over the measured speed range. In Figure 6.8, with floor not inflated, the trend line shows consistently higher tow force with even weight distribution, over the measured speed range. The trend line results tend to indicate that the effect of weight distribution on tow force is influenced by floor inflation.

The combined effects of weight distribution and floor inflation on tow force are clearly indicated in Figure 6.9, in which the following cases are plotted.

Case B – Even weight distribution; Floor inflated; No drogue
Case C – Even weight distribution; Floor not inflated; No drogue
Case F – Uneven weight distribution; Floor not inflated; No drogue

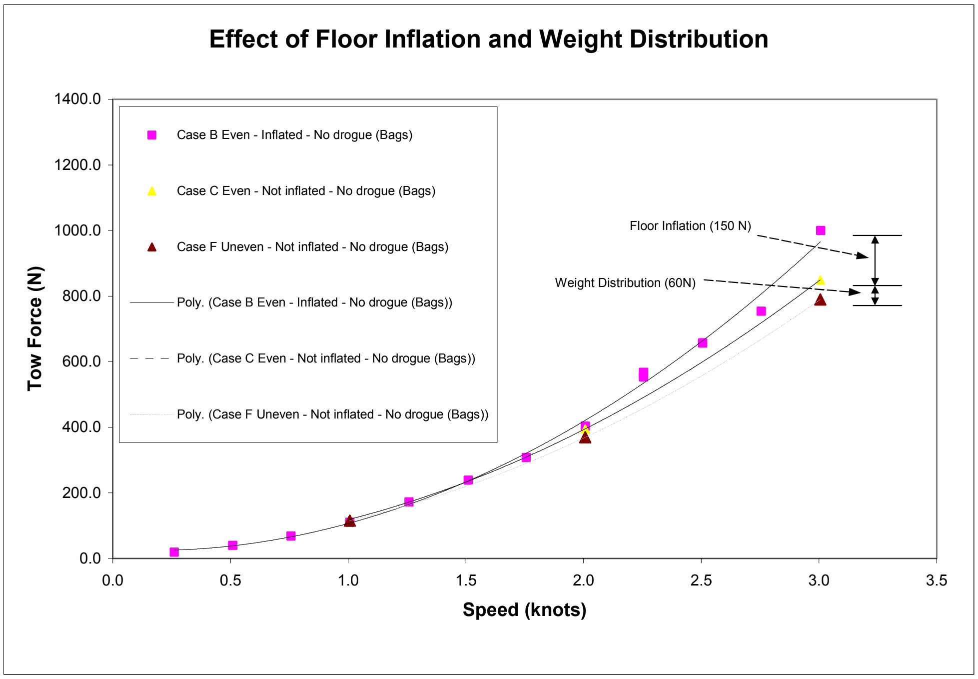


Figure 6.9 Effect of floor inflation and weight distribution

Case F had the lowest tow force. At 3 knots, the tow force for Case C was 60 N higher than the tow force for Case F, due to the effects of weight distribution. The tow force for Case B was about 210 N more than that for Case F, due to the combined effects of floor inflation and weight distribution. From the tow force measured, it appeared that floor inflation contributed more significantly to higher tow force than weight distribution.

With uneven distribution, there was more weight at the back of the raft and on the port side. This tended to lift the front of the raft slightly up, decreasing the plowing effect while being towed. Also, with floor not inflated, the raft was more compliant when being towed. These were possible reasons why tow force was lowest in Case F (uneven weight distribution and no floor inflation), and highest in Case B (even weight distribution and floor inflation).

6.1.5 Combined effects on tow force

With the above knowledge of individual effects from ballast type, drogue deployment, floor inflation and weight distribution on tow force, it is expected that manikin ballast, drogue deployment, inflated floor and even weight distribution will increase tow force.

Therefore, Case A (Even weight distribution, Floor inflated, Drogue) with manikin ballast was expected to have the highest tow force, while Case F (Uneven weight distribution, floor not inflated, no drogue) with bag ballast will have the lowest tow force. This is observed in Figure 6.10. The tow force of all other test conditions fall in between these two cases (Case A and Case F).

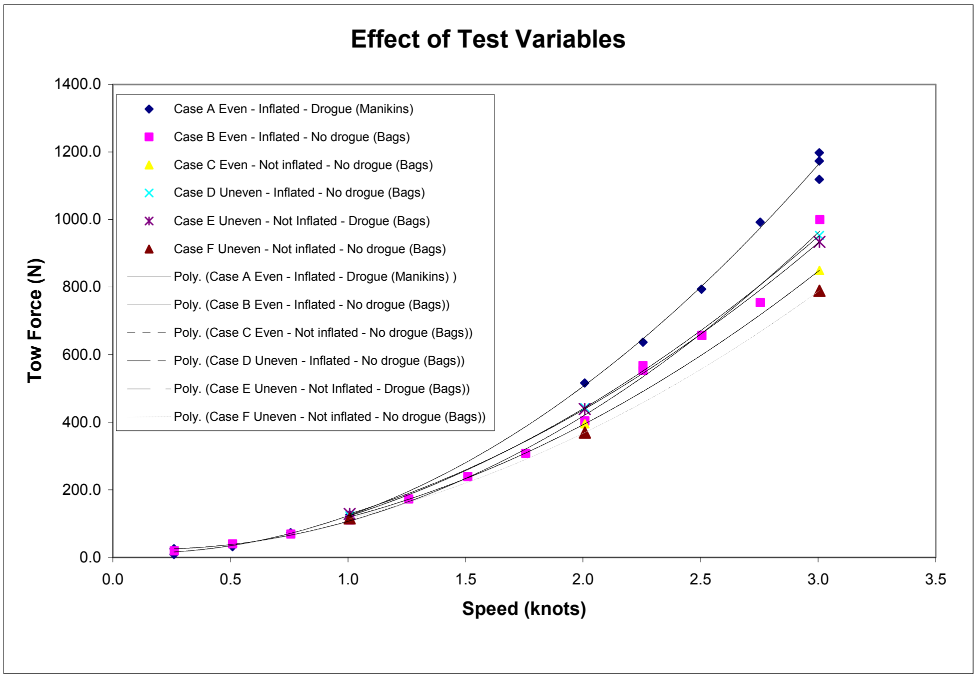


Figure 6.10 Combined effects on tow force at various speeds

Figure 6.11 shows the raft resistance and the drogue resistance at 3 knots tow speed. It demonstrates the same results discussed above in another manner. Even weight distribution contributed to a slight increase in tow force compared to uneven weight distribution. Floor inflation and drogue deployment contributed significantly to an increase in tow force. The results for 1 knot and 2 knots show the same trend. For details, refer to Appendix A.

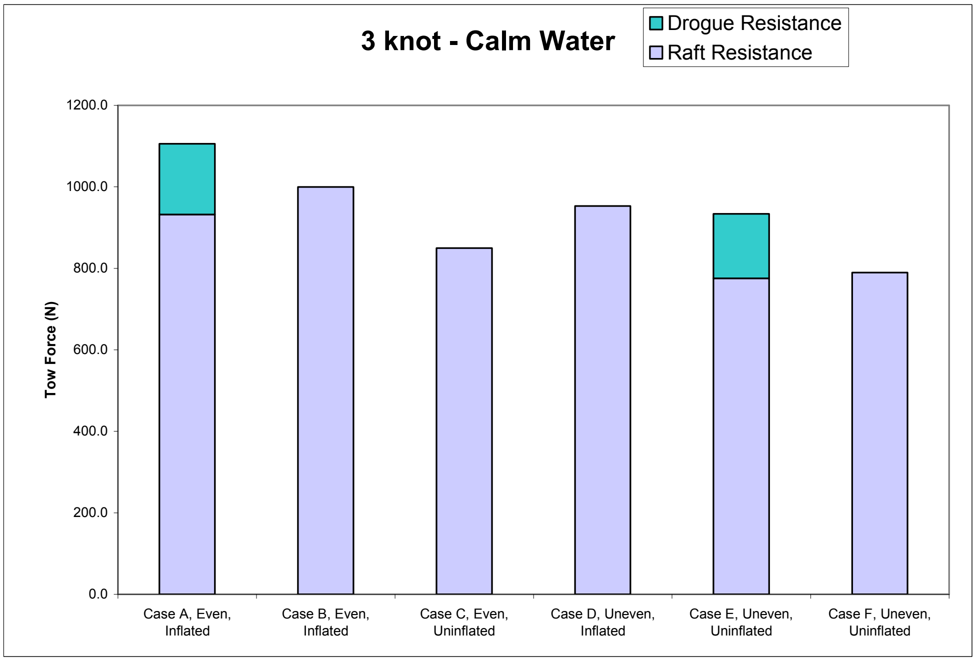


Figure 6.11 Combined effects on tow force (3 knots)

6.1.6 Effects of weight distribution, floor inflation, drogue and ballast type on life raft x-y track

Figure 6.12 shows the x-y track for all calm water tow test conditions. It appears that none of these test variables has any significant influence on life raft x-y track. The deviation from the mean path is about the same.

It should be noted that the tow duration was less than 30 seconds per run, so any phenomenon common to long duration tow test may not be observed in the current experiments.

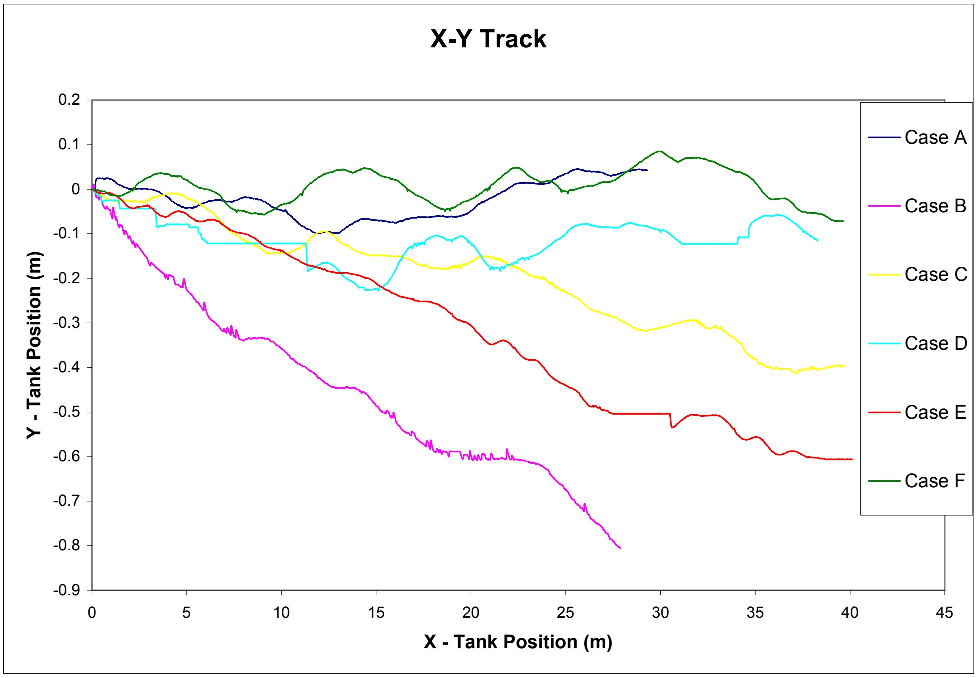


Figure 6.12 Life raft x-y track for different test conditions (3 knots)

6.2 Regular and Irregular Waves

In this section, the results of life raft towing in regular and irregular waves are presented.

Raft surge, heave and tow force RAOs in regular waves were computed as amplitude of surge, heave and tow force divided by amplitude of incident wave respectively. The incident wave frequency was then converted to encounter frequency.

Raft pitch RAO in regular waves was computed as amplitude of pitch divided by slope of incident wave. The incident wave frequency was then converted to encounter frequency.

Raft surge, heave and tow force RAOs in irregular waves were computed using GEDAP program VSD_IMD, by dividing the amplitude spectrum Sy(f) of the response by the amplitude spectrum Sx(f) of the encounter wave.

Raft pitch RAO in irregular waves was computed as above and then multiplied by (wavelength / 360).

Two vertical dotted lines bound the range of frequencies where 90% of the wave energy is concentrated around the peak of the wave spectrum on the plots.

Encounter frequencies from 0.33 Hz to 0.86 Hz for 1 knot;
Encounter frequencies from 0.36 Hz to 1.02 Hz for 2 knots and
Encounter frequencies from 0.39 Hz to 1.19 Hz for 3 knots.

The encounter wave probe in Case A, 3 knots, appeared to be erroneous, so no comparison was made with that case.

Since the raft MotionPak and the tree for Qualisys optical tracking system were placed at the circumference of the raft, heave measured was coupled with pitch. For vessels, which have a rigid hull, the usual way to uncouple pitch from heave is to translate the motions to its CG. Figures 6.13 to 6.15 show comparisons of the raft heave RAO measured from Qualisys at the circumference of the raft (i.e. coupled with pitch) and at the geometric center of the raft (i.e. uncoupled with pitch), at 1 knot, 2 knots and 3 knots, respectively. As expected, heave when uncoupled with pitch, had a lower RAO, which is less than one. When coupled with pitch, the heave RAO is greater than one. Over the frequency range with significant wave energy, the couple and decoupled heave RAO generally have a similar trend.

Since the life raft is not a rigid body. It deforms under wave forces, tow force, drogue force and occupant loading. The transformation to the geometric center of the raft is questionable. Also, occupants are sitting at the circumference of the raft and not the center of the raft. So, the motion measured at the circumference would represent more closely the motion that occupants experience. Therefore, it was decided that all the heave results presented in the subsequent sections would not be translated (i.e. heave was not uncoupled).

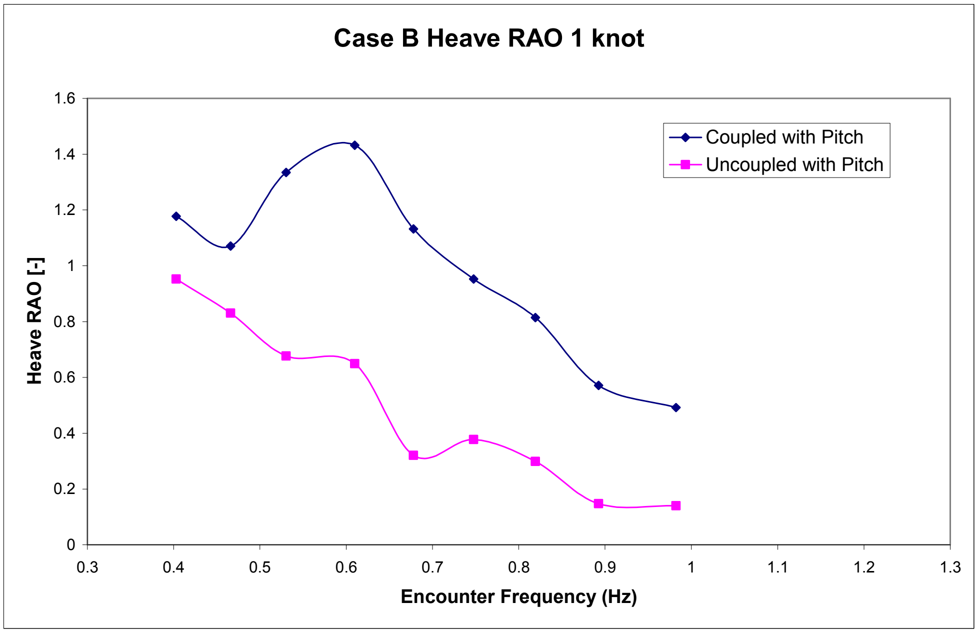


Figure 6.13 Comparison of coupled and uncoupled heave RAO, Case B, 1 knot

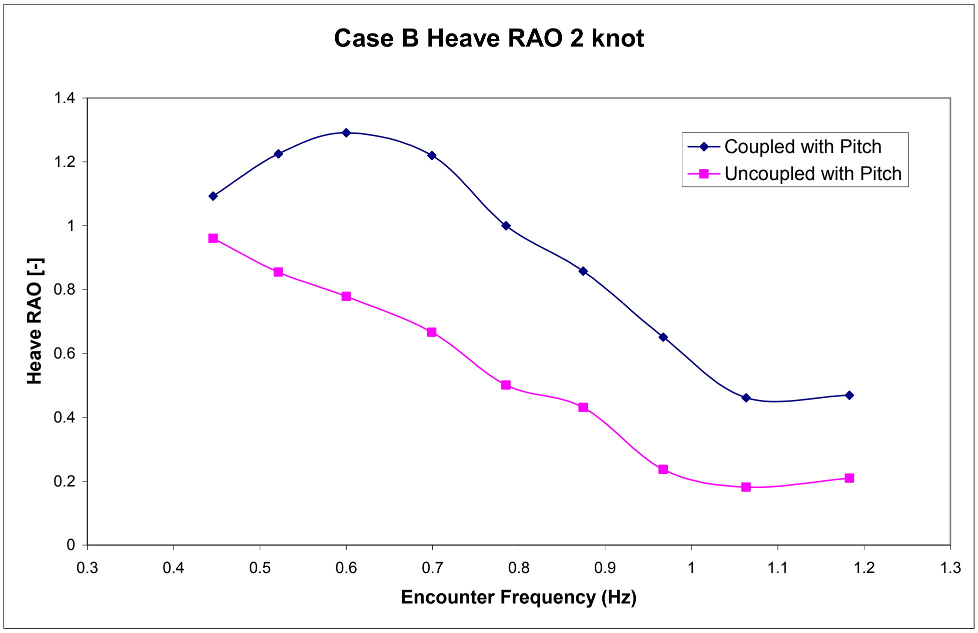


Figure 6.14 Comparison of coupled and uncoupled heave RAO, Case B, 2 knots

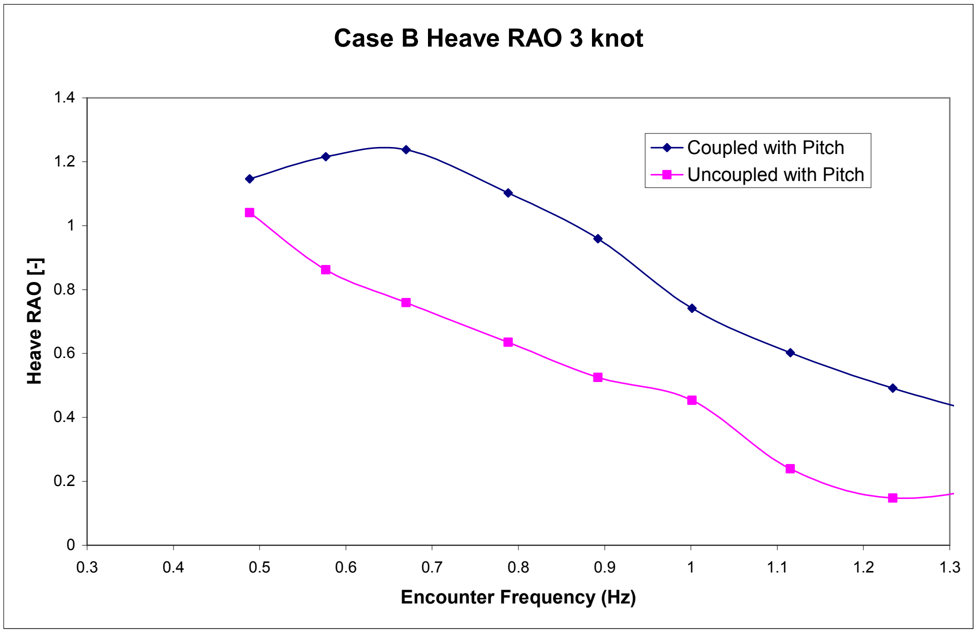


Figure 6.15 Comparison of coupled and uncoupled heave RAO, Case B, 3 knots

6.2.1 Comparison of life raft motion RAO and tow force RAO in regular and irregular waves with different test variables and tow speeds

A comparison of RAOs in regular and irregular waves for life raft surge (Figures 6.16 to 6.18), heave (Figures 6.19 to 6.21), pitch (Figures 6.22 to 6.24) and tow force variation (i.e. variation about mean tow force) (Figures 6.25 to 6.27) in Case B at 1, 2 and 3 knots tow speed are presented in the following pages.

Overall, there is very good agreement between the comparison of life raft RAO in regular and irregular wave. RAO in regular and irregular waves showed the same trend throughout the frequency range with significant wave energy. This demonstrated that irregular waves could be used effectively to determine the motion response and tow force response of the life raft in the frequency range with significant wave energy, without running individual regular waves. It also showed in high tow speed cases, where the irregular wave was completed in two separate runs due to limited tank length, the irregular wave and motion data could be spliced together for analysis, as if it is run as one wave without inducing much error.

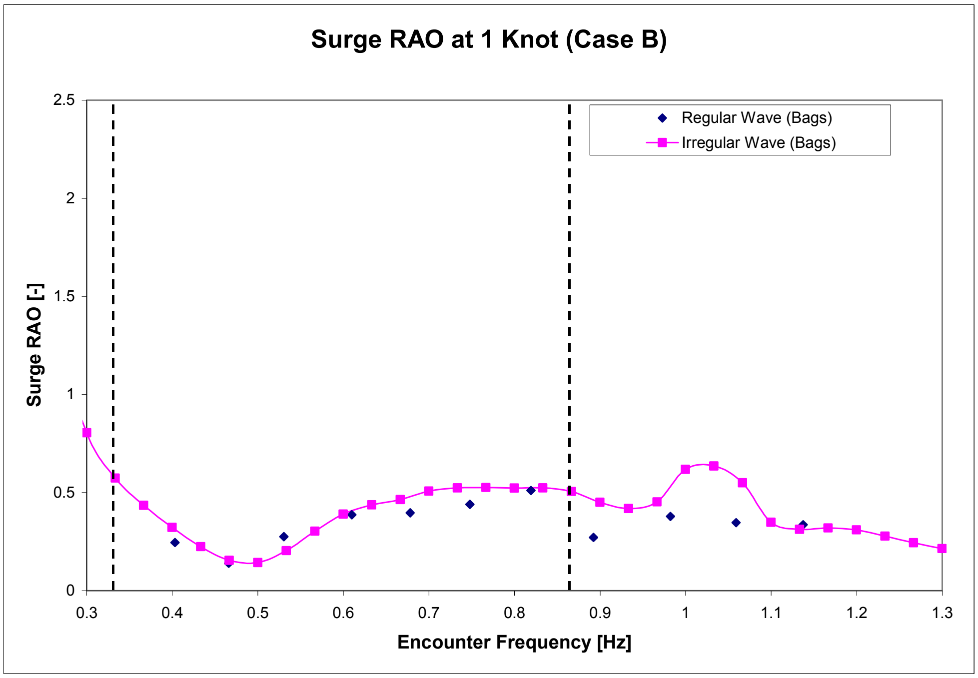


Figure 6.16 Raft surge RAO in regular and irregular waves, Case B, 1 knot

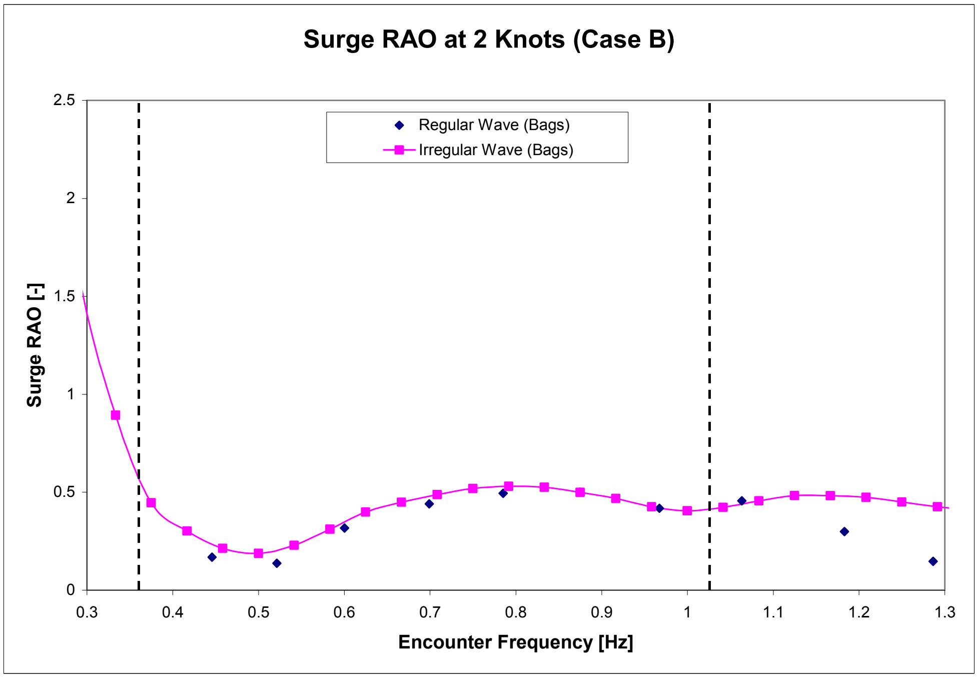


Figure 6.17 Raft surge RAO in regular and irregular waves, Case B, 2 knots

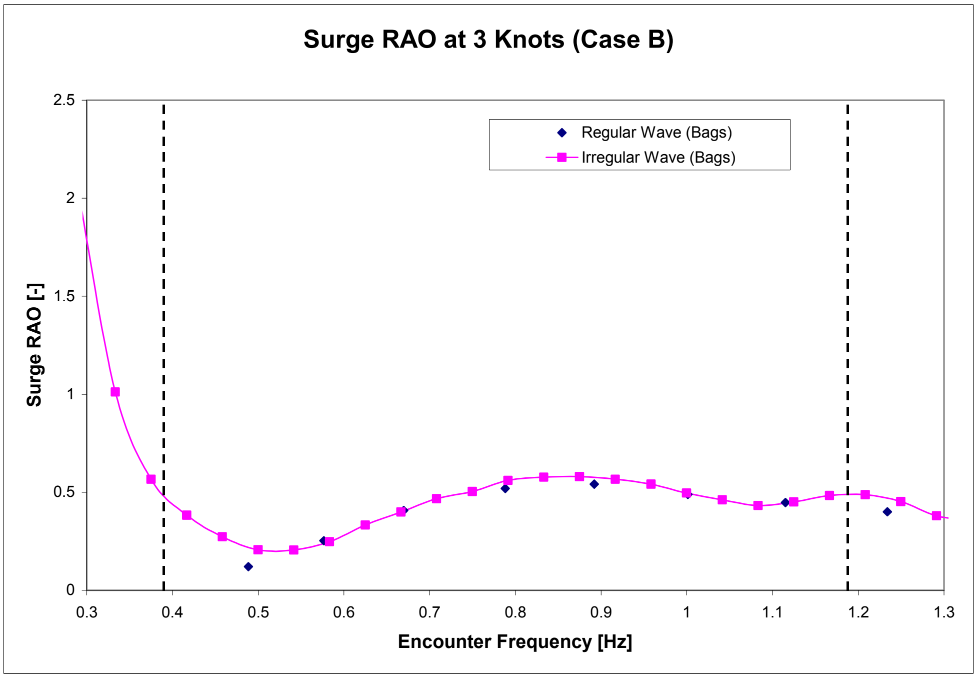


Figure 6.18 Raft surge RAO in regular and irregular waves, Case B, 3 knots

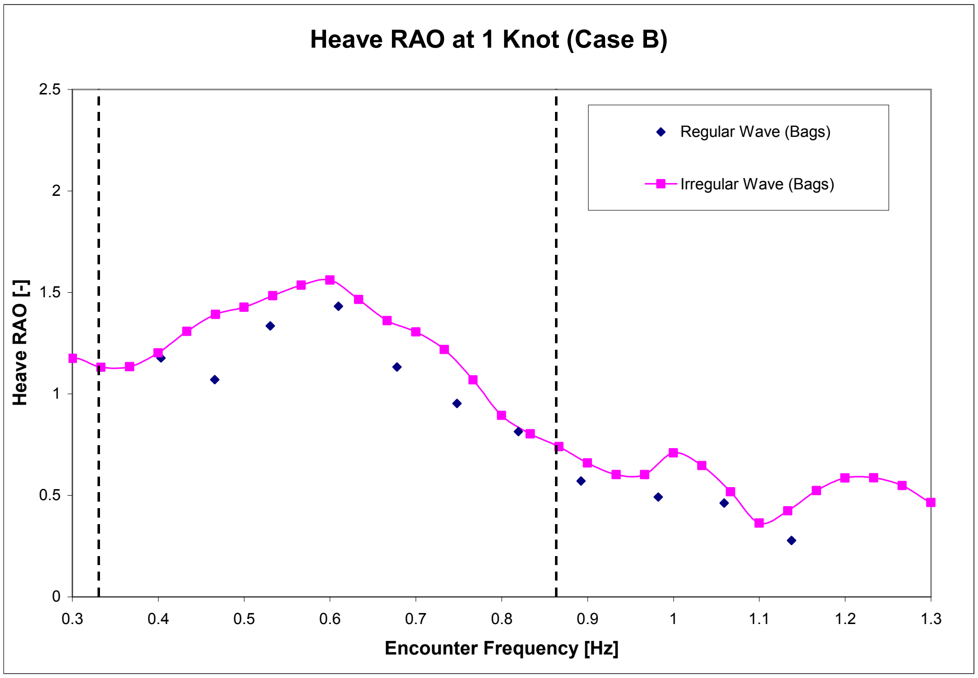


Figure 6.19 Raft heave RAO in regular and irregular waves, Case B, 1 knot

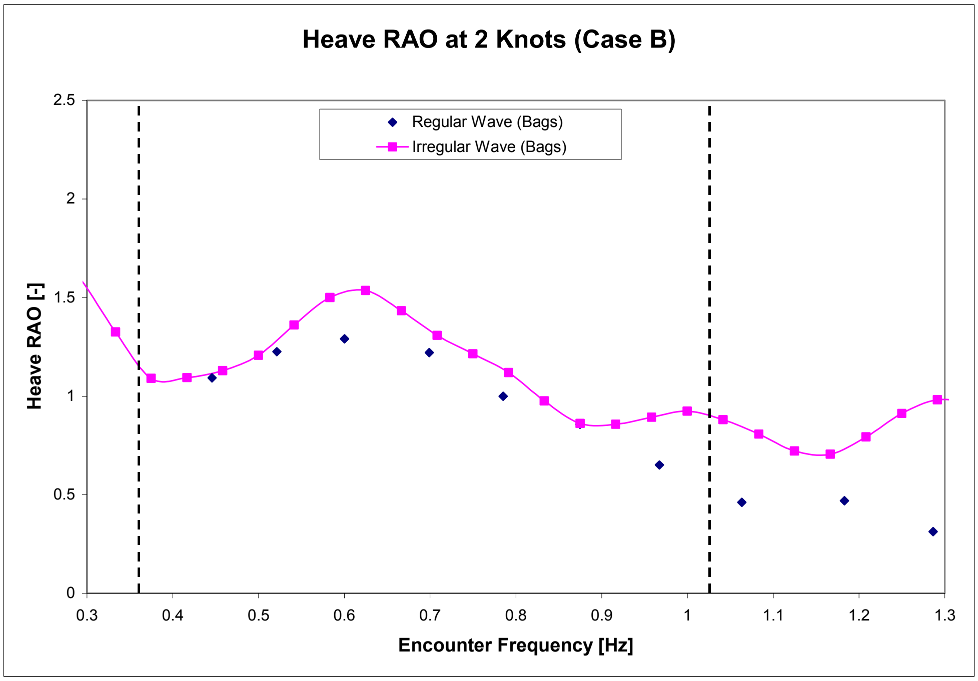


Figure 6.20 Raft heave RAO in regular and irregular waves, Case B, 2 knots

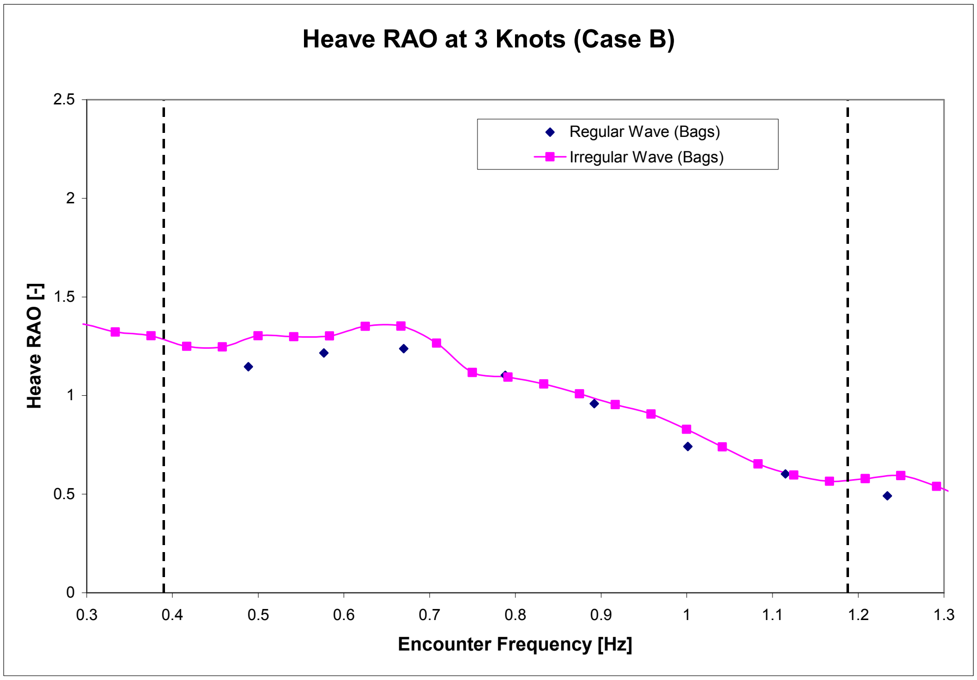


Figure 6.21 Raft heave RAO in regular and irregular waves, Case B, 3 knots

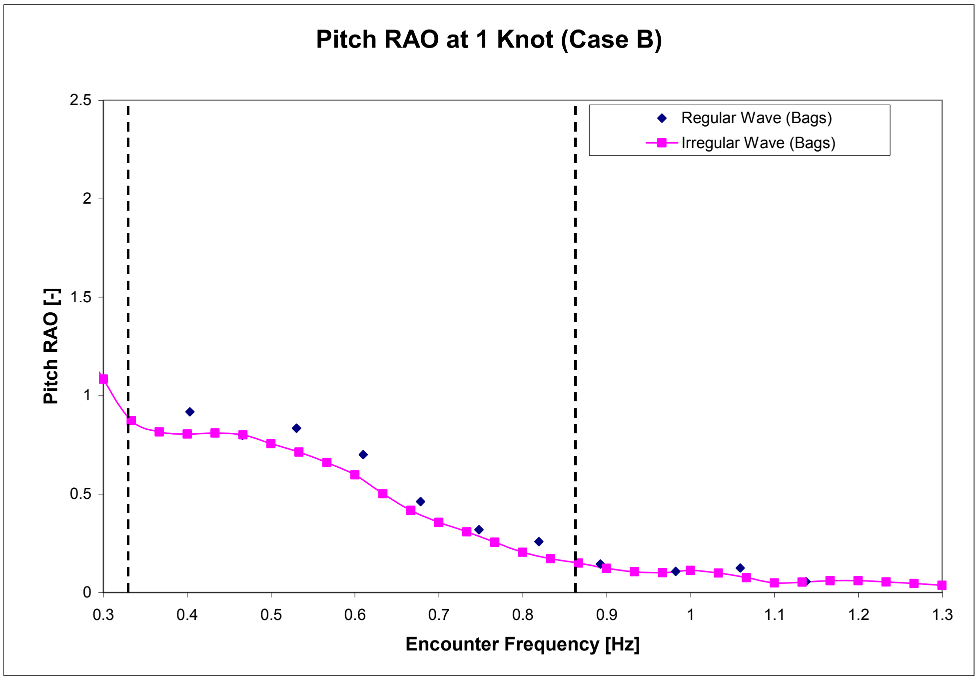


Figure 6.22 Raft pitch RAO in regular and irregular waves, Case B, 1 knot

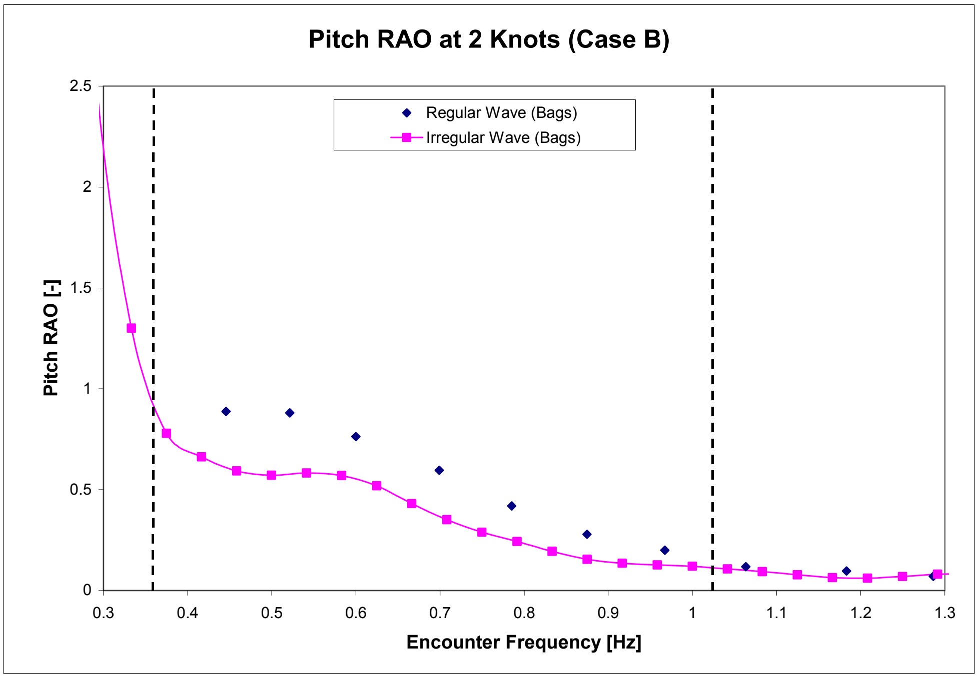


Figure 6.23 Raft pitch RAO in regular and irregular waves, Case B, 2 knots

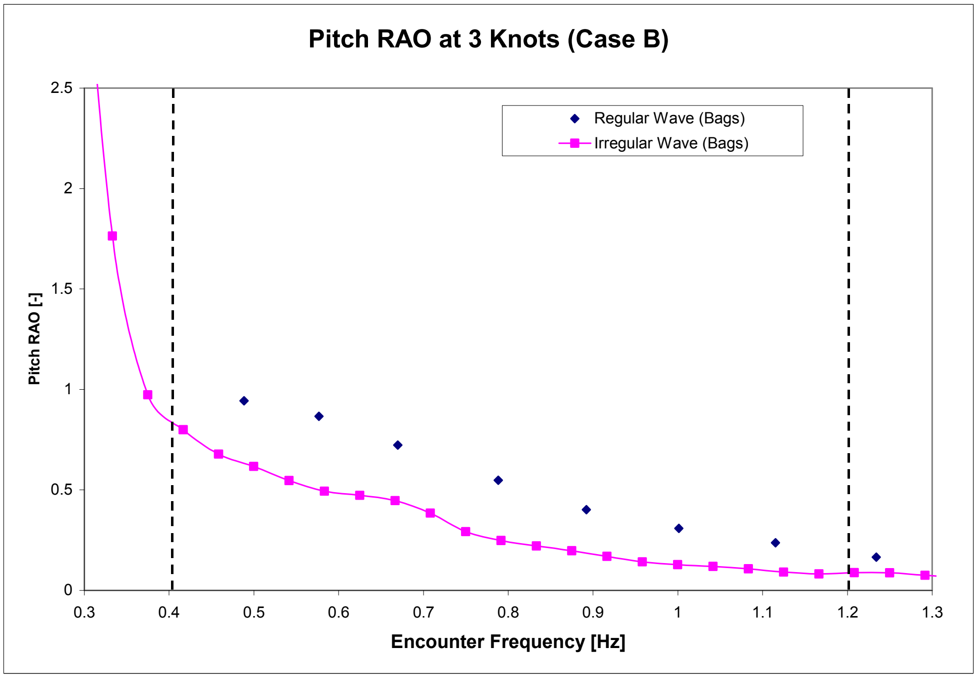


Figure 6.24 Raft pitch RAO in regular and irregular waves, Case B, 3 knots

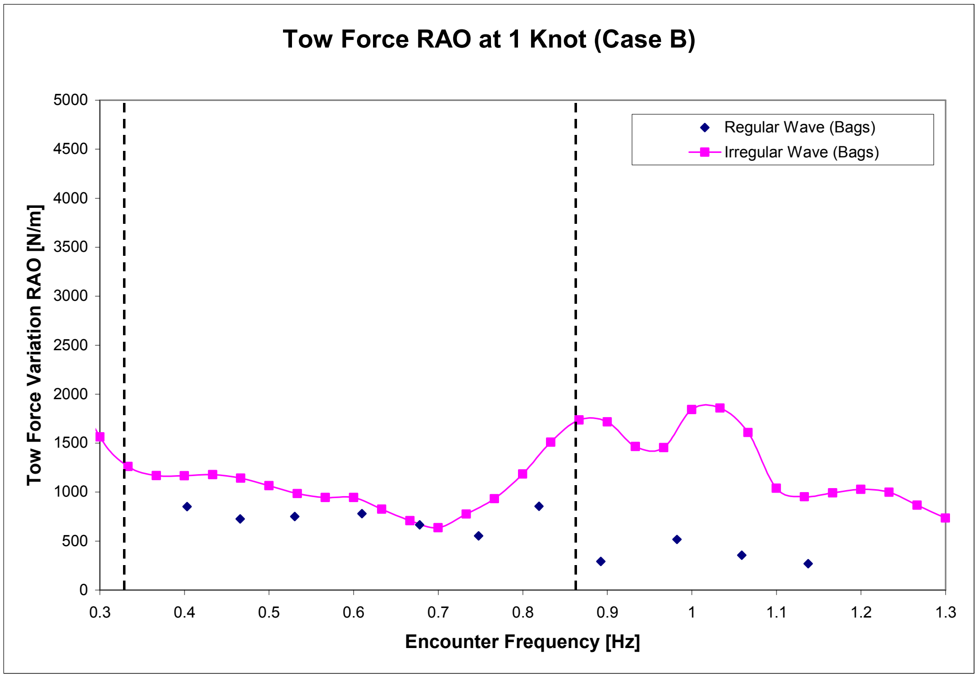


Figure 6.25 Raft tow force variation RAO in regular and irregular waves, Case B, 1 knot

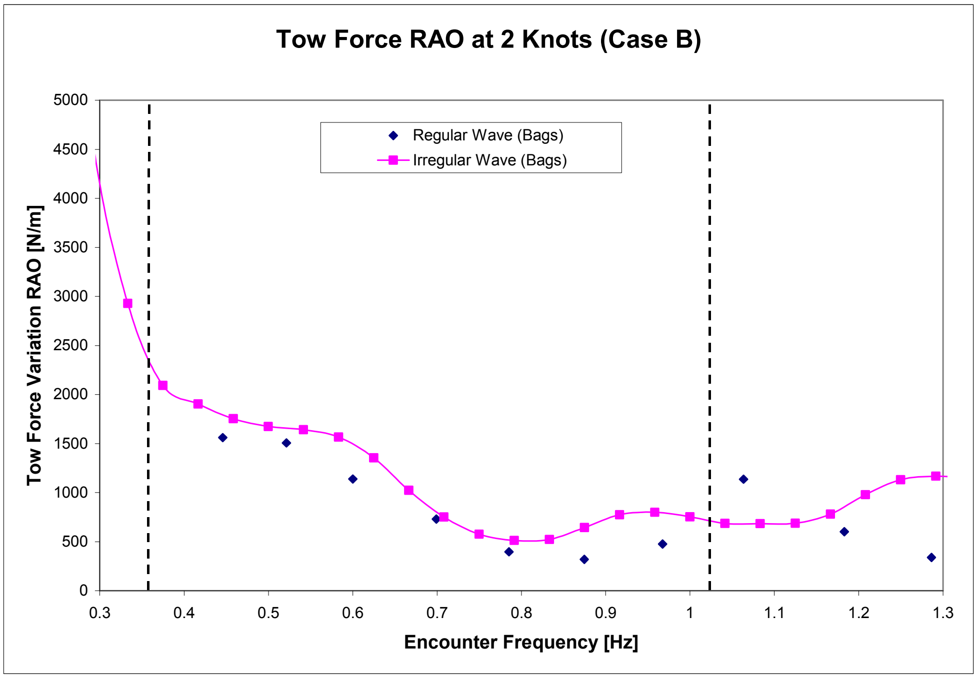


Figure 6.26 Raft tow force variation RAO in regular and irregular waves, Case B, 2 knots

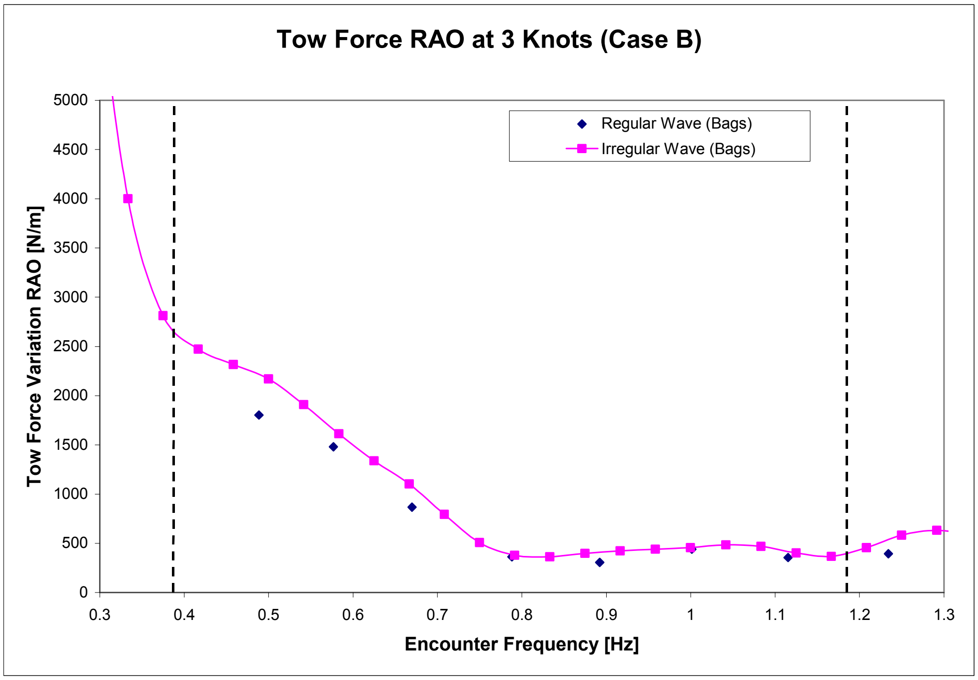


Figure 6.27 Raft tow force variation RAO in regular and irregular waves, Case B, 3 knots

The differences between RAOs in regular and irregular waves are within the expected margins of error of experimental testing. There are a number of possible sources of error:

(1) There were wave generation and propagation errors at different positions of the tank. High frequency waves generally did not have enough energy to propagate uniformly down the whole length of the tank.

(2) There was wave reflection, which builds up with time. Wave reflection may affect 1 knot runs more because each test took one 120 seconds run down the take. With 2 knots and 3 knots runs, each test was split into two 60 seconds run down the tank. So, there is more time for reflection to build up in 1 knot runs.

(3) There was measurement error associated with each individual run and data channel.

(4) There might be transient effects when the life raft was towed in the regular wave field at three speeds in one run down the tank.

(5) At high tow speed, there was more deflection of the encounter wave probe electrical wire, which results in less accurate wave height measurements.

(6) The life raft was a non-rigid body, which deforms in waves. When it deforms, it results in masked motion measurements.

The surge, heave, pitch and tow force variation RAO in regular and irregular waves for other test conditions are presented in Appendix B. Good agreement between regular and irregular wave RAO was observed in all cases. This provided justification and confidence in the use of irregular waves to assess the effects of different variables on raft towing in the following sections.

6.2.2 Effect of tow speeds on life raft surge RAO

The effect of tow speed on life raft surge in Case B (Even weight distribution; Floor inflated; No drogue) are shown in Figure 6.28. The differences in surge RAOs were small. The RAO curves for different speeds crossed over each other at different frequencies. There was no consistent trend in other test cases either. Therefore, it can be concluded that for the current towing arrangement, towline length and environmental conditions that life raft surge motions are speed independent.

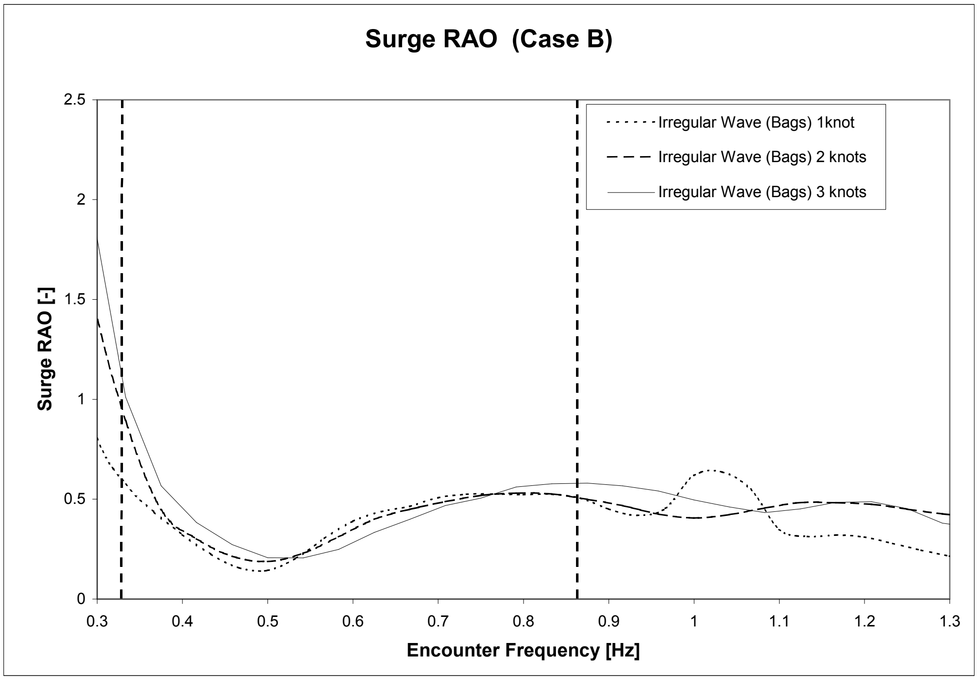


Figure 6.28 Speed effect on raft surge motion (Case B)

6.2.3 Effect of tow speeds on life raft pitch RAO

The effect of tow speed on life raft pitch in Case B (Even weight distribution; Floor inflated; No drogue) are shown in Figure 6.29. In the frequency range with significant wave energy, it was observed that pitch motion was independent of speed in most test cases. However, in Case B, pitch motion appeared to be highest when life raft was being towed at 1 knot in all cases. This may be due to the raft riding on the wave crest rather than plowing through waves at high speed.

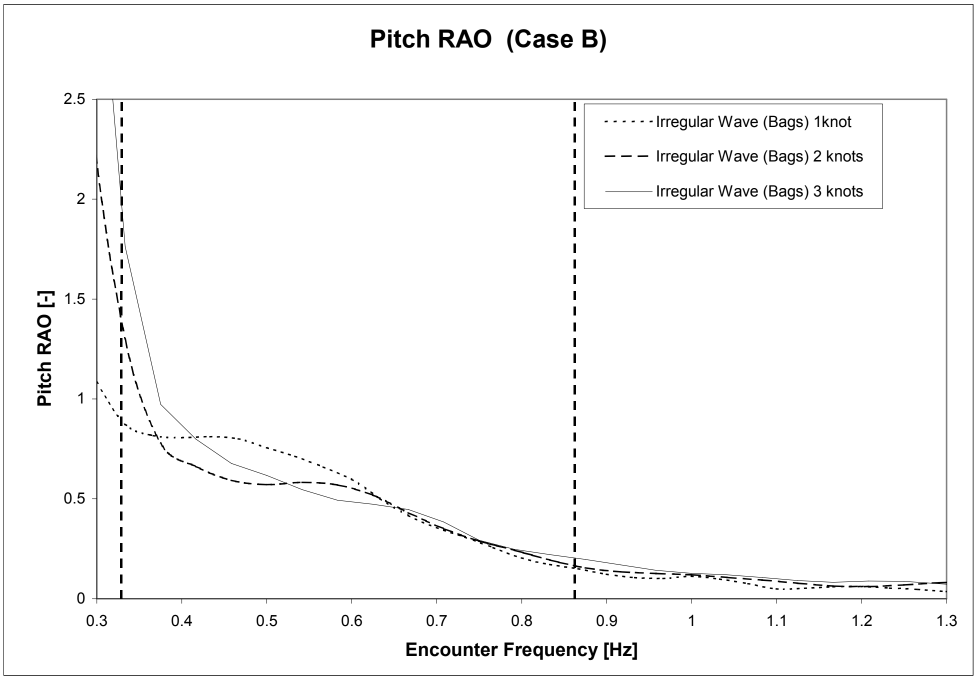


Figure 6.29 Speed effect on raft pitch motion (Case B)

6.2.4 Effect of tow speeds on life raft heave RAO

The tow speed effect on life raft heave in Case D (Uneven weight distribution; Floor inflated; No drogue) is shown in Figure 6.30. Between encounter frequencies 0.4 and 0.6 Hz, life raft heave tends to decrease with increased tow speed. This effect was also observed in Case B (Even weight distribution, Floor inflated; No drogue) and Case C (Even weight distribution, Floor not inflated; No drogue). The lower heave response at high speed may be due to wave plowing. At low speed, the raft may tend to ride with the wave crests.

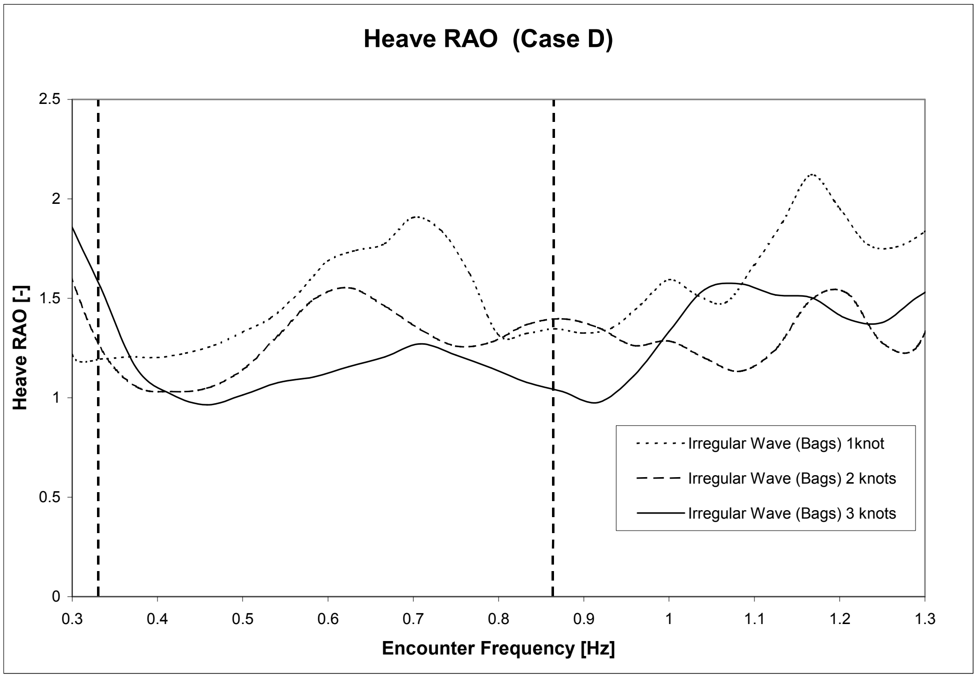


Figure 6.30 Speed effect on raft heave motion (Case D)

6.2.5 Effect of tow speeds on life raft tow force variation RAO

The effect of tow speed on tow force variation about its mean for Case B (Even weight distribution, Floor inflated; No drogue) is shown in Figure 6.31. It showed that tow force variation increases with tow speed for a large range of frequencies where the significant amount of wave energy is concentrated. This phenomenon is observed consistently in all test conditions.

Plots showing the effect of speed for other test conditions are presented in Appendix C.

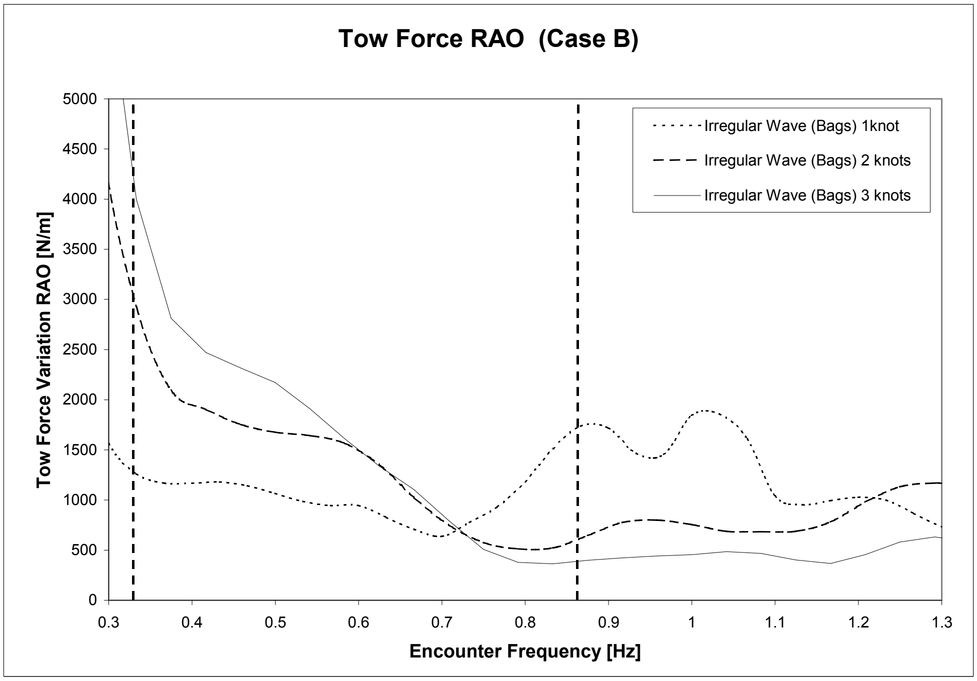


Figure 6.31 Speed effect on raft tow force variation (Case B)

6.2.6 Effect of ballast type on life raft tow force variation and mean tow force

The effect of ballast type on life raft tow force variation for 1 and 2 knots tow speed in Case E (Uneven weight distribution; Floor not inflated; Drogue) is presented in Figure 6.32 and 6.33. It showed that manikin ballast consistently results in higher tow force variation. The difference in tow force variation between manikin ballast and water bag ballast increased with speed.

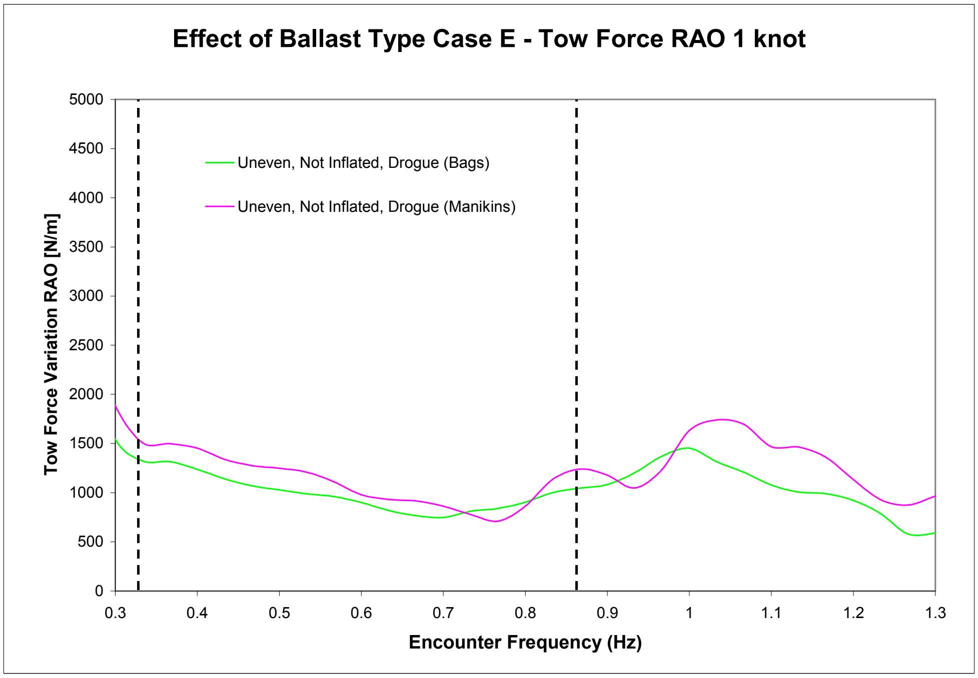


Figure 6.32 Effect of ballast type on tow force variation, Case E, 1 knot

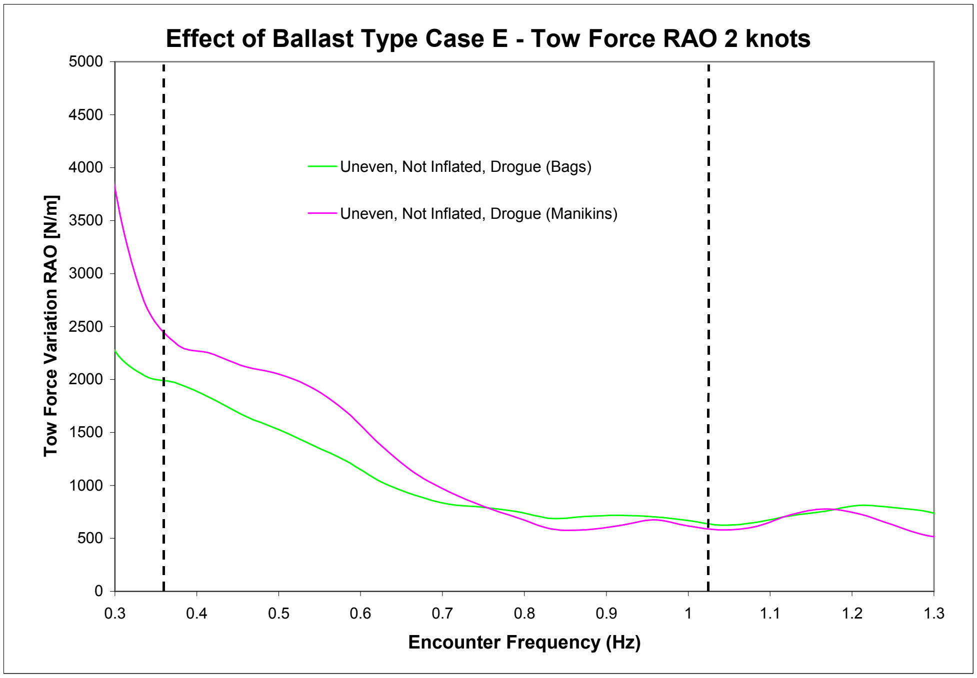


Figure 6.33 Effect of ballast type on tow force variation, Case E, 2 knots

The effect of ballast type on life raft mean tow force for 2 knots tow speed in Case E (Uneven weight distribution; Floor not inflated; Drogue) and Case F (Uneven weight distribution; Floor not inflated; No drogue) is presented in Figure 6.34. Mean tow force without drogue is shown as raft resistance. For test cases with drogue, mean tow force is the sum of raft resistance and drogue resistance.

It shows that manikin ballast consistently resulted in much higher mean tow force. The increase in mean tow force was significant. This implies that direct comparison of effects, such as floor inflation, drogue, weight distribution etc. need to be made with the same ballast type.

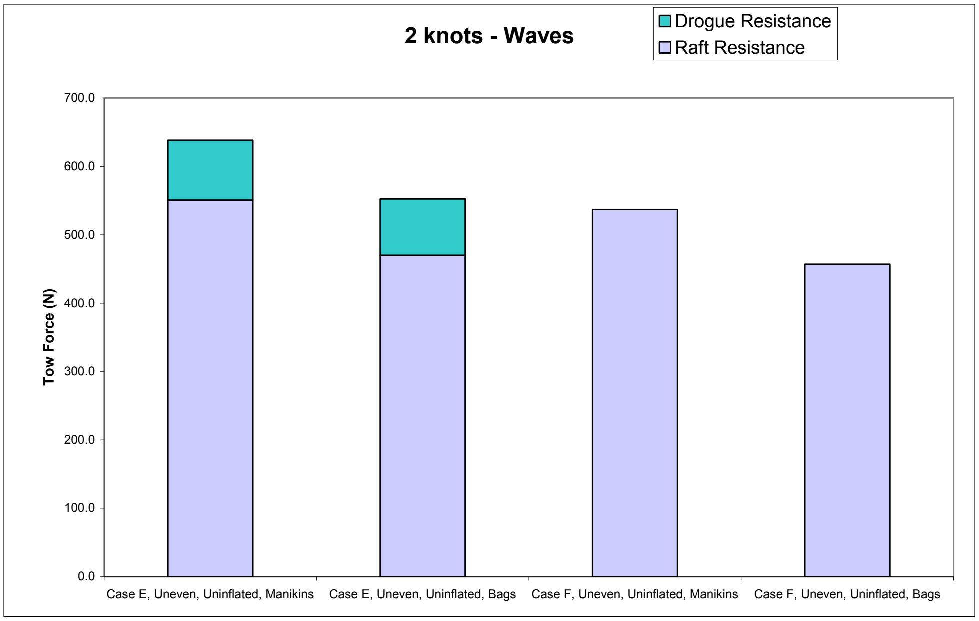


Figure 6.34 Effect of ballast type on mean tow force, Case E and Case F, 2 knots

6.2.7 Effects of test variables on tow force variation about its mean

Figure 6.35 shows a typical tow force time series. During the tow test, the tow force rises to a mean value and then it fluctuates about the mean. In this section, the effect of test variables on tow force variation about its mean is assessed. In the next section, the effect of test variables on mean tow force is assessed.

The effects of test variables on tow force variation about its mean at 3 knots are shown in Figure 6.36. Plots for other tow speeds are shown in Appendix D.

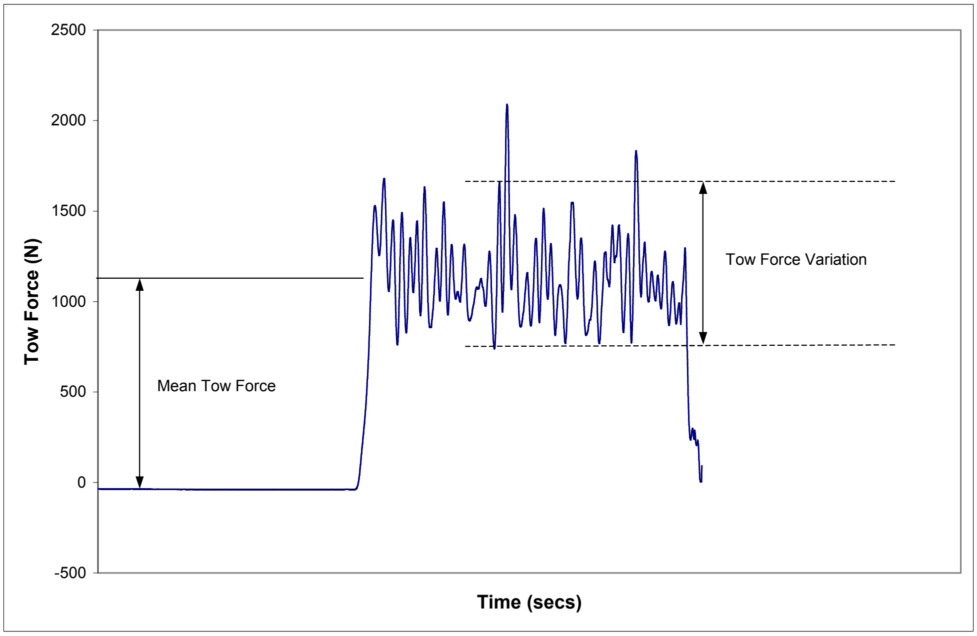


Figure 6.35 Tow Force time series

The following discussion is focused on the region where the wave spectrum peaks, between 0.4 Hz and 0.7 Hz encounter frequency (thin dashed lines), where 75% of the energy in the wave spectrum was concentrated. Beyond these frequencies, the wave heights were small and the margin of error increased. 90% of the wave energy is bounded by frequencies between the thick dashed lines.

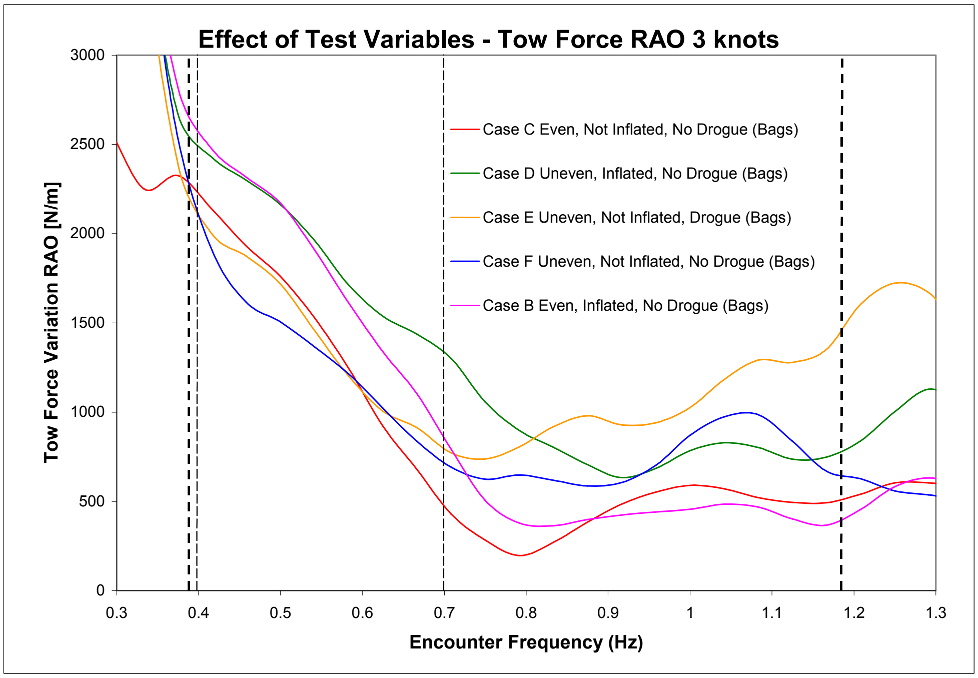


Figure 6.36 Effect of test variables on tow force variation about its mean, 3 knots

- The effect of floor inflation on tow force variation is assessed using the following comparisons in the figure:

  Case D – Uneven weight distribution; Floor inflated; No drogue
  Case F – Uneven weight distribution; Floor not inflated; No drogue

  And

  Case B – Even weight distribution; Floor inflated; No drogue
  Case C – Even weight distribution; Floor not inflated; No drogue

  It showed that floor inflation increased the tow force variation significantly in all cases – even and uneven distribution, and with and without drogue.

- The effect of drogue on tow force variation is assessed using the following comparison in the figure:

  Case E – Uneven weight distribution; Floor not inflated; Drogue
  Case F – Uneven weight distribution; Floor not inflated; No drogue

  It showed that drogue has no discernable effects on tow force variation.

- The effect of weight distribution on tow force variation is assessed using the following comparisons in the figure:

  Case B – Even weight distribution; Floor inflated; No drogue
  Case D – Uneven weight distribution; Floor inflated; No drogue

  And

  Case C - Even weight distribution; Floor not inflated; No drogue
  Case F - Uneven weight distribution; Floor not inflated; No drogue

  It showed that with floor inflated, uneven weight distribution increased tow force variation. With floor not inflated, weight distribution has no significant effect.

Comparing all the test cases, the highest tow force variation about its mean was observed in

Case D - Uneven weight distribution; Floor inflated; No drogue
Case B - Even weight distribution; Floor inflated; No drogue

This was observed in all tow speeds and was more pronounced at high tow speeds. Since the other test conditions with floor not inflated produce lower values regardless of whether it was even or uneven ballasted, and with or without drogue, it appeared to indicate that floor inflation was causing significantly higher variation in tow force about its mean than other variables.

6.2.8 Effects of test variables on mean tow force

The effects of test variables on mean tow force at 3 knots are shown in Figure 6.37. The results for other tow speeds are shown in Appendix D.

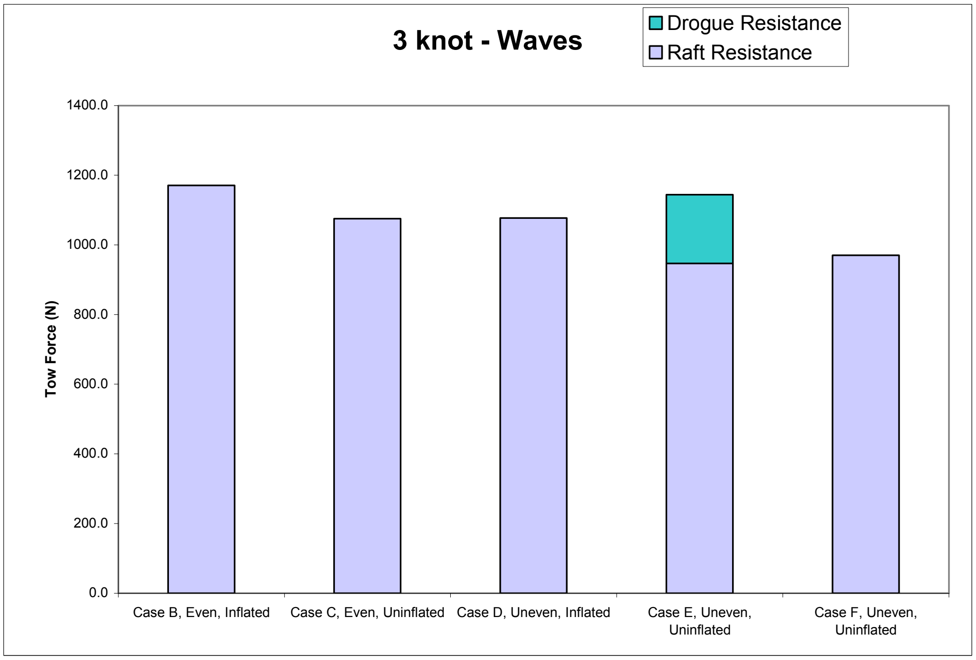


Figure 6.37 Effect of test variables on mean tow force, 3 knots

Mean tow force without drogue is shown as raft resistance on the plots. For test cases with drogue, mean tow force is the sum of raft resistance and drogue resistance.

- The effect of weight distribution on mean tow force is assessed using the following comparisons in the figure:
    Case B – Even weight distribution; Floor inflated; No drogue
    Case D – Uneven weight distribution; Floor inflated; No drogue
  And
    Case C - Even weight distribution; Floor not inflated; No drogue
    Case F - Uneven weight distribution; Floor not inflated; No drogue

  Even distribution contributed to higher mean tow force. The difference in raft resistance between even and uneven weight distribution was 93 and 105 N respectively with floor inflated and floor not inflated. This effect was also observed in 2 knots but there was no measurable effect at 1 knot.

- The effect of floor inflation on mean tow force is assessed using the following comparisons in the figure:
    Case D – Uneven weight distribution; Floor inflated; No drogue

Case F – Uneven weight distribution; Floor not inflated; No drogue
And
Case B – Even weight distribution; Floor inflated; No drogue
Case C – Even weight distribution; Floor not inflated; No drogue

Floor inflation increased mean tow force. The difference in raft resistance between floor inflated and floor not inflated was 107 and 95 N respectively for the above comparisons. The same effect was observed in all tow speed.

- The effect of drogue on mean tow force was assessed using the following comparison in the figure:
  Case E – Uneven weight distribution; Floor not inflated; Drogue
  Case F – Uneven weight distribution; Floor not inflated; No drogue

  Drogue contributed the most to the increase in mean tow force. The difference in resistance between drogue and no drogue was 197 N for the above comparison.

The following table shows the mean, RMS, max, min and average one-third highest tow force and mean drogue force.

			Tow Force (N)					Drogue (N)
Tow Speed	Case	Ballast	Mean	RMS	Max	Min	H1/3	Mean
1 knot	B	Bags	153	205	666	6	533	
	C	Bags	142	185	658	9	470	
	D	Bags	153	207	736	9	564	
	E	Manikins	188	246	1163	9	624	24
	E	Bags	169	218	888	9	532	25
	F	Manikins	153	210	979	10	579	
2 knots	B	Bags	546	585	1430	159	751	
	C	Bags	493	524	1387	156	650	
	D	Bags	537	579	1505	160	761	
	E	Manikins	636	671	1778	250	760	88
	E	Bags	550	579	1461	222	670	82
	F	Manikins	537	577	1528	174	777	
	F	Bags	457	492	1241	146	660	
3 knots	B	Bags	1171	1196	2309	728	860	
	C	Bags	1075	1095	1808	606	759	
	D	Bags	1077	1104	1953	316	843	
	E	Bags	1139	1160	2125	173	723	197
	F	Bags	970	988	1662	539	717	

Table 6.1 Tow force and drogue force statistics

6.2.9 Effects of test variables on life raft surge

The effects of test variables on life raft surge at 3 knots are shown in Figure 6.38. The following discussion is focused on the region where the wave spectrum peaks, between 0.4 Hz and 0.7 Hz encounter frequency (thin dashed lines), where 75% of the energy in the wave spectrum was concentrated. Beyond these frequencies, the wave heights were small and the margin of error increased. 90% of the wave energy is bounded by frequencies between the thick dashed lines.

- It is observed in Figure 6.38 that Case D and Case B had the lowest surge responses.
  Case D - Uneven weight distribution; Floor inflated; No drogue
  Case B - Even weight distribution; Floor inflated; No drogue
  These cases corresponded to the ones that had the highest tow force variations in Section 6.2.7.

- The highest surge response was observed here in Cases F, C and E, which correspond to the cases with the lowest tow force variations in Section 6.2.7.
  Case F - Uneven weight distribution; Floor not inflated; No drogue
  Case C - Even weight distribution; Floor not inflated; No drogue
  Case E - Uneven weight distribution; Floor not inflated; Drogue

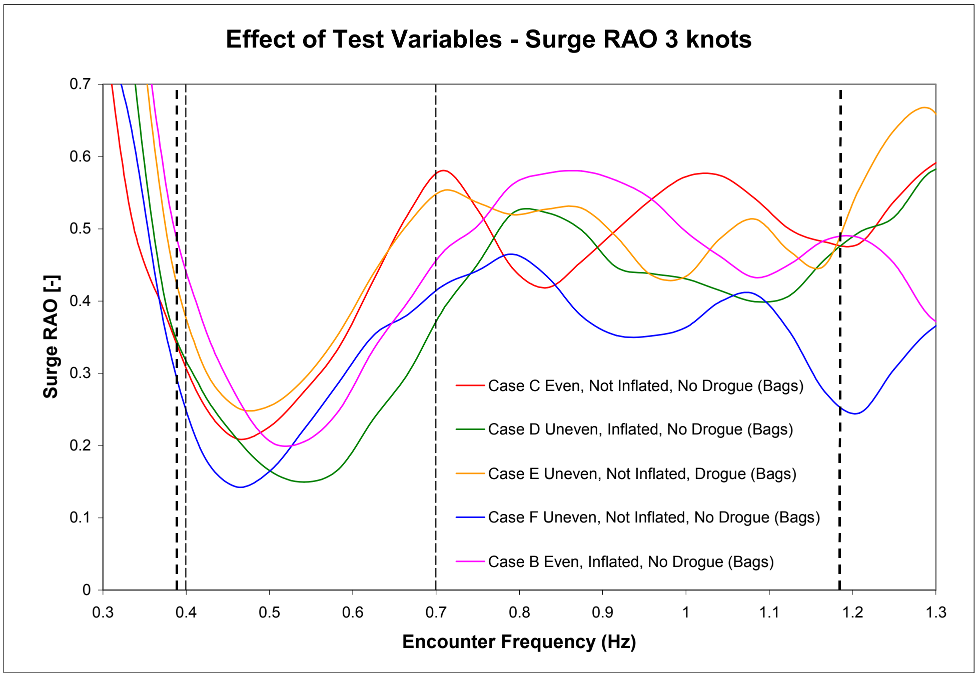


Figure 6.38 Effect of test variables on life raft surge, 3 knots

It thus appeared that in test conditions where there was high tow force variation, there was low life raft surge response and vice versa. This was observed for all tow speeds but was most pronounced at 3 knots. The higher tow force variations may be due to wave plowing, which tends to prevent the life raft from traveling forward, resulting in lower life raft surge response.

- The effect of weight distribution on life raft surge is assessed using the following comparisons in the figure:
    - Case B – Even weight distribution; Floor inflated; No drogue
    - Case D – Uneven weight distribution; Floor inflated; No drogue

  And
    - Case C – Even weight distribution; Floor not inflated; No drogue
    - Case F - Uneven weight distribution; Floor not inflated; No drogue

  It shows that even distribution contributes to higher life raft surge.

- The effect of floor inflation on life raft surge is assessed using the following comparisons in the figure:
    - Case B - Even weight distribution; Floor inflated; No drogue
    - Case C - Even weight distribution; Floor not inflated; No drogue

  And
    - Case D – Uneven weight distribution; Floor inflated; No drogue
    - Case F – Uneven weight distribution; Floor not inflated; No drogue

  It shows that inflated floor decreases life raft surge motion.

- The effect of drogue on life raft surge is assessed using the following comparison in the figure:
    - Case E - Uneven weight distribution; Floor not inflated; Drogue
    - Case F - Uneven weight distribution; Floor not inflated; No drogue

  It shows that drogue contributes to higher life raft surge motion.

6.2.10 Effects of test variables on life raft heave

The effects of test variables on life raft heave at 3 knots are shown in Figure 6.39. The following discussion is focused on the region where the wave spectrum peaks, between 0.4 Hz and 0.7 Hz encounter frequency (thin dashed lines), where 75% of the energy in the wave spectrum was concentrated. Beyond these frequencies, the wave heights were small and the margin of error increased. 90% of the wave energy is bounded by frequencies between the thick dashed lines.

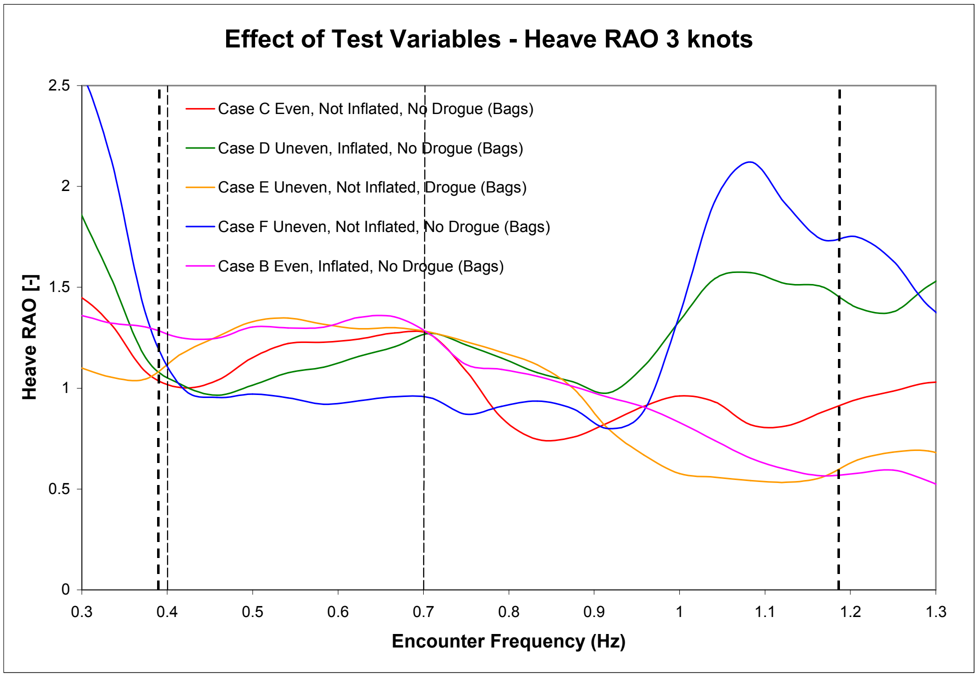


Figure 6.39 Effect of test variables on life raft heave, 3 knots

- The effect of floor inflation on life raft heave motion is assessed using the following comparisons in the figure:
  Case B – Even weight distribution; Floor inflated; No drogue
  Case C - Even weight distribution; Floor not inflated; No drogue
  And
  Case D – Uneven weight distribution; Floor inflated; No drogue
  Case F – Uneven weight distribution; Floor not inflated; No drogue

  It shows that floor inflation contributes to larger life raft heave motion. This was observed at all speeds.

- The effect of drogue on life raft heave motion is assessed using the following comparison in the figure:
  Case E - Uneven weight distribution; Floor not inflated; Drogue
  Case F - Uneven weight distribution; Floor not inflated; No drogue

  It shows that drogue contributes significantly to larger life raft heave motion. The contribution of larger heave motion is observed for 2-knot results as well.

- The effect of weight distribution on life raft heave motion is assessed using the following comparisons in the figure:
  Case B – Even weight distribution; Floor inflated; No drogue
  Case D – Uneven weight distribution; Floor inflated; No drogue
  And

Case C – Even weight distribution; Floor not inflated; No drogue
Case F - Uneven weight distribution; Floor not inflated; No drogue

It shows that even weight distribution contributes significantly to larger life raft heave motion. This is also observed at lower tow speed but it is more pronounced at high tow speed.

6.2.11 Effects of test variables on life raft pitch

The effects of test variables on life raft pitch at 3 knots are presented in Figure 6.40.

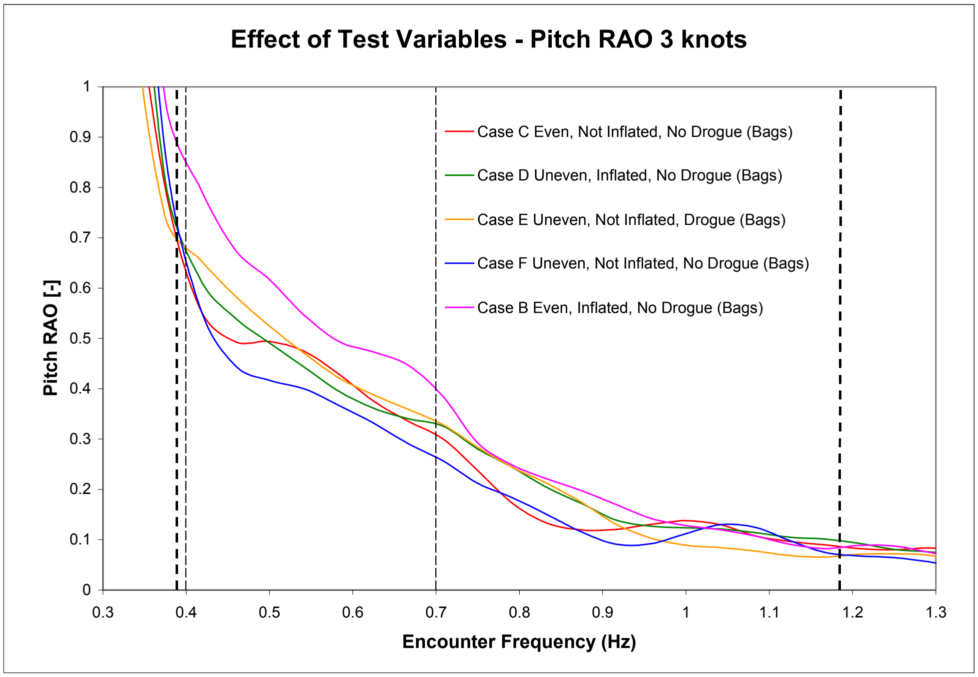


Figure 6.40 Effect of test variables on life raft pitch, 3 knots

- The effect of floor inflation on life raft pitch motion is assessed using the following comparisons in the figure:
  Case B – Even weight distribution; Floor inflated; No drogue
  Case C - Even weight distribution; Floor not inflated; No drogue
  And
  Case D – Uneven weight distribution; Floor inflated; No drogue
  Case F – Uneven weight distribution; Floor not inflated; No drogue

  It shows raft pitch increases with floor inflated, however, the pitch RAO is very small.

- The effect of drogue on life raft pitch motion is assessed using the following comparison in the figure:
  Case E - Uneven weight distribution; Floor not inflated; Drogue
  Case F - Uneven weight distribution; Floor not inflated; No drogue

  It shows that the drogue increases raft pitch but in general the raft pitch may be too small to be of any significance.

- The effect of weight distribution on life raft heave motion is assessed using the following comparisons in the figure:
  Case B – Even weight distribution; Floor inflated; No drogue
  Case D – Uneven weight distribution; Floor inflated; No drogue
  And
  Case C – Even weight distribution; Floor not inflated; No drogue
  Case F - Uneven weight distribution; Floor not inflated; No drogue

  It shows that even weight distribution increases life raft pitch but the pitch RAO is very small.

6.2.12 Life raft occupant motion

A manikin equipped with a MotionPak in its chest was used to record motion that an occupant would experience inside the life raft. Unfortunately, the manikin MotionPak malfunctioned shortly after the test program began. So, there were only four runs conducted with reliable motion data measured from the manikin, Case B (Even weight distribution; Floor inflated; No drogue) and Case C (Even weight distribution; Floor not inflated; No drogue) at 1 knot, and Case D (Uneven weight distribution; Floor inflated; No drogue) and Case F (Uneven weight distribution; Floor not inflated; No drogue) at 3 knots.

Figures 6.41 and 6.42 show the amplitude spectrum of the manikin heave divided by the amplitude spectrum of the life raft heave. Figure 6.41 shows 1 knot results for Case B and Case C. Figure 6.42 shows 3 knots results for Case D and Case F.

The following discussion focuses in the region where 90% of the energy in the wave spectrum is concentrated (between 0.33 Hz and 0.86 Hz encounter frequency for 1 knot results and between 0.39 Hz and 1.19 Hz encounter frequency for 3 knots results). Beyond these frequencies, the wave heights are small and the margin of error increases.

In all cases, it is observed that the measured manikin heave motion is about the same as the measured raft heave motion, indicating that its occupants would experience almost all the raft heave motion.

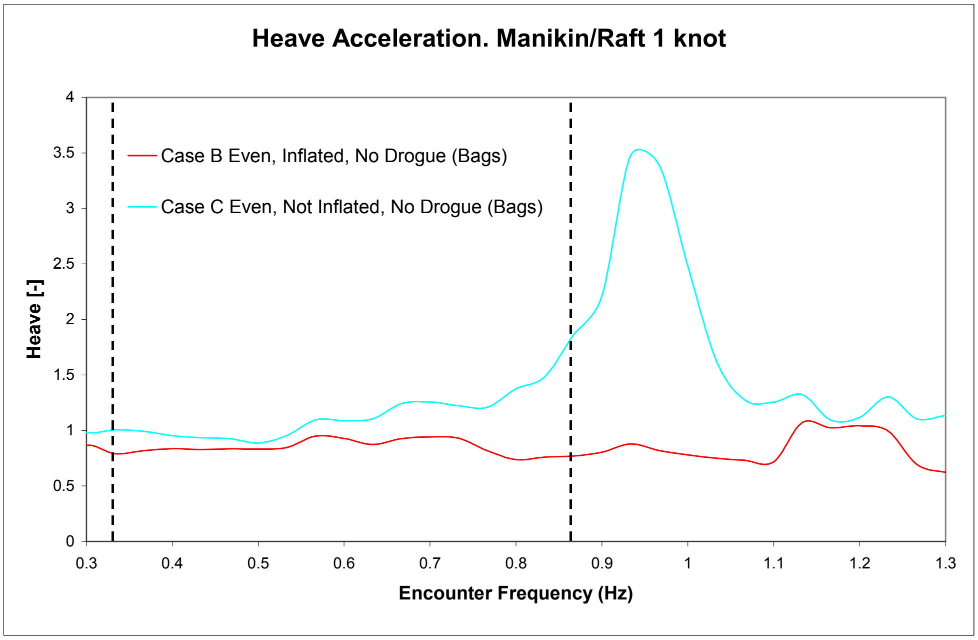


Figure 6.41 Comparison of manikin and raft heave motion, 1 knot

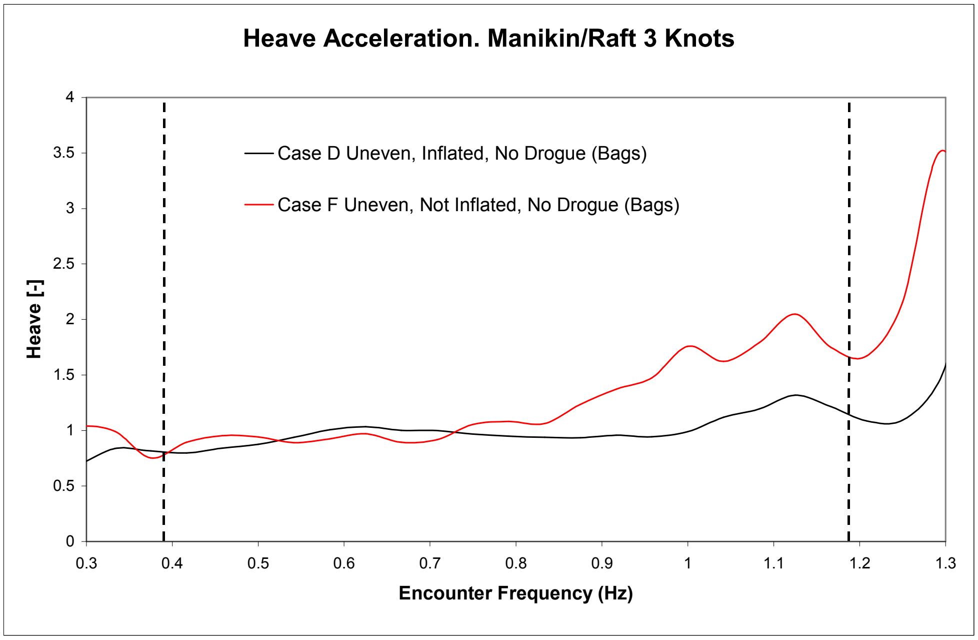


Figure 6.42 Comparison of manikin and raft heave motion, 3 knots

Table 6.2 compares the significant (i.e. average of 1/3 highest) heave motion in the raft and manikin as measured by the MotionPaks.

		Significant Heave Motion	
Case	Tow Speed [knot]	Raft [g]	Manikin [g]
Case B	1	0.45	0.39
Case C	1	0.43	0.45
Case D	3	0.67	0.65
Case F	3	0.62	0.71

Table 6.2 Comparison of raft and manikin significant heave motion

In some instances, the manikin significant heave motion was larger than the raft significant heave motion. This may be explained by the location of the MotionPak for the manikin and the raft, which were placed at two different locations. The manikin MotionPak is located at the forward end of the raft, close to the tow point, while the raft MotionPak is located at the aft end of the raft. Distance between the two positions was about 2.45 m. The measured heave motion is coupled with pitch since the two MotionPaks are located at the circumference of the raft. The table shows that the magnitudes of the raft and manikin significant heave motion are approximately the same, thus the occupants seated at the circumference of the raft experience the same heave motion as the raft.

6.2.13 Occupant Motion Sickness Assessment

Motion sickness in occupants was accessed using International Standard ISO 2631-1:1997 “ Mechanical Vibration and Shock - Evaluation of human exposure to whole-body vibration”. In this standard, motion sickness is assessed using heave acceleration. For the purpose of this study, measured heave acceleration from the raft MotionPak was used.

The motion sickness dose value, $MSDV_Z$, was calculated from frequency-weighted r.m.s heave acceleration values. Higher values correspond to a greater incidence of motion sickness. The percentage of people who may vomit is approximated by K_m x $MSDV_Z$, where K_m is 1/3 for a mixed population of unadapted male and female adults. The following table shows the result of motion sickness assessment for Case B (Even weight distribution; Floor inflated; No drogue). The other test conditions show similar values.

	1 knot		2 knot		3 knot	
Duration	% $MSDV_Z$	% Vomit	% $MSDV_Z$	% Vomit	% $MSDV_Z$	% Vomit
1 hour	15	5	16	5	12	4
5 hours	35	11	37	12	28	9
10 hours	49	16	50	17	39	13
20 hours	69	23	71	24	55	18

Table 6.3 Motion sickness assessment

The % vomit values in the table show that about 20% of occupants would vomit after 20 hours in the life raft. The percentage of occupants suffering motion sickness at high tow speed was slightly lower than at low tow speed.

6.2.14 Occupant Injury Assessment

The possibility of occupant injury was assessed using the square-root-sum-of-the-squares (SRSS) acceleration criteria. This method is very easy to apply but the major weakness is that it only considers the magnitude of the acceleration force. The duration of the force is not considered. Therefore, the SRSS criteria tend to overestimate the injury potential of an acceleration field. In this program, it is desirable to have conservative estimates because there are many variables in life raft towing that are not directly controllable by the life raft occupants and the tow craft operator.

The SRSS criteria are cast in the form of an interaction equation. The resulting CAR (combined acceleration response) index is a measure of the potential for the acceleration to cause human injury. Injury should not occur if the CAR index is less than unity.

The occupant injury assessment was conducted using the measured raft surge, sway and heave acceleration time series in Case B at 3 knots. A CAR index was computed for each time step. The largest CAR index computed was 0.11. Since it is an order of magnitude smaller than unity, it was concluded that occupants are unlikely to suffer injury during life raft towing in the sea state tested.

6.2.15 Qualitative Observations

During the test program, it was observed that sometimes a lot of water splashed onto the canopy during towing. It is advisable that occupants close the raft entrance covers to minimize the amount of water entering the raft. If water enters the raft, it is very difficult to bail all the water out of the raft. There is always a layer of water on the floor. Occupants can lose body heat much faster with wet clothing and water on the raft floor. Figure 6.43 shows the amount of water splashed on the canopy during towing.

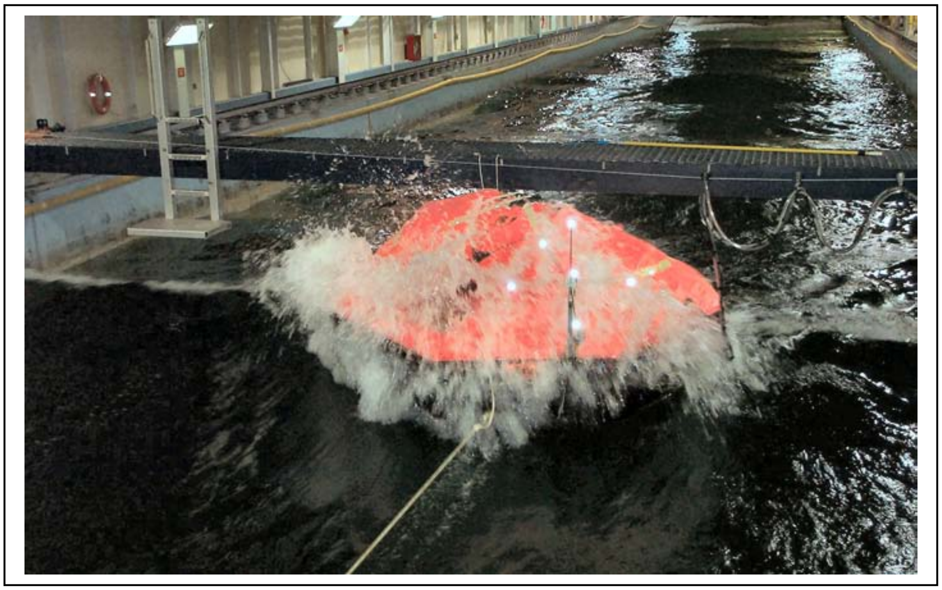


Figure 6.43 Water splash on canopy during towing

Sometimes, it was observed that the weight of water splashed on the canopy caused the canopy to collapse. This occurred with raft entrance cover opened and closed. Figure 6.44 shows the canopy collapsed after a large amount of water splashed on the canopy during towing. A puddle of water remained on the collapsed canopy.

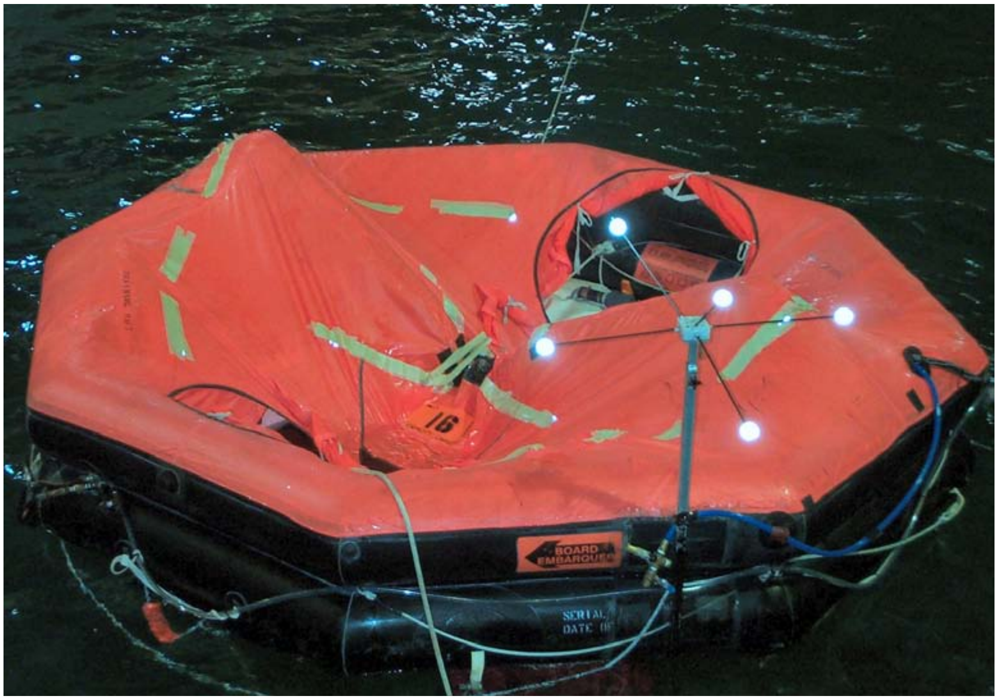


Figure 6.44 A puddle of water remained on the collapsed canopy.

Figure 6.45 shows water accumulating on the flat spot of the raft entrance cover after water splashed on the canopy. The water would continue to accumulate with each large wave, splashing water on the canopy. The weight of the water eventually collapsed the canopy.

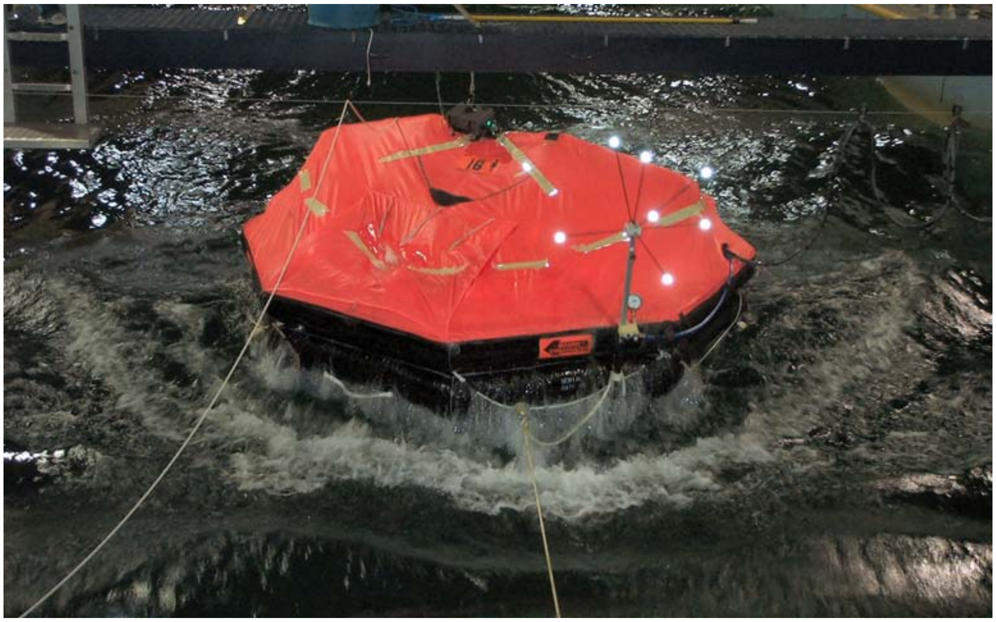


Figure 6.45 Water accumulating on the flat spot of the entrance cover.

These observations indicated that one arch canopy support might be inadequate. Additional support must be used to reinforce the canopy, so it does not collapse on the raft occupants.

Even with the raft entrance covers closed, there was still water entering the raft, possibly through the spacing between the canopy and the entrance cover. When water enters the raft, occupant heat loss increases and it requires occupants to bail water consistently. Thus, it should be minimized with better waterproof entrance cover design.

According to Transport Canada, "Standards for Life Rafts and Inflatable Rescue Platforms", the sea anchor approved for life rafts accommodating more than 10 persons shall have a minimum mouth diameter of 500 mm and a minimum sloping length of 670 mm. The drogue supplied with the raft did not conform to this specification. Also, the mouth of the sea anchor did not stay open immediately on deployment as required by the standard. In this test program, a light wire frame was fitted at the mouth of the drogue to keep the mouth of the sea anchor open all the time.

6.2.16 Effects of weight distribution, floor inflation, drogue and ballast type on life raft x-y track

Figure 6.46 shows a comparison of the life raft x-y track for different test cases at 1 knot. Similar tracks were observed at higher tow speeds.

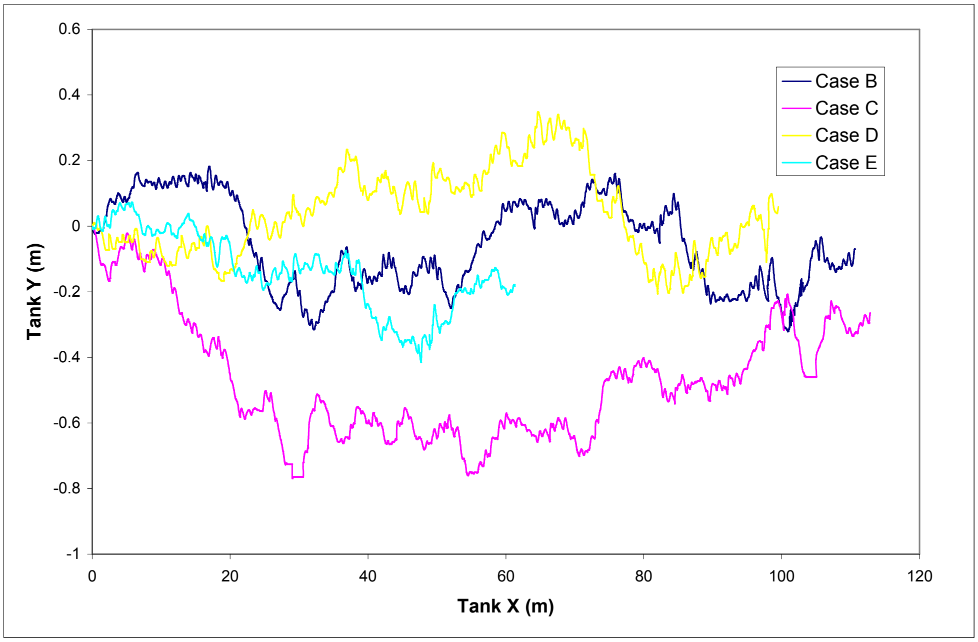


Figure 6.46 Life raft x-y track for different cases (1 knot)

It is observed that the life raft exhibited minor sideway deviation from the mean tow direction in all cases. It swayed back and forth about the mean tow direction, forming a sinusoidal motion down the tank. As the deviation from the mean tow direction was small and about the same in all cases, it appeared that none of the test variables had a major effect on the life raft x-y track.

Figure 6.47 shows the life raft x-y track for Case B at different tow speeds. Similar tracks were observed in other cases. It appeared that the deviation about the mean tow direction was about the same in all tow speeds. It indicated that deviation about the mean tow direction is not affected by tow speed.

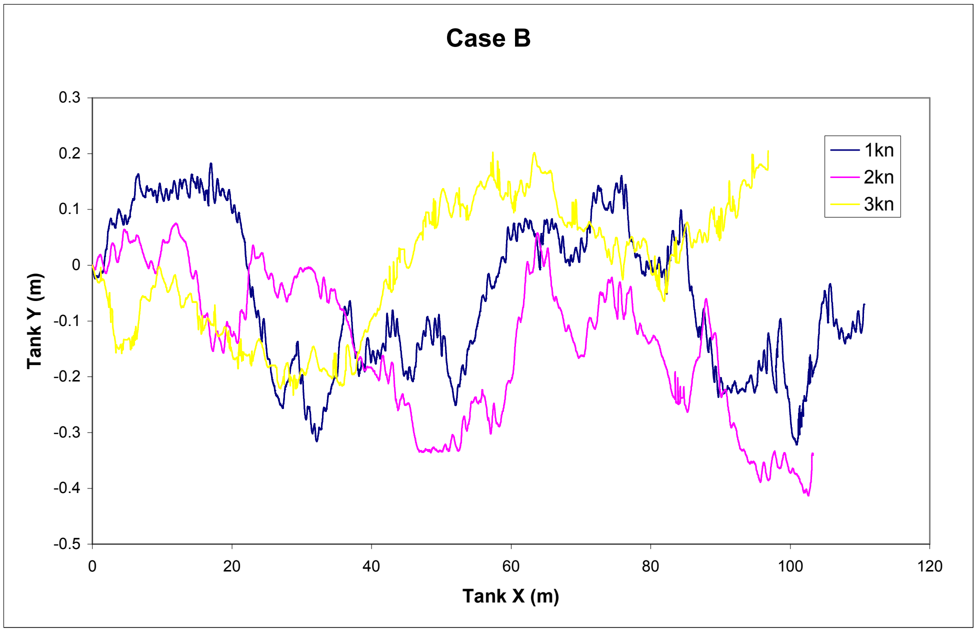


Figure 6.47 Effect of tow speed on life raft x-y track

7.0 Conclusions

1. In calm water, manikin ballast resulted in higher tow force than water bag ballast for the same test condition. The difference in tow force with manikin ballast and water bag ballast increased with tow speed and it was more pronounced with drogue deployment. At 3 knots, the difference in tow force with manikin ballast and water bag ballast was 70 N and 37 N with drogue and without drogue respectively.

2. In calm water, drogue deployment and floor inflation increased tow force. Floor inflation stiffens the raft and a rigid raft is less compliant. Therefore, it may push more water and thus increase tow force. The increase in tow force was more pronounced with increased tow speed. At 3 knots, the increase in tow force from drogue deployment was 175 N. The increase in tow force from floor inflation was 150 N.

   With floor inflated, tow force at different speeds with even weight distribution was comparable to that with uneven weight distribution. With floor not inflated, tow force was slightly higher with even weight distribution. The increase in tow force became more pronounced with increased tow speed. At 3 knots, the increase in tow force from even weight distribution was 60 N.

   This demonstrated that drogue deployment and floor inflation contributed significantly to an increase in tow force as compared to even weight distribution.

   The individual effects appeared to be cumulative. For example, the tow force for Case B (Even weight distribution; Floor inflated; No drogue) was about 210 N more than that for Case F (Uneven weight distribution; Floor not inflated; No drogue) due to the combined effects of floor inflation and weight distribution. With uneven weight distribution, the front of the raft tended to lift upwards. It may plow less into water when being towed. With floor not inflated, the raft was more compliant and may push less water when being towed. These may have contributed to lower tow force.

   Overall, Case A (even weight distribution; Floor inflated; Drogue) with manikin ballast had the highest tow force. Case F (Uneven weight distribution, Floor not inflated; No Drogue) with water bag ballast had the lowest tow force. All the other test cases fall in between Case A and Case F.

3. In calm water, weight distribution, floor inflation, drogue deployment and ballast type did not have any significant effect on the life raft x-y tow track. The deviation from the mean path in all test cases was about the same. It should be noted that the tow duration was less than 30 seconds in each run. So, any phenomenon common to long duration tow tests may not be present in the calm water experiments. However, in the longer duration wave tests, the life raft tow track was sinusoidal.

4. In waves, the measured raft heave RAO (coupled with pitch) at the circumference of the raft had similar trend as the decoupled heave RAO at the geometric center of the

raft, over the frequency range with significant wave energy. As expected, the decoupled heave RAO was less than one, while the coupled heave RAO was larger than one. Since the life raft is not a rigid body, the transformation of motions to the geometric center of the raft is questionable. Also, occupants are sitting at the circumference of the raft. So, motion measured at the circumference would more closely represent the motions that occupants would experience. Therefore, heave results presented in this report were not translated (i.e. heave was not decoupled).

5. There was very good agreement between the comparison of life raft RAOs (surge, heave, pitch and tow force variation) in regular and irregular waves, throughout the frequency range with significant wave energy. This demonstrated that irregular waves can be used effectively to determine the motion response and tow force response of the life raft without running individual regular waves. It also showed in high tow speed cases, where the irregular wave was completed in two separate runs due to limited tank length, the irregular wave and motion data could be spliced together for analysis, as if it is run as one wave.

6. In waves, life raft surge and pitch motions were speed independent. Life raft heave tended to decrease with increased tow speed. The lower heave response at high tow speed may be due to wave plowing. At low speed, the raft may tend to ride with the waves. Tow force variation about its mean tended to increase with tow speed.

7. In waves, manikin ballast consistently resulted in higher mean tow force and tow force variation about its mean. The difference in tow force variation between manikin ballast and water bag ballast increased with speed. This implies that direct comparison of effects, such as floor inflation, weight distribution, drogue deployment etc., need to be made with the same ballast type.

8. In waves, floor inflation increased tow force variations significantly in all cases (even and uneven weight distribution; drogue and no drogue). Drogue deployment had no measurable effect on tow force variation. With floor inflated, uneven weight distribution increased tow force variation slightly. With floor not inflated, weight distribution has no significant effect. The increase in tow force variation due to floor inflation was significantly more than drogue deployment or weight distribution.

9. In waves, drogue deployment contributed the most to the increase in mean tow force. At 3 knots, drogue deployment increased mean tow force by about 200 N. In comparison, even weight distribution increased mean tow force by about 100 N with and without floor inflation. Floor inflation increased mean tow force by about 100 N.

10. In waves, it appeared that in test cases where there was high tow force variation, there was low raft surge response and vice versa. The higher tow force variations may be due to wave plowing, which tends to prevent the life raft from traveling forward, resulting in lower surge response.

    Even distribution and drogue deployment contributed to larger raft surge and floor inflation tended to reduce raft surge.

11. In waves, floor inflation, drogue deployment and even weight distribution significantly increased life raft heave.

12. In waves, raft pitch was very small. Floor inflation and even weight distribution increased raft pitch slightly. With uneven weight distribution and floor not inflated, drogue increased raft pitch.

13. The measured manikin heave motion was about the same as the measured raft heave motion, indicating that the occupants would experience almost all the raft heave motion.

14. The motion sickness dose value predicts that 20% of occupants would vomit after 20 hours in the life raft. The percentage of occupants vomiting is slightly lower at high tow speed.

15. Occupants have a very low risk of injury from life raft towing in the sea state tested.

16. It appeared that weight distribution, floor inflation, drogue, ballast type and tow speed had no major effects on life raft x-y tracks.

8.0 Recommendations

1. Large volumes of water splashed onto the canopy during towing. It is advisable that occupants close the raft entrance covers during towing to minimize the amount of water from entering the raft.

2. In the tests, it was observed that the weight of water splashed on the canopy caused the canopy to collapse. This occurred with raft entrance cover opened and closed. Strengthening the canopy support would reduce this situation.

3. Even with the raft entrance covers closed, water still entered the raft, possibly through spacing between the canopy and the entrance cover. A better waterproof design would minimize this.

4. It is recommended that rafts be supplied with drogues that meet current recommended standards. The drogue supplied with the raft used in this test did not conform to Transport Canada standard. It may also be useful to assess the raft motions and tow force with the series type drogue and Icelandic drogue.

5. The results presented in the report are based on water bag ballast. As the results show, there is significant difference between water bag and manikin ballast. It may be useful to assess the raft motions and tow force with manikin as ballast because it closely reflect the raft load when laden with occupants.

6. The test program did not consider the effects of wind. It may be useful to assess the raft motions and tow force when it is towed in waves and wind. This will be assessed at model scale.

7. Currently IMO regulations only require that the raft be towed in calm water. The results indicated that the raft motions and tow force in waves are quite different from those in calm water, even in a relatively calm sea state such as those tested. To ensure that the towing crafts are capable of towing the life rafts in realistic environment conditions, tow patches are sufficiently strong to withstand the tow loads and occupants motion sickness is minimized, it is recommended that consideration be given to amending the regulations to consider the effect of waves in life raft tow tests.

8. The current tests were conducted in relatively calm sea state. In actual rescue situations, it is quite possible that towing may be conducted at higher sea states. Therefore, it is recommended that further tow tests be conducted at more severe sea states with waves and wind.

9.0 References

International Standard ISO 2631-1:1997 “Mechanical Vibration and Shock - Evaluation of human exposure to whole-body vibration”.

Life Saving Appliances 2003 Edition, International Marine Organization.

Standards for Life Rafts and Inflatable Rescue Platforms, Transport Canada, Marine Safety Directorate, TP 7321E, 1992.

Forman, E.J. (1983), “Full Scale Trials of Inflatable Liferafts”, International Conference on Marine Survival Craft, Paper #3.

Babardson, H.R. (1983), “Inflatable Liferafts and Their Drift Anchors”, Proceedings of the International Conference on Marine Survival Craft, Paper #8.

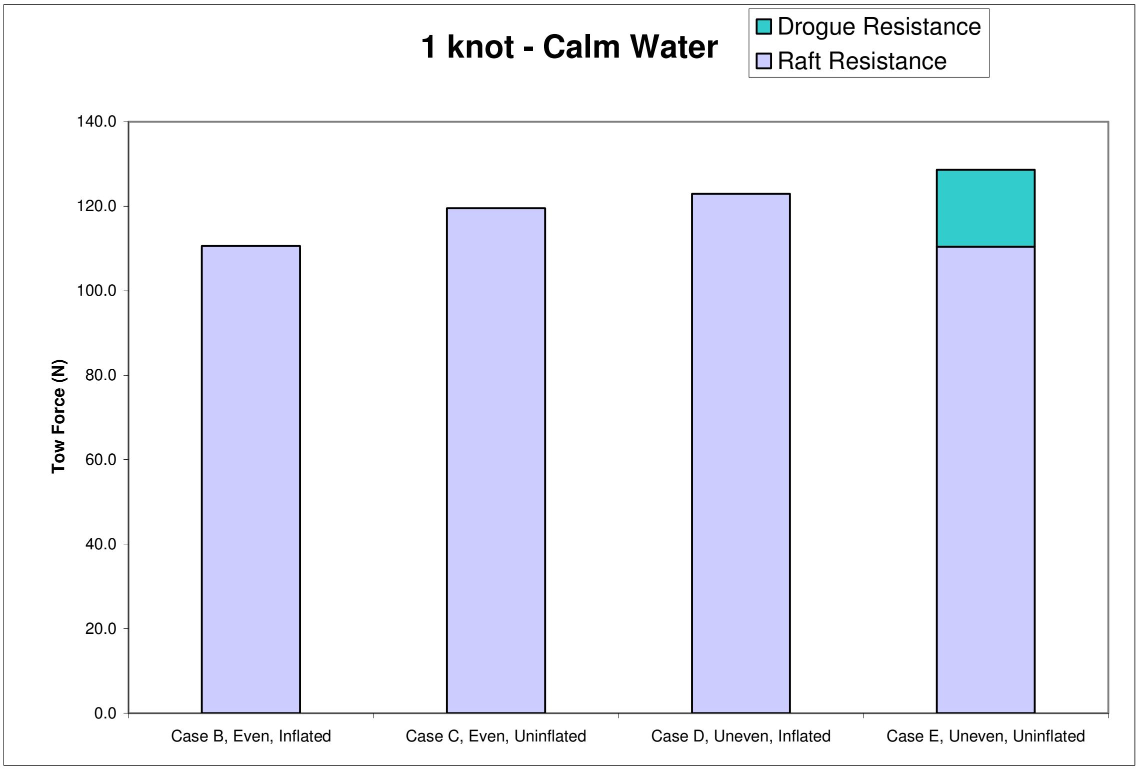
Cole, LR and Wills, JAB (1981), “An Investigation of Model Liferaft Stability in Combined Wind and Waves”, National Maritime Institute, NMI R123

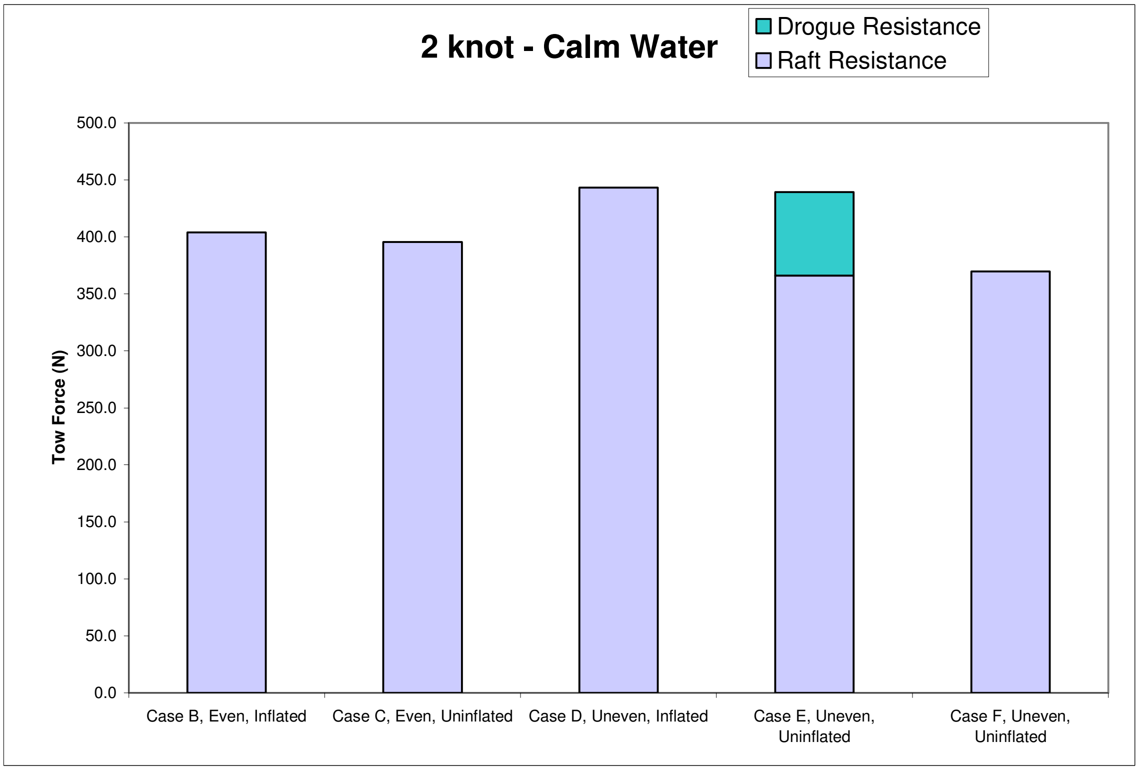
McKenna, R.F. and Paulin, M.J. (1997), “Performance of Inflatable Life Rafts and Drogues in Wind and Waves”, Volumes 1 and 2, C-Core, Memorial University of Newfoundland, Canada. C-Core Publication 96-C24

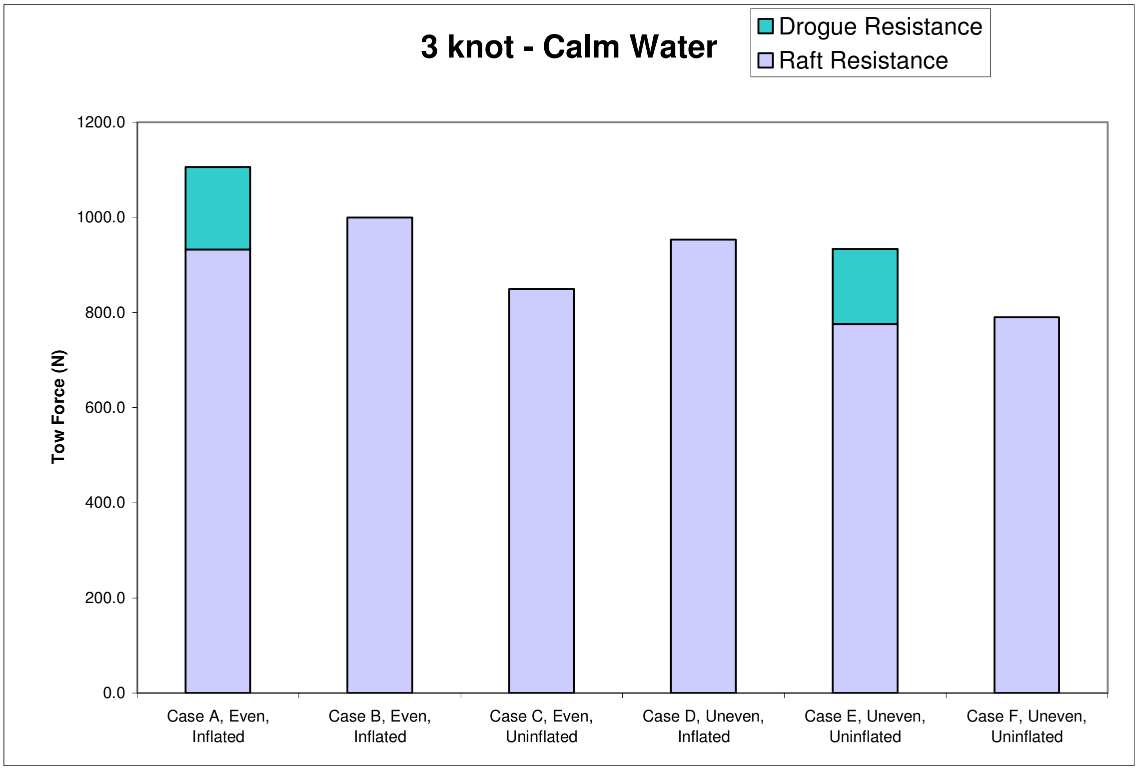
Hardiman, K.C. and Harris, C. (1996), “Final Test Report on Capsizing Model Tests Conducted on a 1:7 Scale Model of an Inflatable Life Raft”, Marineering Ltd., report prepared for Fleet Technology Ltd., 24p.

Appendix A

Lift raft towing results in calm water

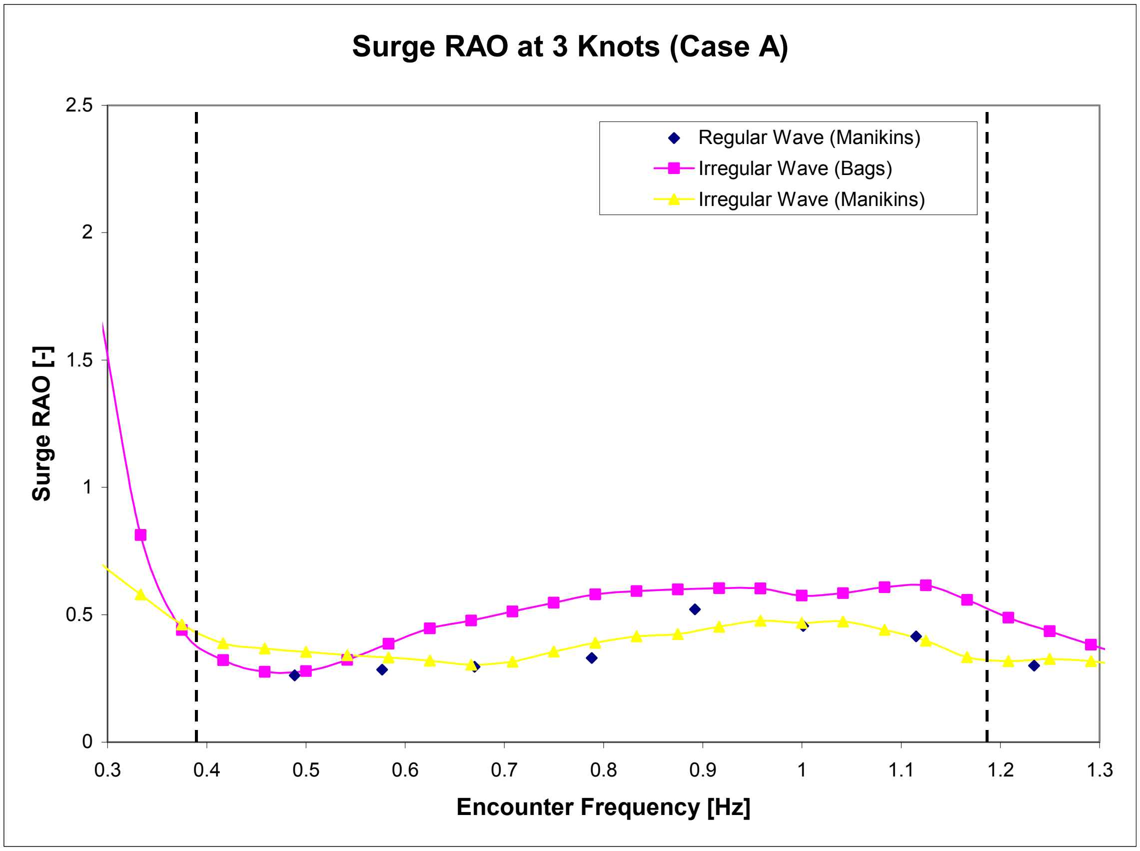

1 knot - Calm Water
Drogue Resistance
Raft Resistance
Tow Force (N)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Case B, Even, Inflated
Case C, Even, Uninflated
Case D, Uneven, Inflated
Case E, Uneven, Uninflated

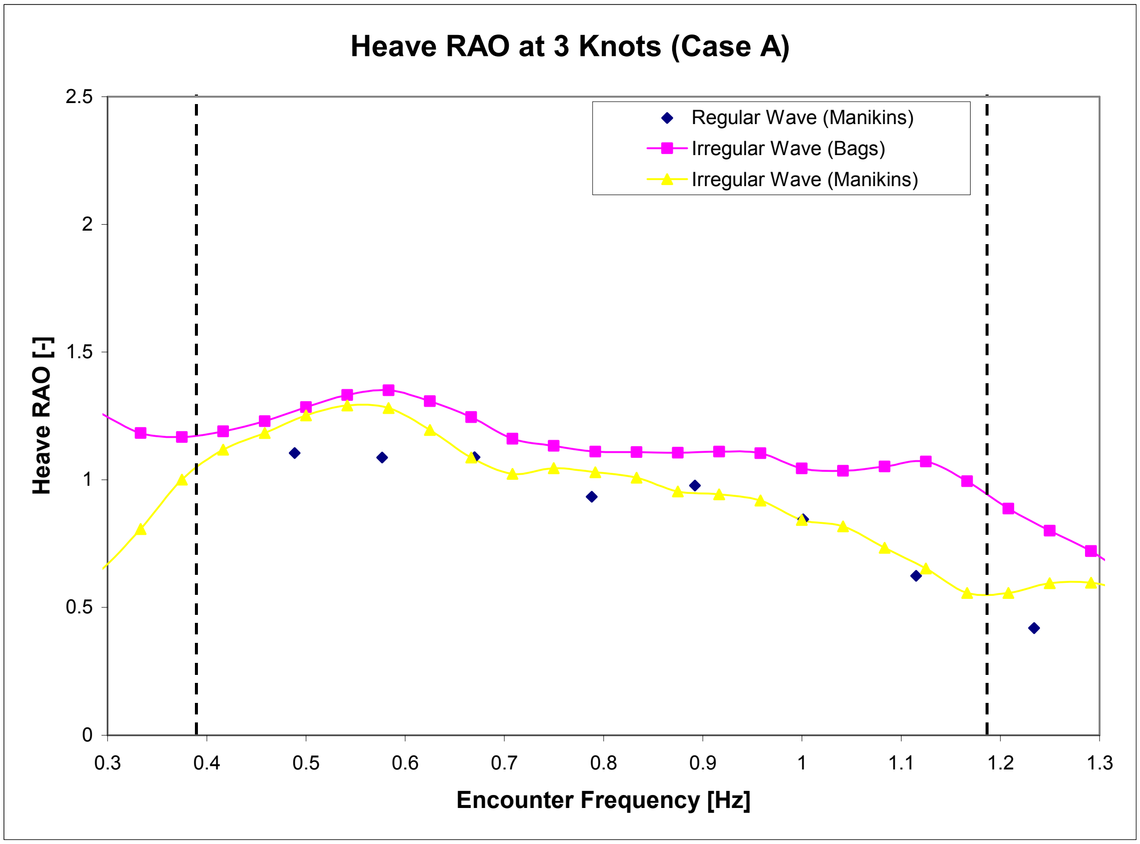

2 knot - Calm Water
Drogue Resistance
Raft Resistance
Tow Force (N)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Case B, Even, Inflated
Case C, Even, Uninflated
Case D, Uneven, Inflated
Case E, Uneven, Uninflated
Case F, Uneven, Uninflated

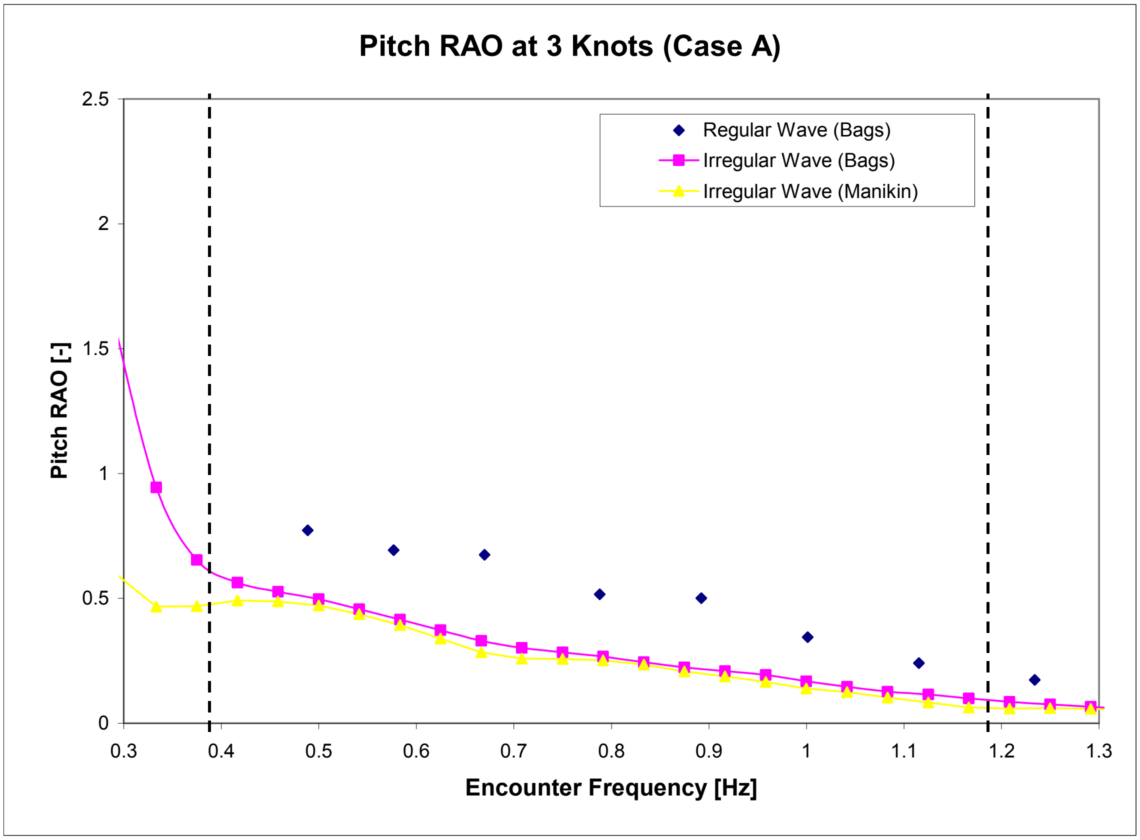

3 knot - Calm Water
Drogue Resistance
Raft Resistance
Tow Force (N)
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
Case A, Even, Inflated
Case B, Even, Inflated
Case C, Even, Uninflated
Case D, Uneven, Inflated
Case E, Uneven, Uninflated
Case F, Uneven, Uninflated

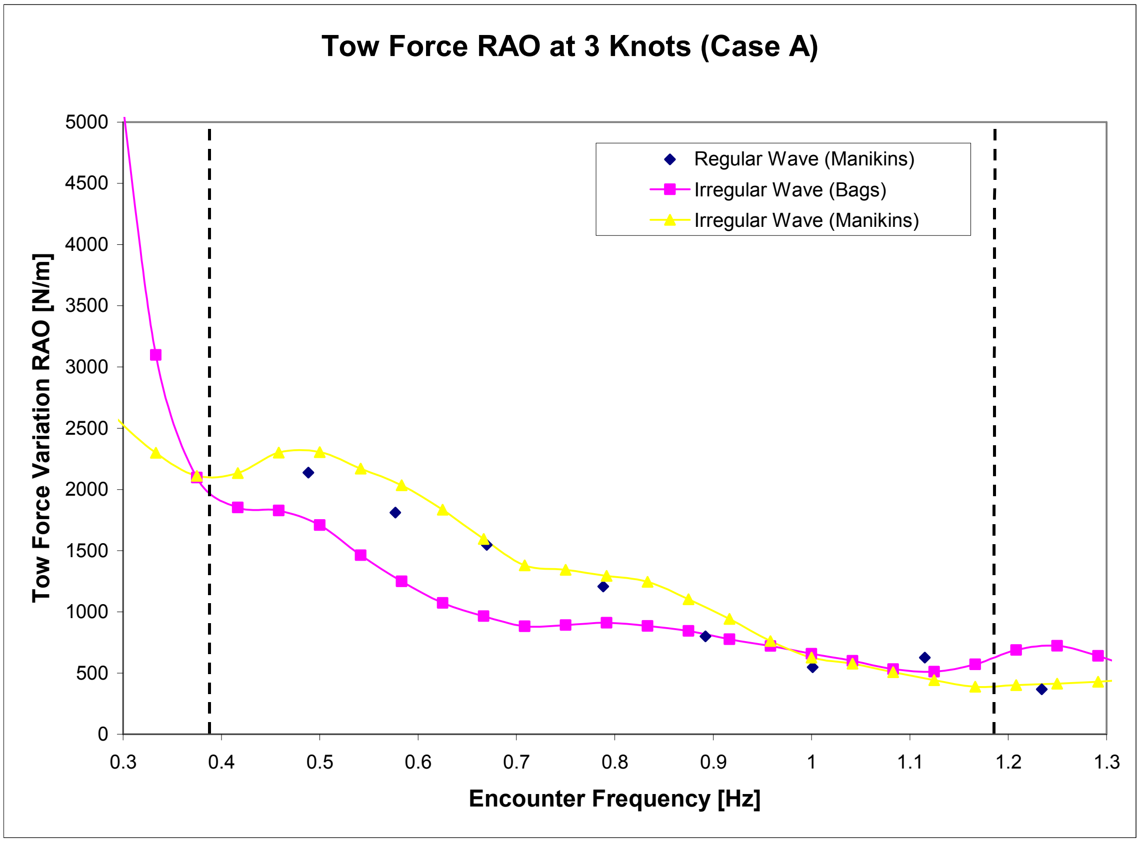
Appendix B

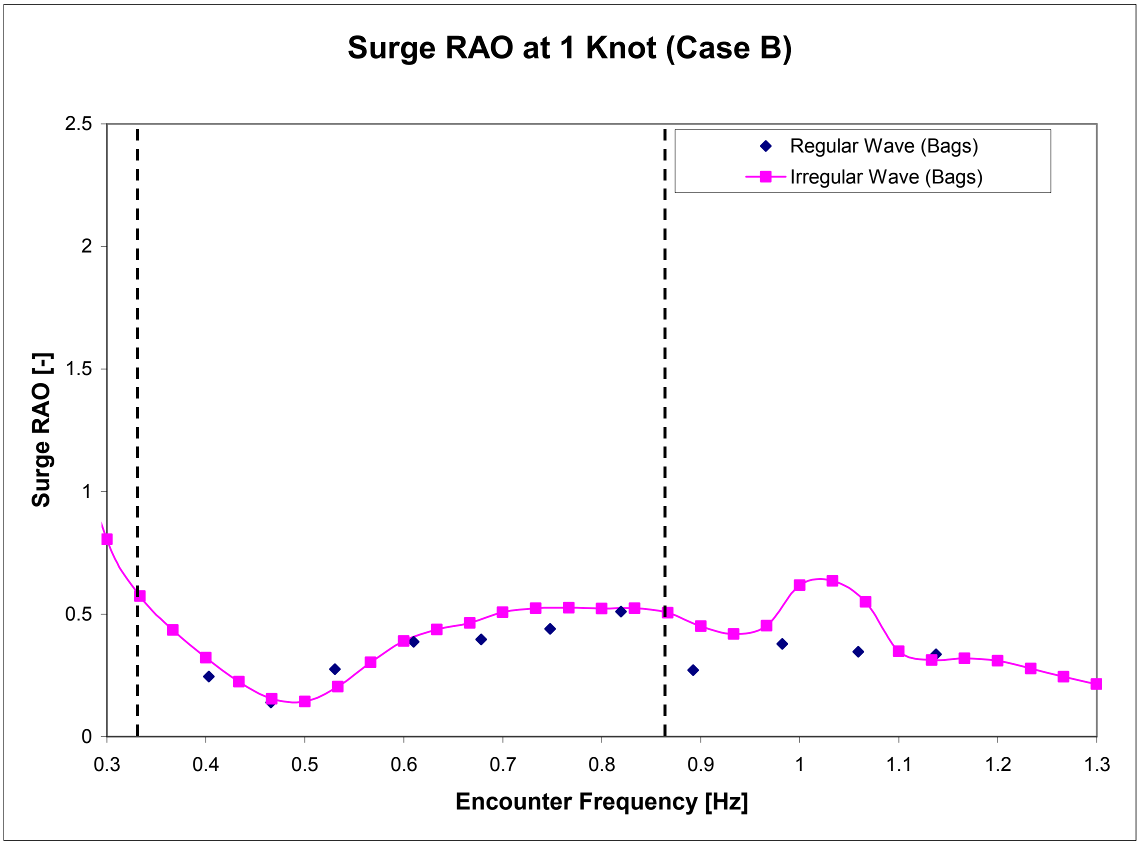
Comparison of life raft motion and tow force variation RAO in regular and irregular waves.

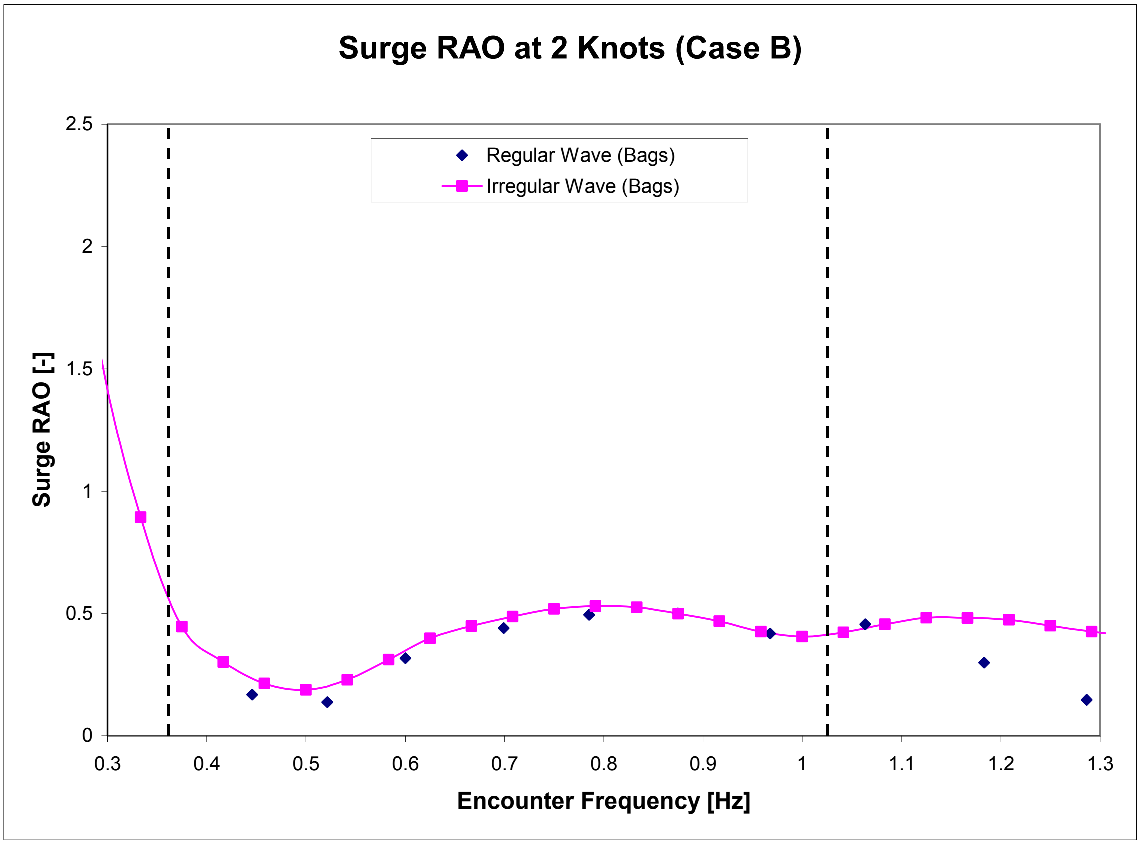

Surge RAO at 3 Knots (Case A)
Surge RAO [-]
Encounter Frequency [Hz]
Regular Wave (Manikins)
Irregular Wave (Bags)
Irregular Wave (Manikins)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

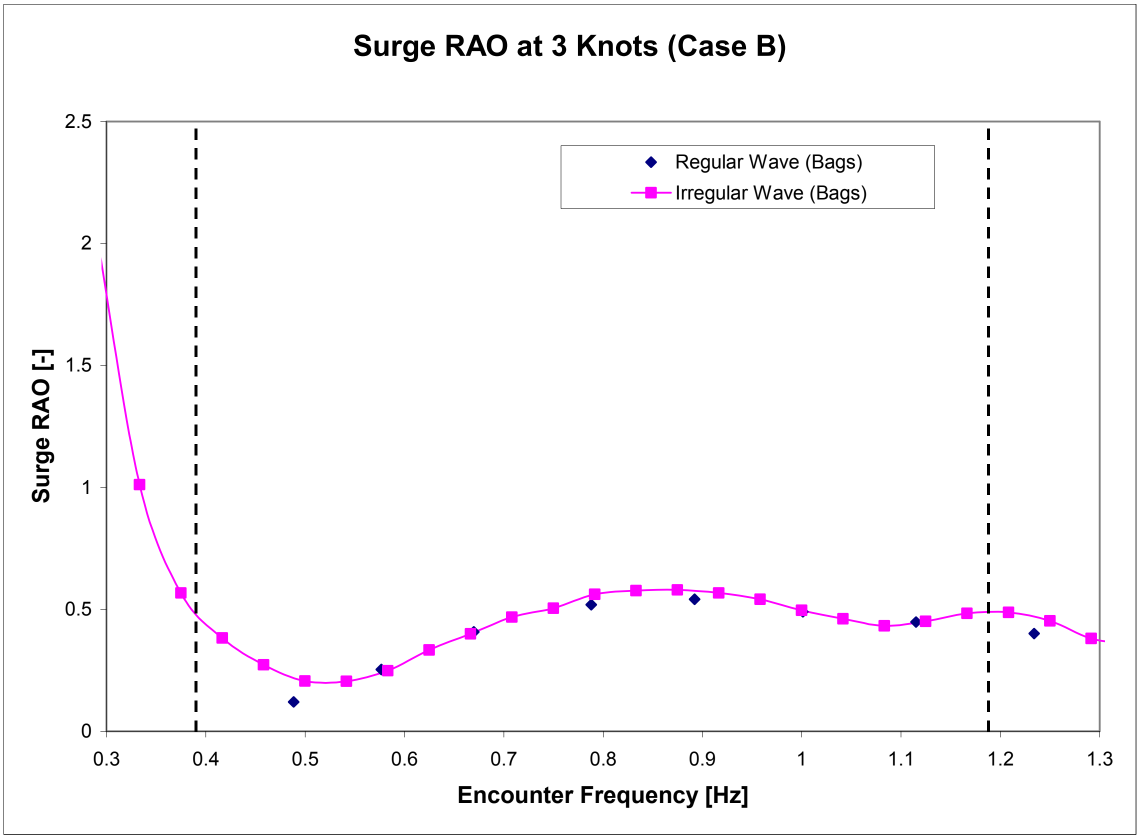

Heave RAO at 3 Knots (Case A)
Heave RAO [-]
Encounter Frequency [Hz]
Regular Wave (Manikins)
Irregular Wave (Bags)
Irregular Wave (Manikins)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

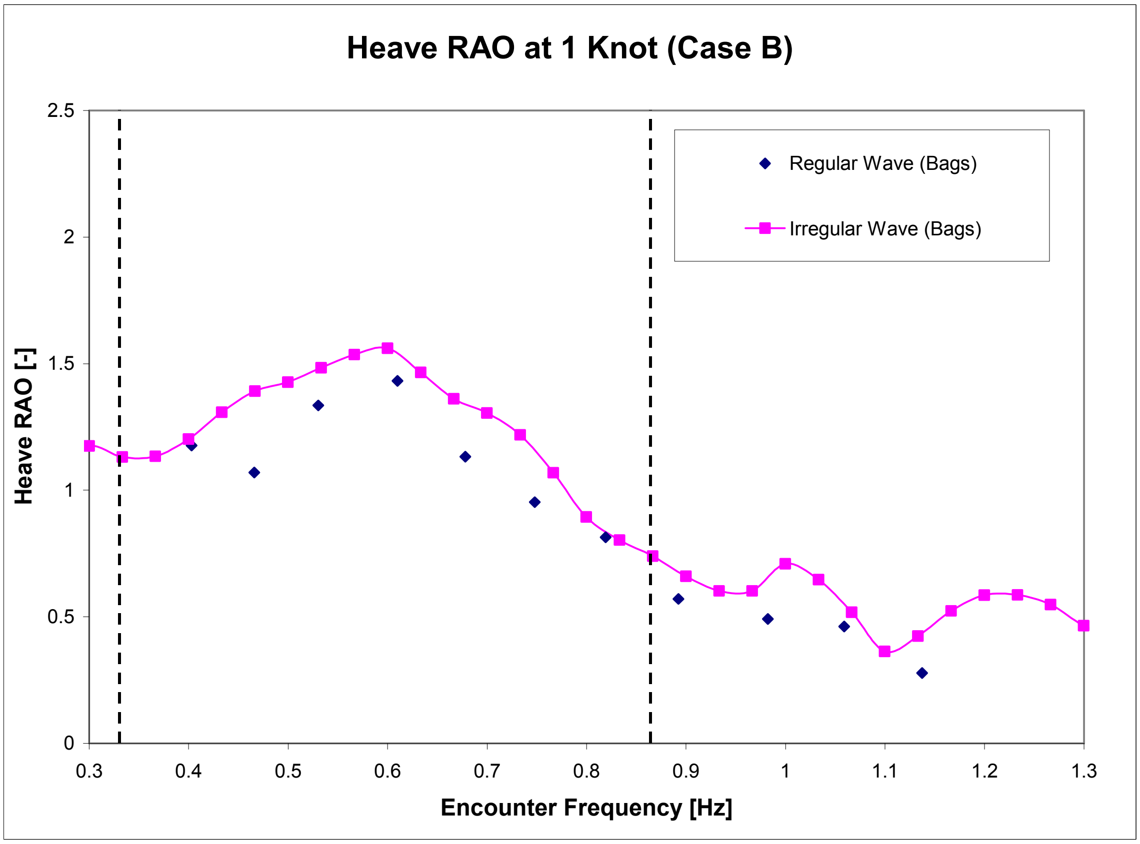

Pitch RAO at 3 Knots (Case A)
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikin)

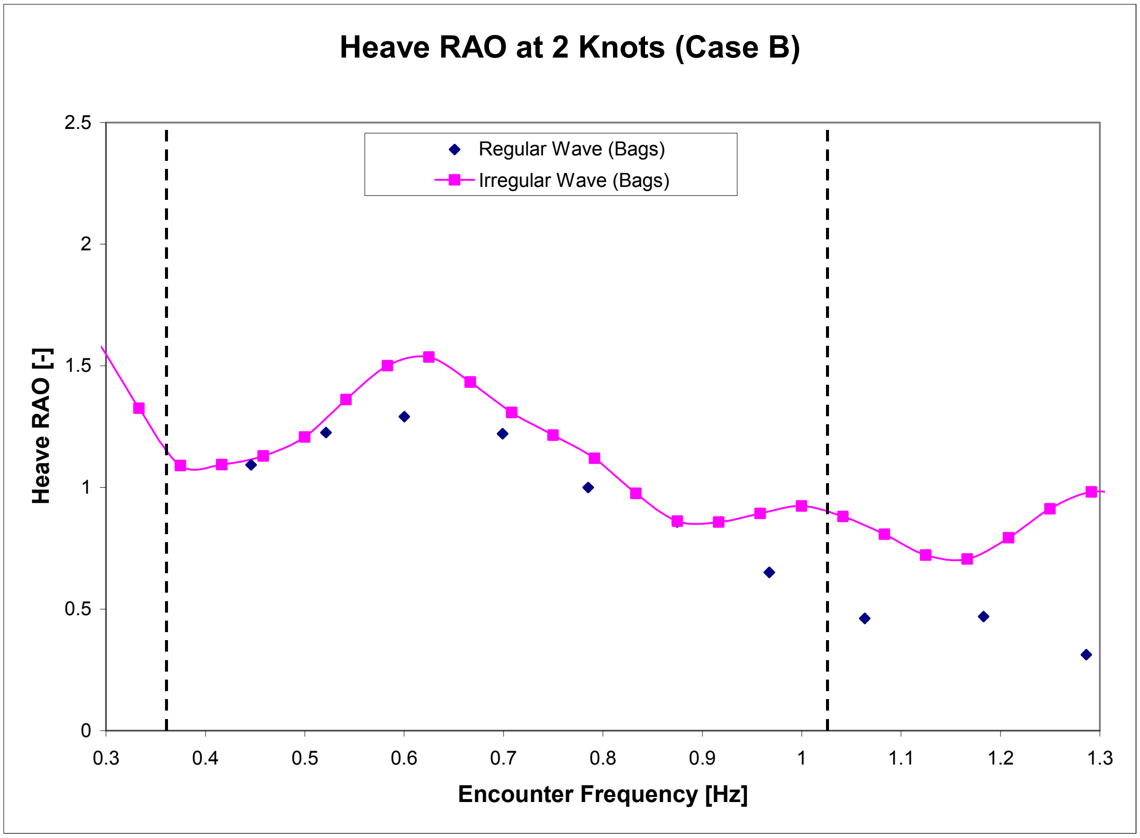

Tow Force RAO at 3 Knots (Case A)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Manikins)
Irregular Wave (Bags)
Irregular Wave (Manikins)

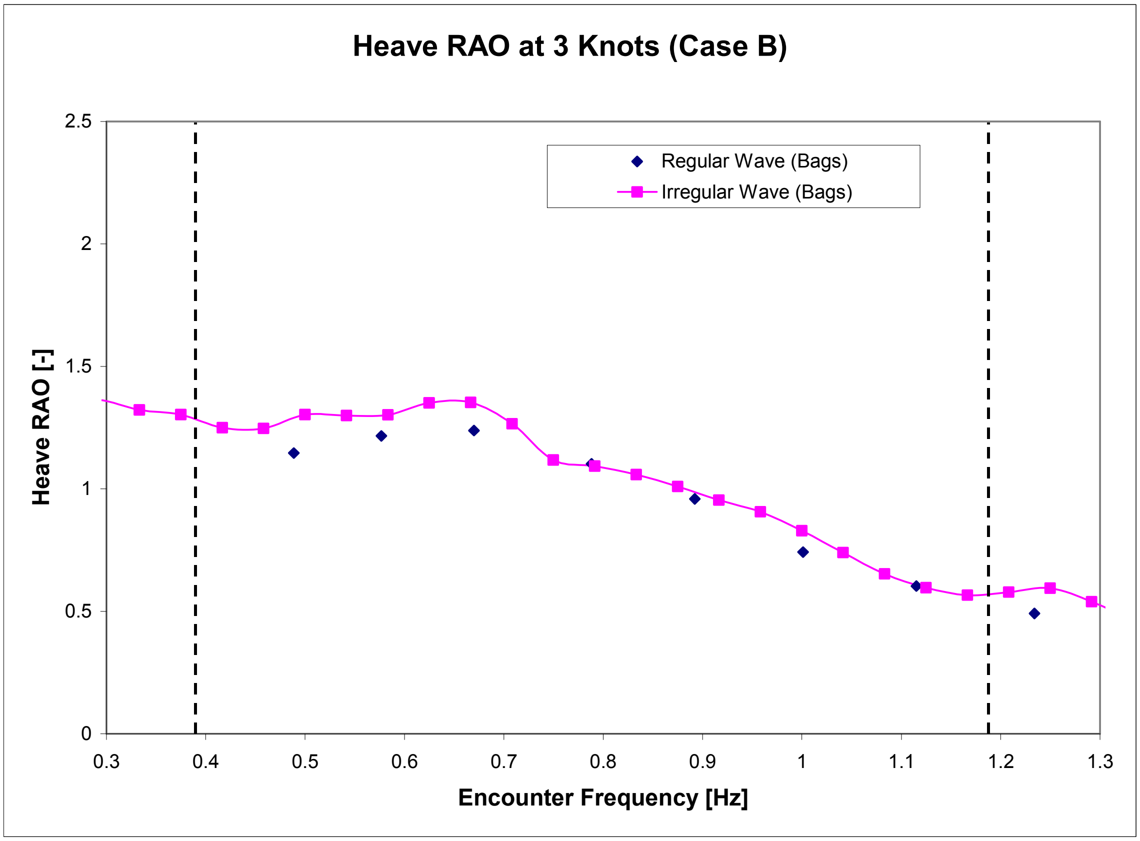

Surge RAO at 1 Knot (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

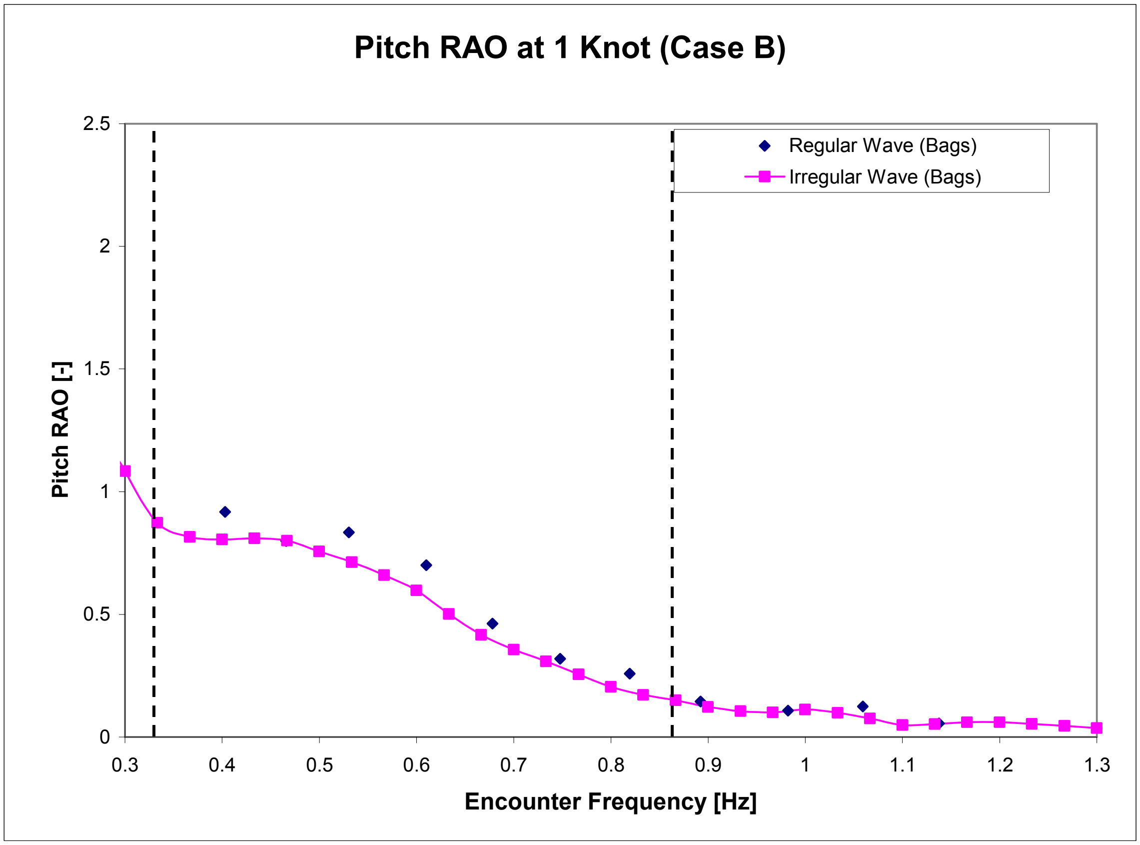

Surge RAO at 2 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

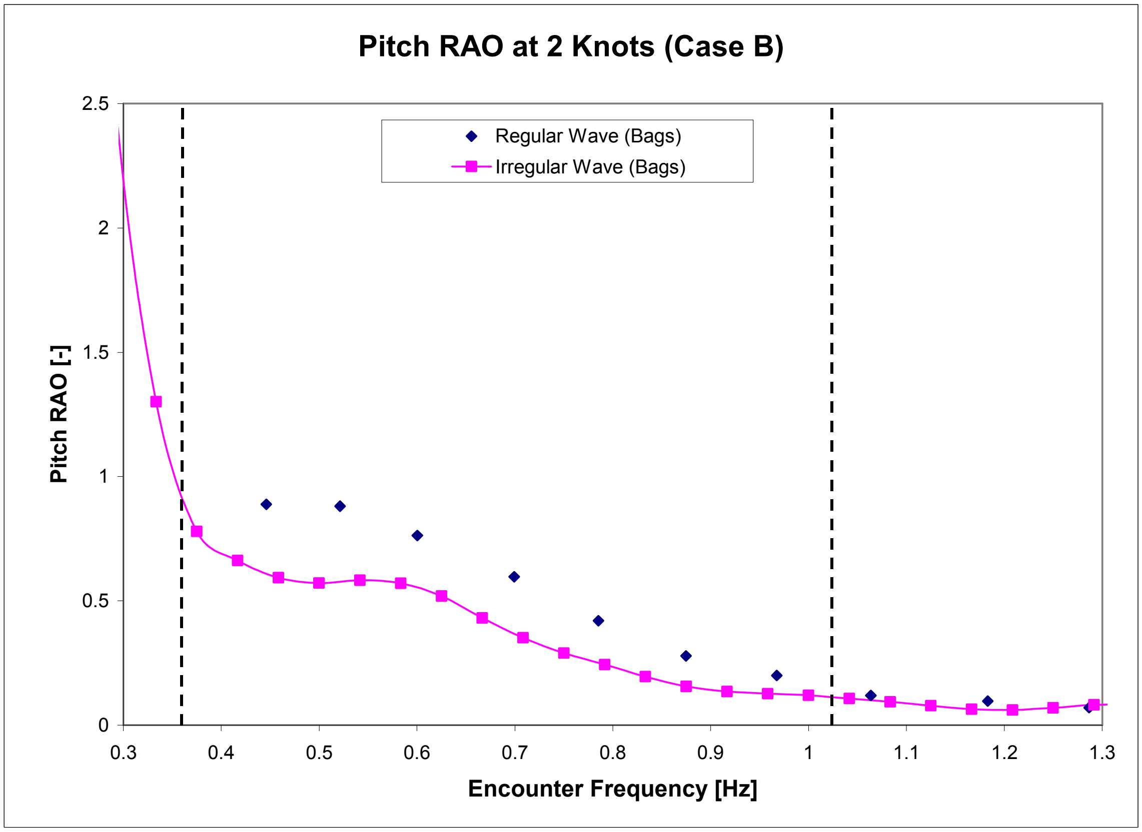

Surge RAO at 3 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

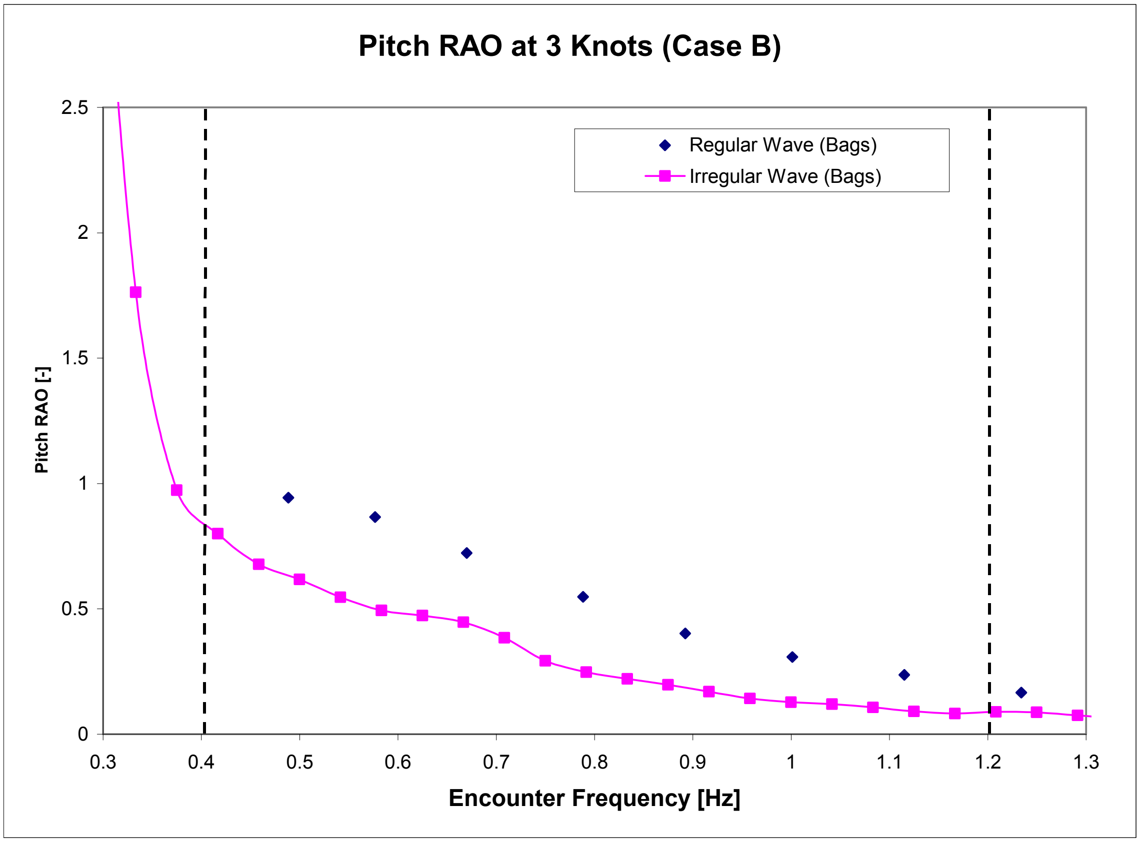

Heave RAO at 1 Knot (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

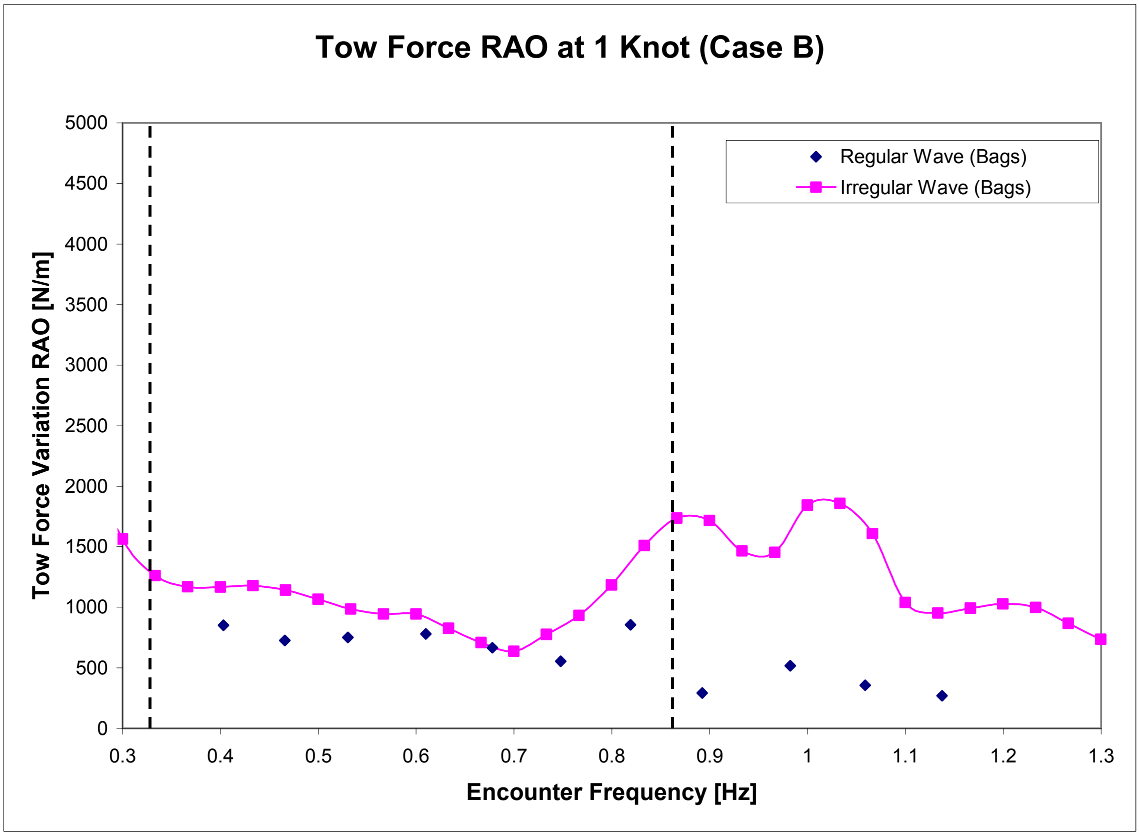

Heave RAO at 2 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

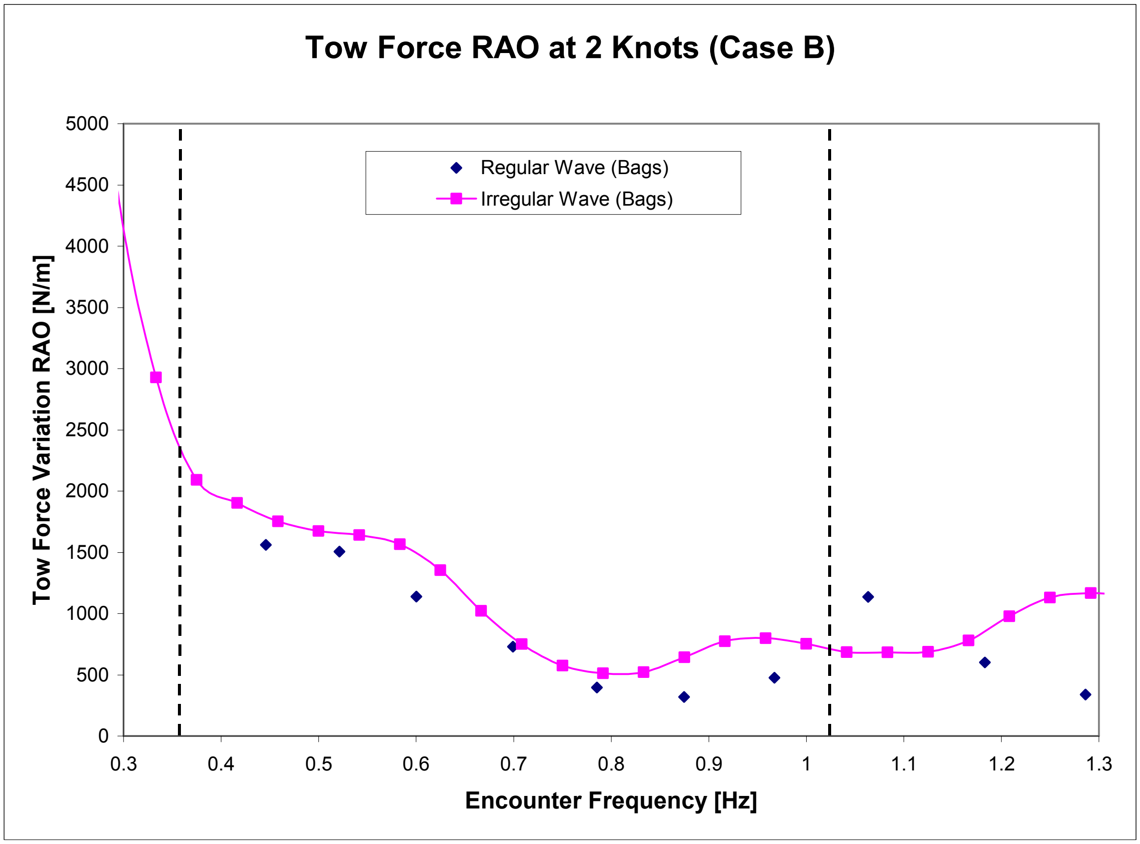

Heave RAO at 3 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

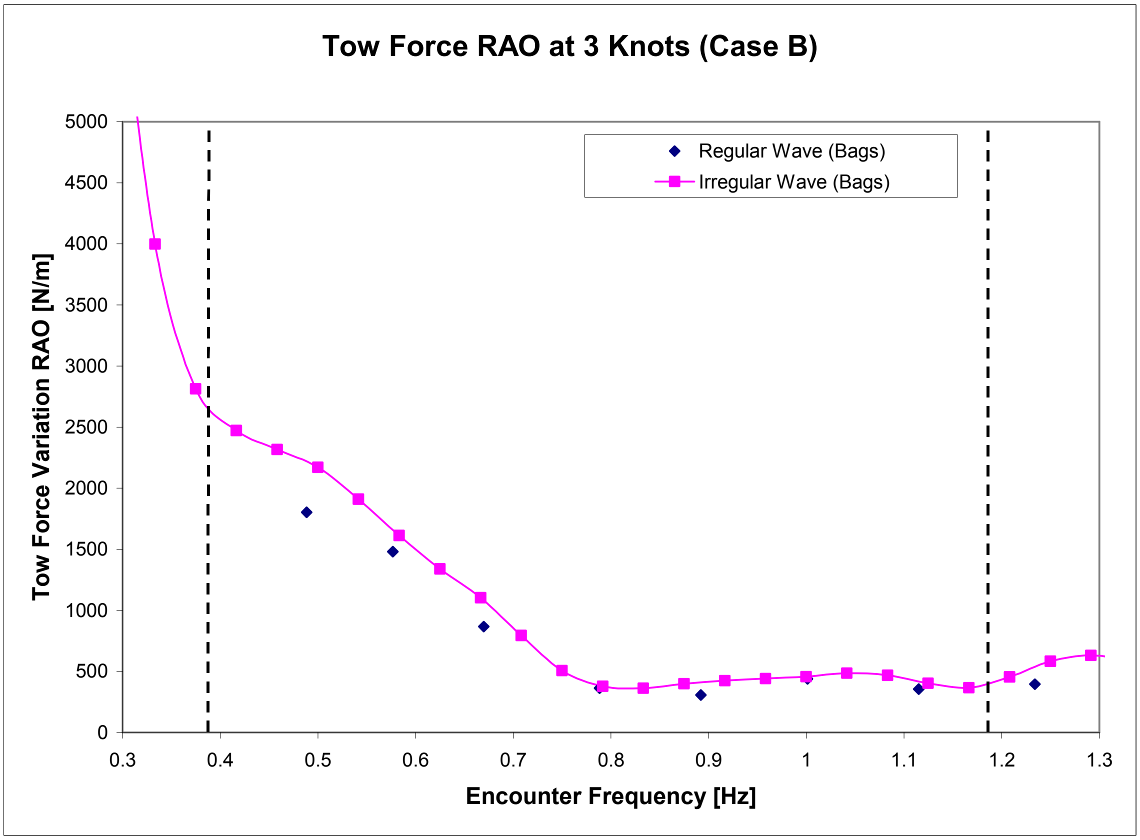

Pitch RAO at 1 Knot (Case B)

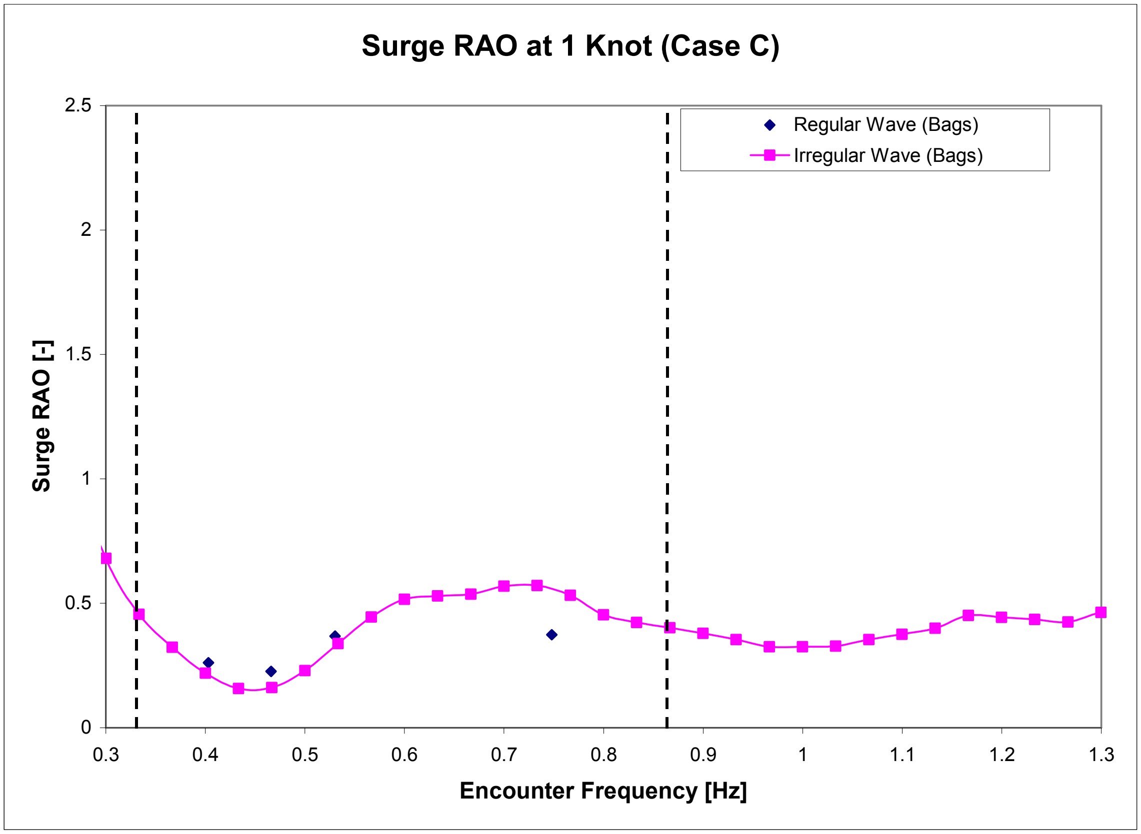

Pitch RAO at 2 Knots (Case B)

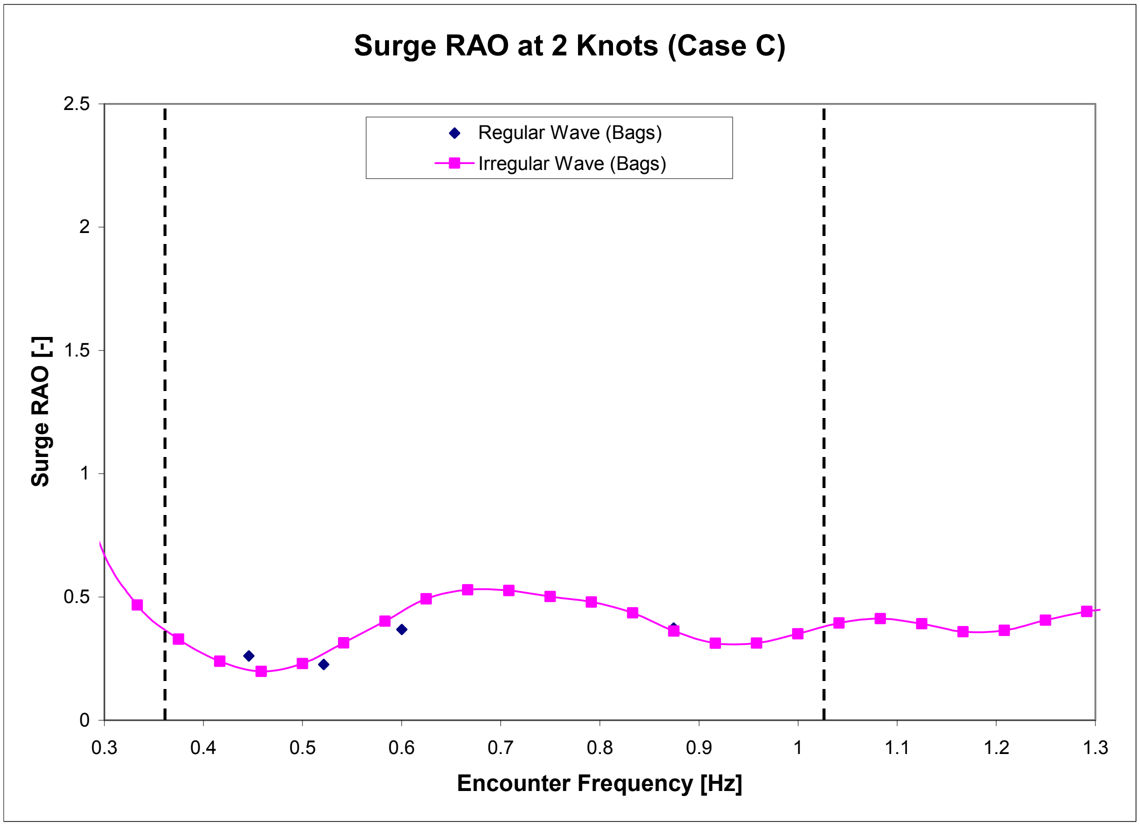

Pitch RAO at 3 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

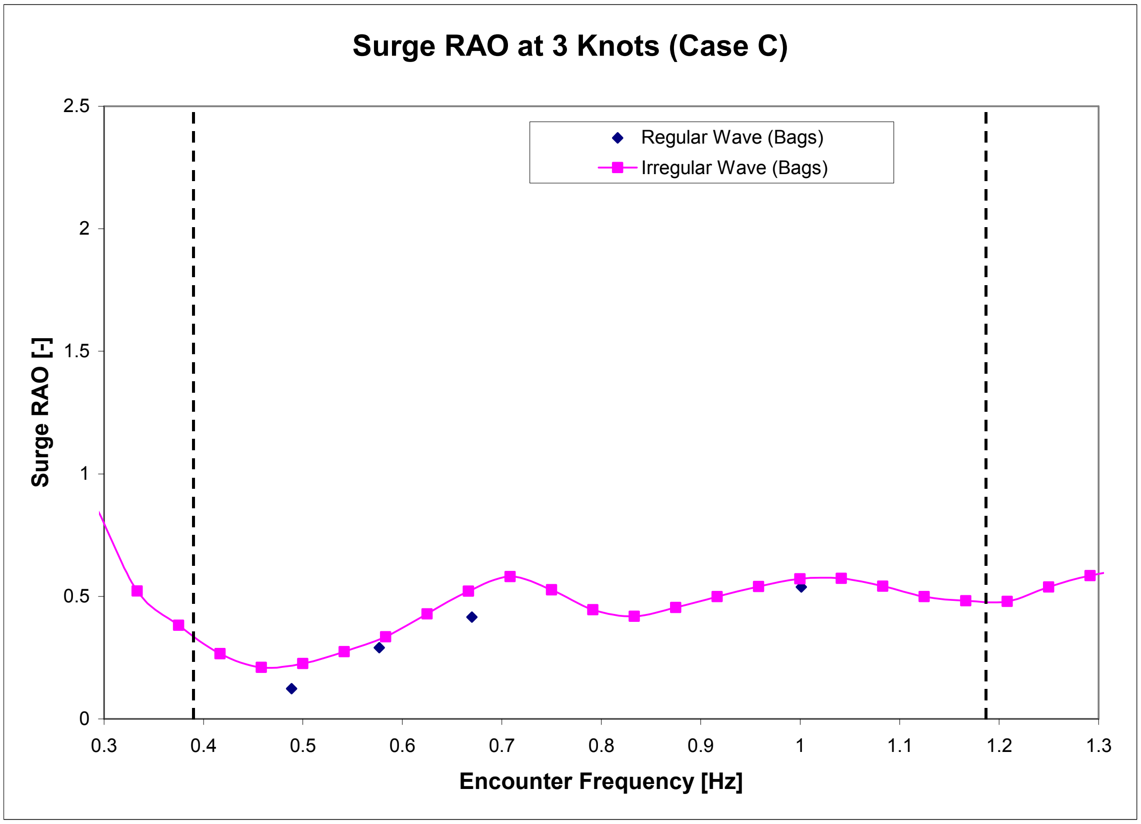

Tow Force RAO at 1 Knot (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

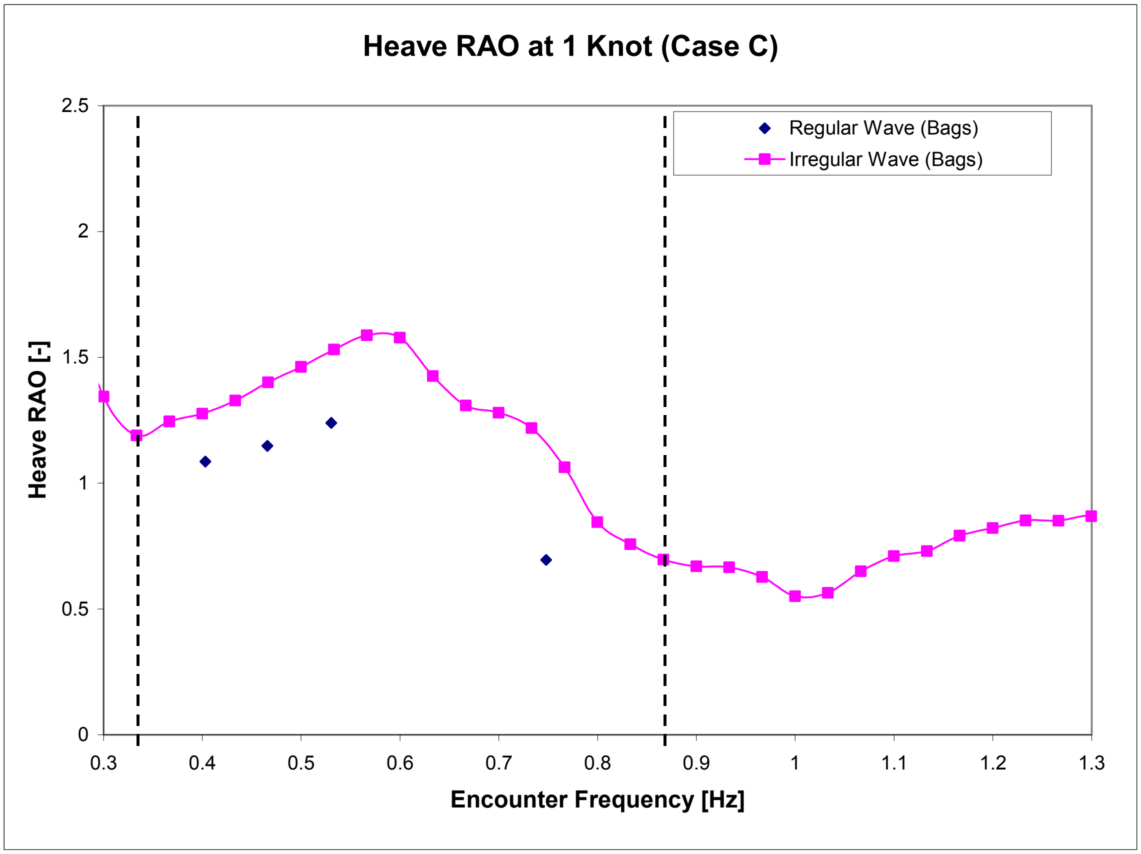

Tow Force RAO at 2 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

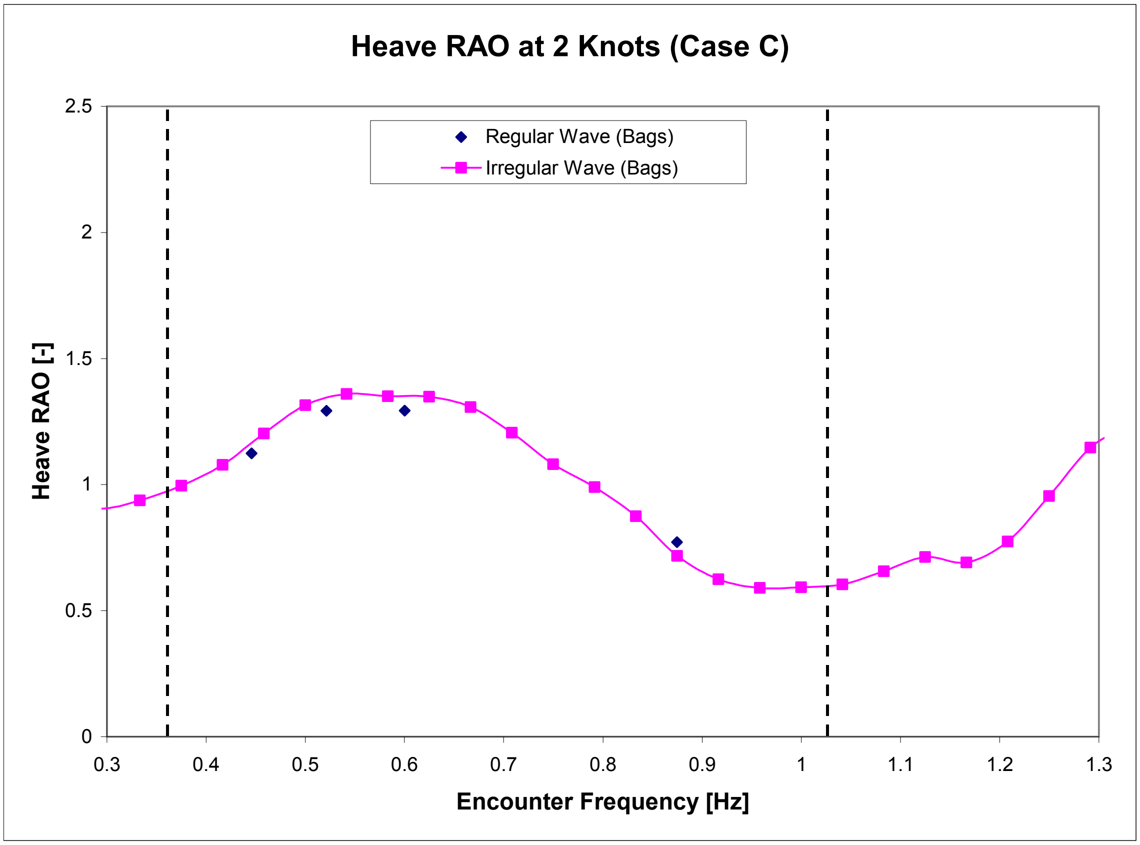

Tow Force RAO at 3 Knots (Case B)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

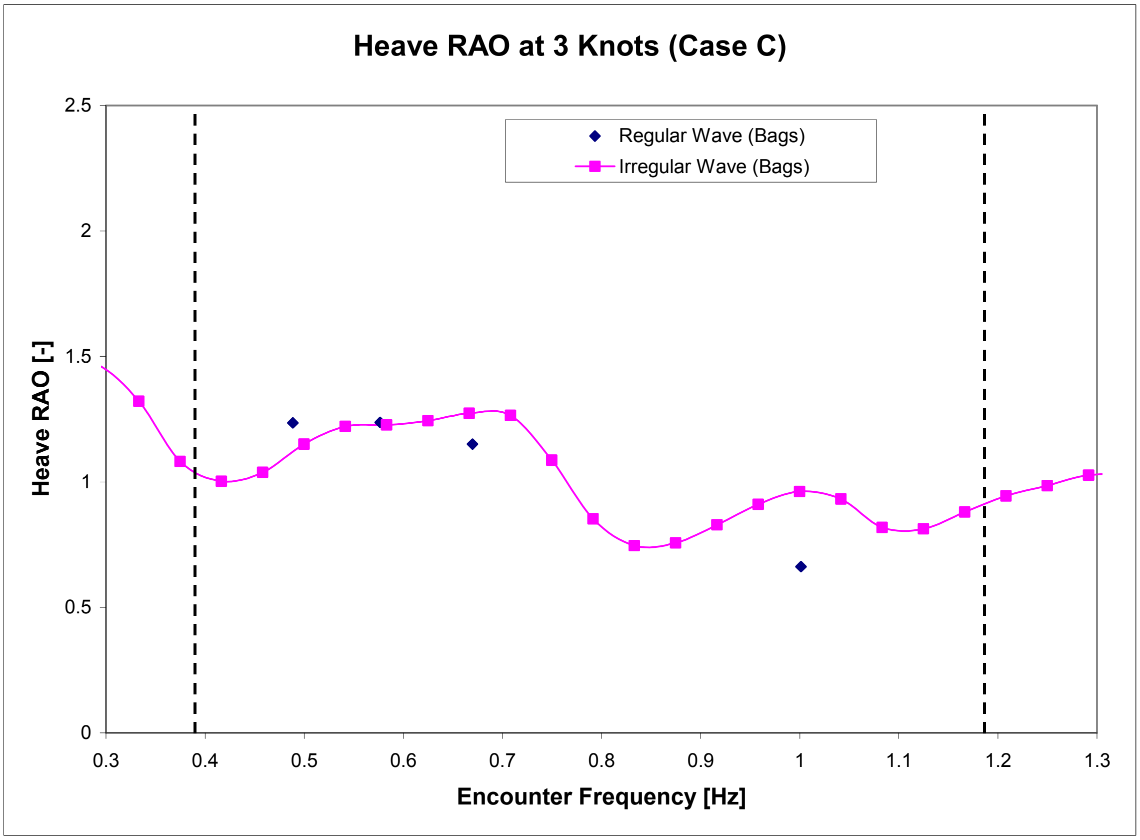

Surge RAO at 1 Knot (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

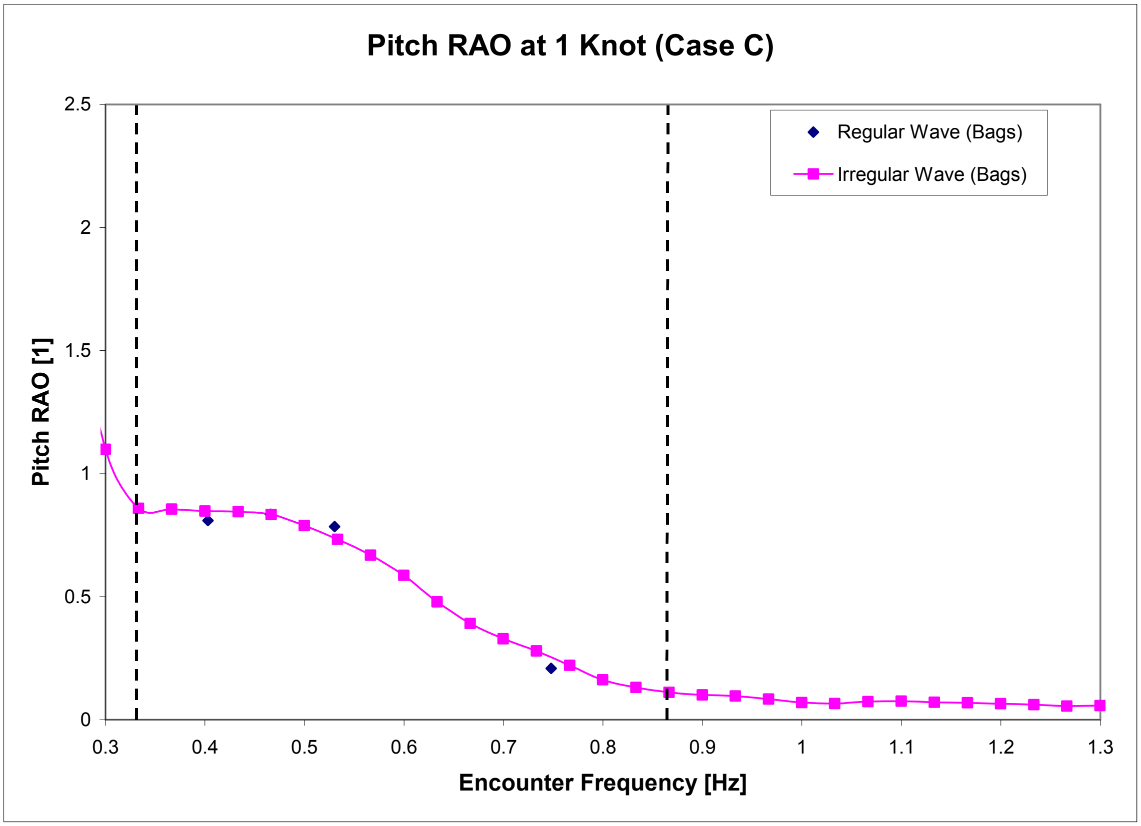

Surge RAO at 2 Knots (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

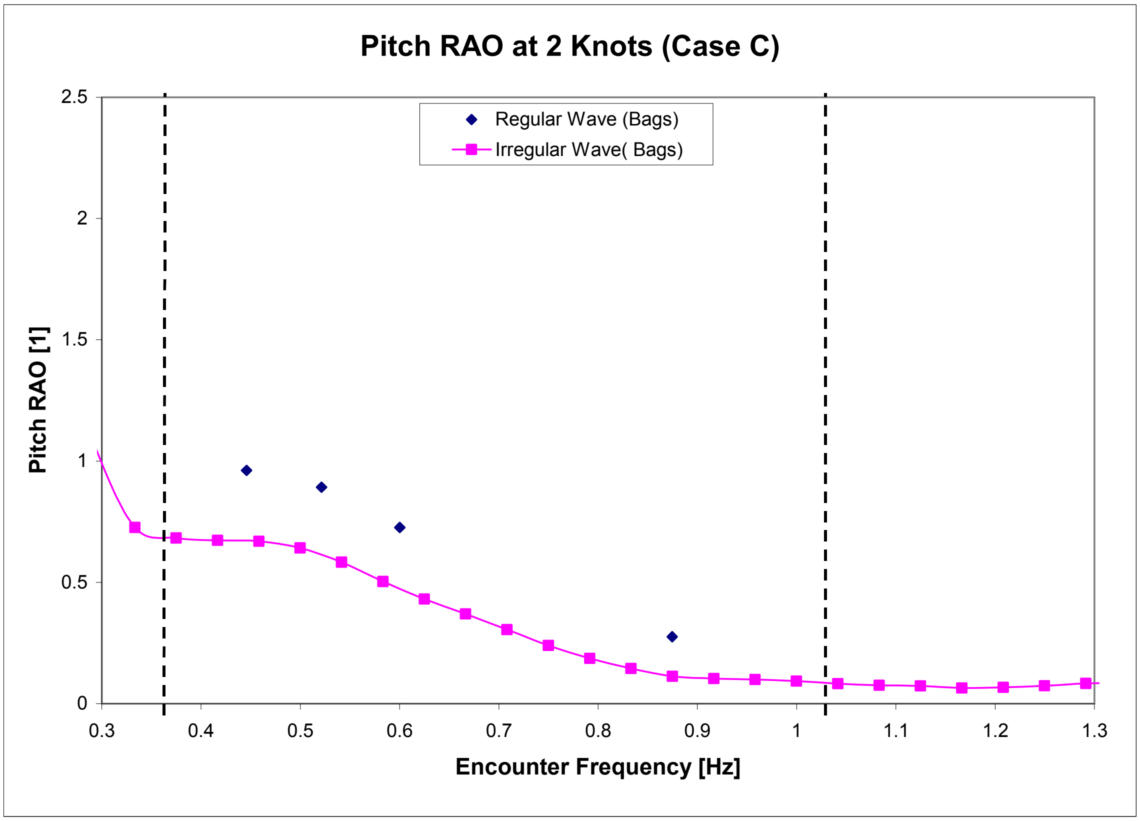

Surge RAO at 3 Knots (Case C)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
◆ Regular Wave (Bags)
■ Irregular Wave (Bags)

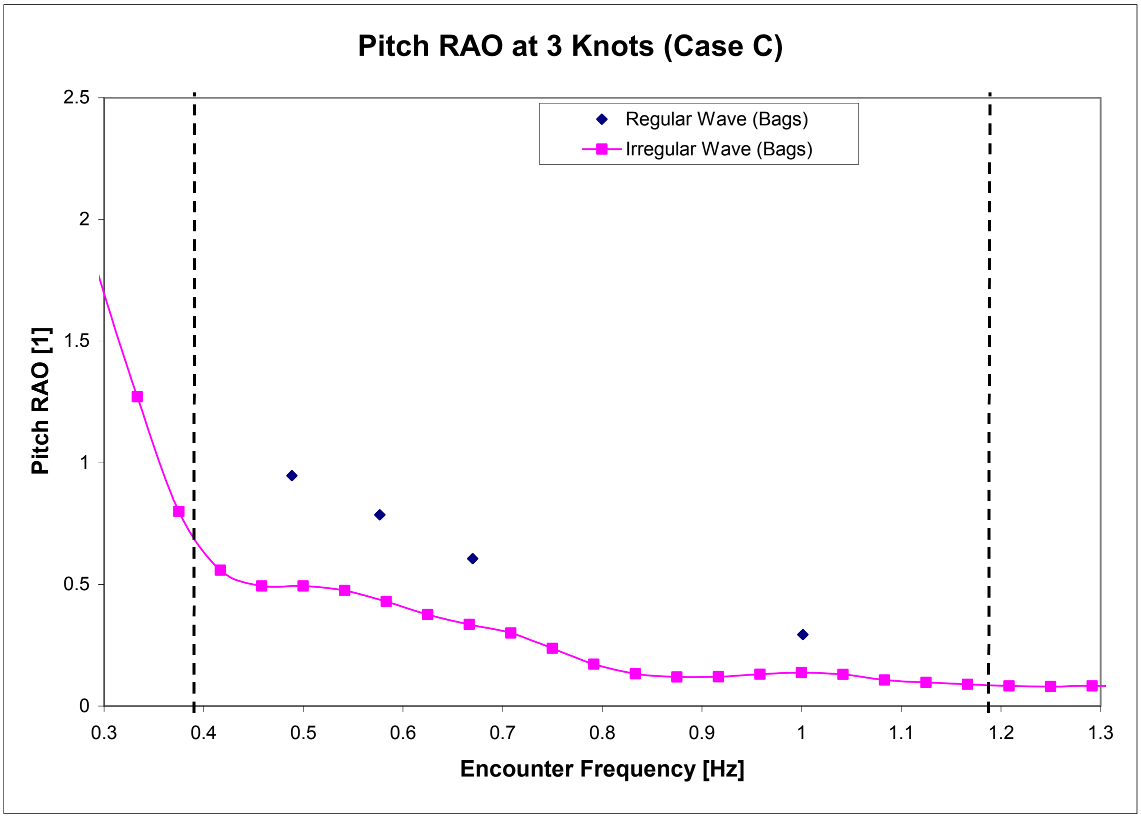

Heave RAO at 1 Knot (Case C)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
◆ Regular Wave (Bags)
■ Irregular Wave (Bags)

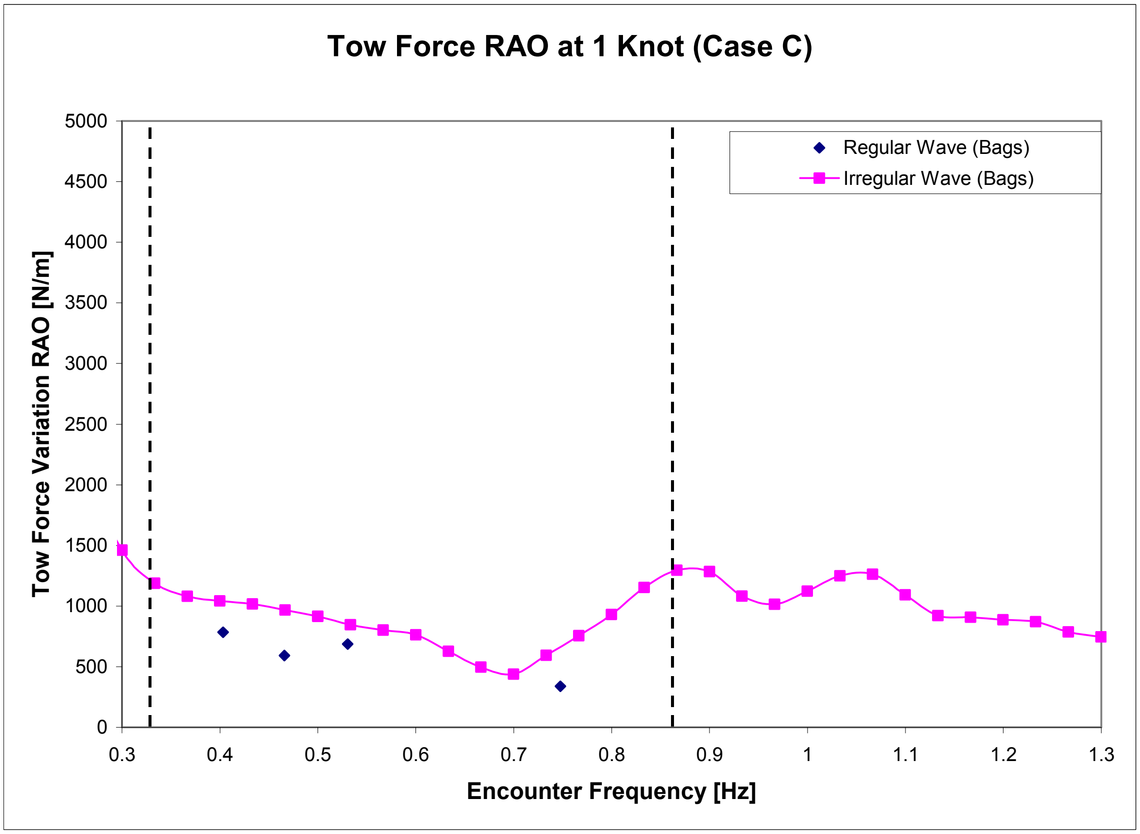

Heave RAO at 2 Knots (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

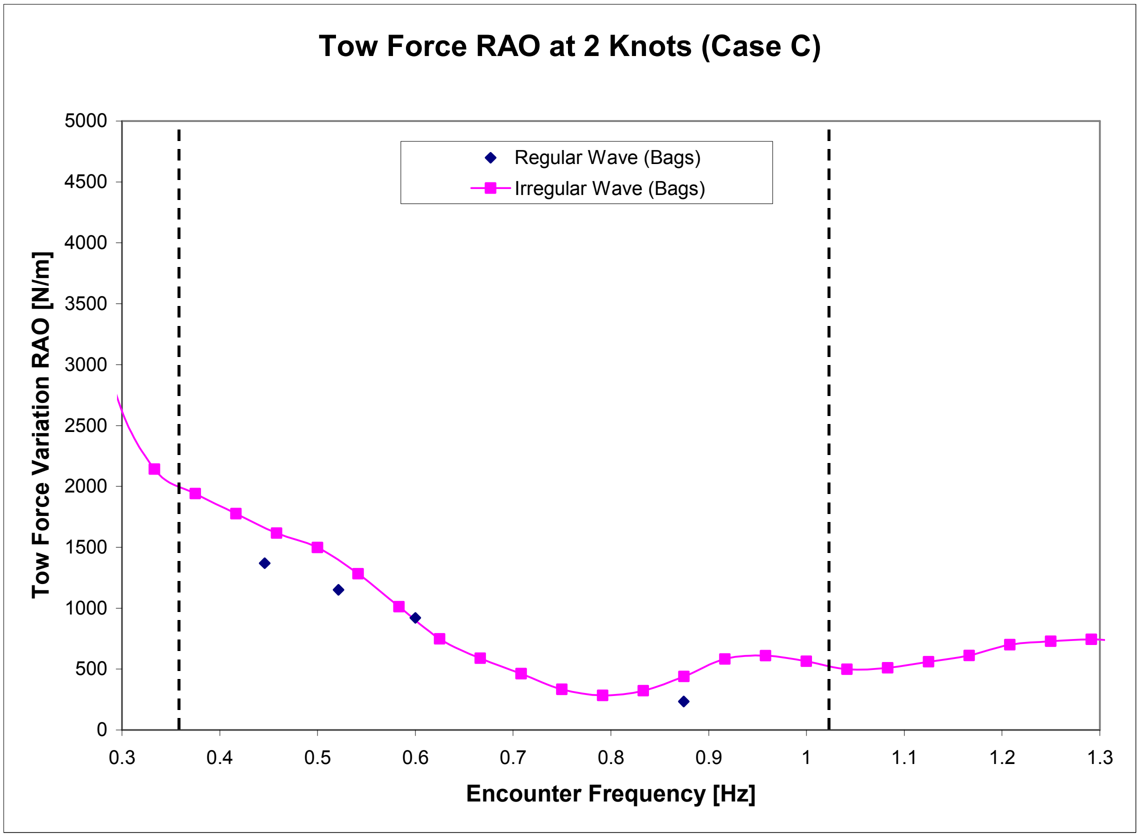

Heave RAO at 3 Knots (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

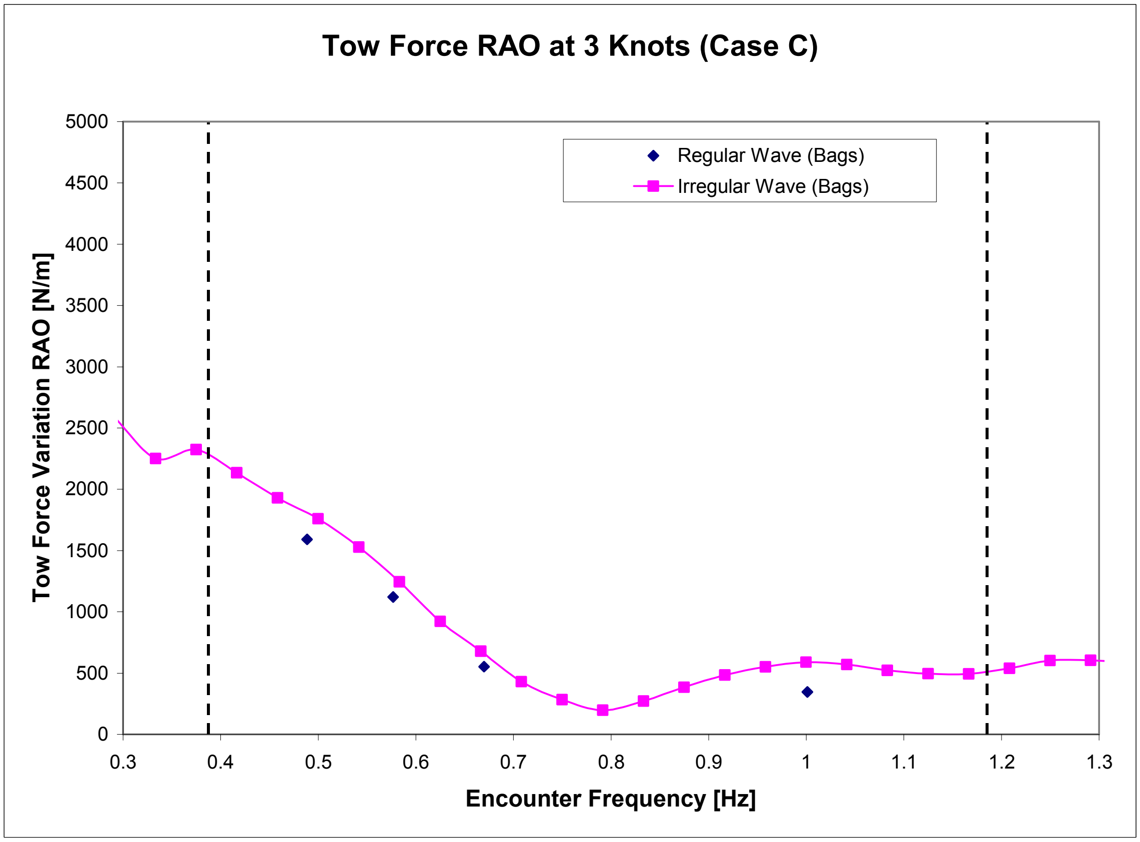

Pitch RAO at 1 Knot (Case C)
Pitch RAO [1]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)

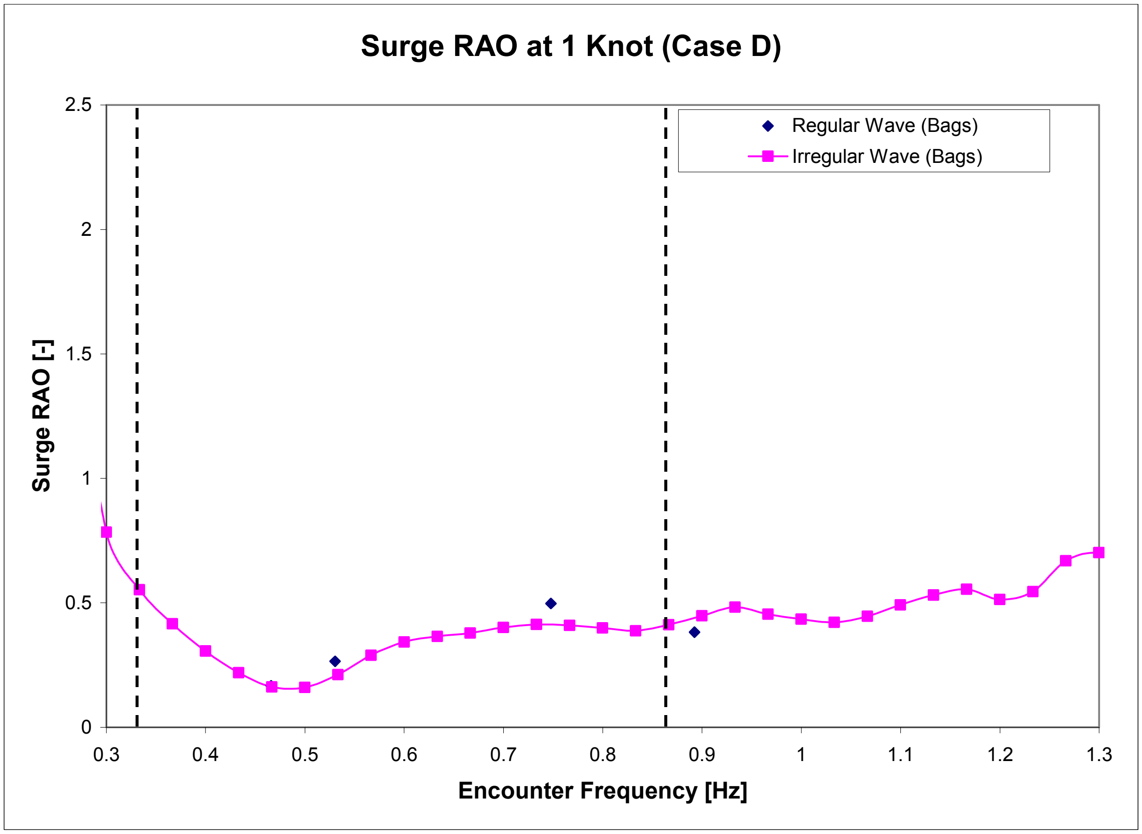

Pitch RAO at 2 Knots (Case C)
Pitch RAO [1]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave(Bags)

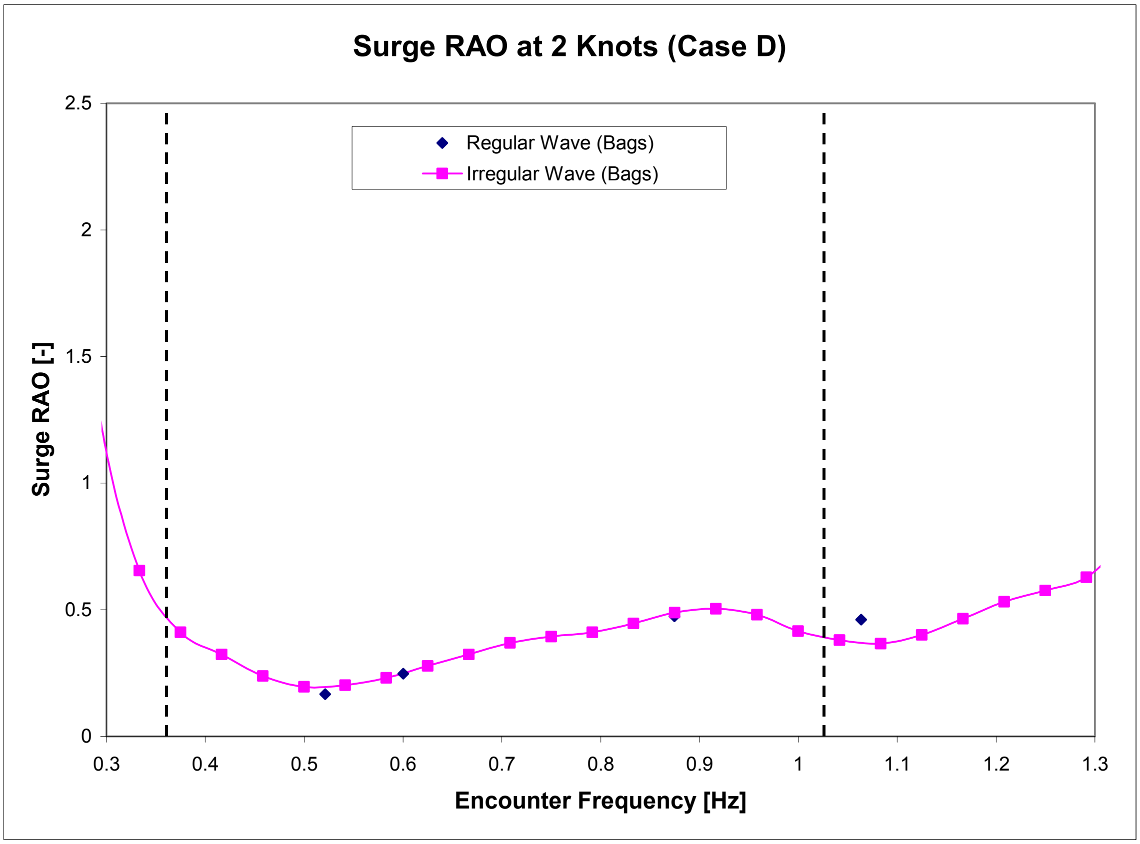

Pitch RAO at 3 Knots (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Pitch RAO [1]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

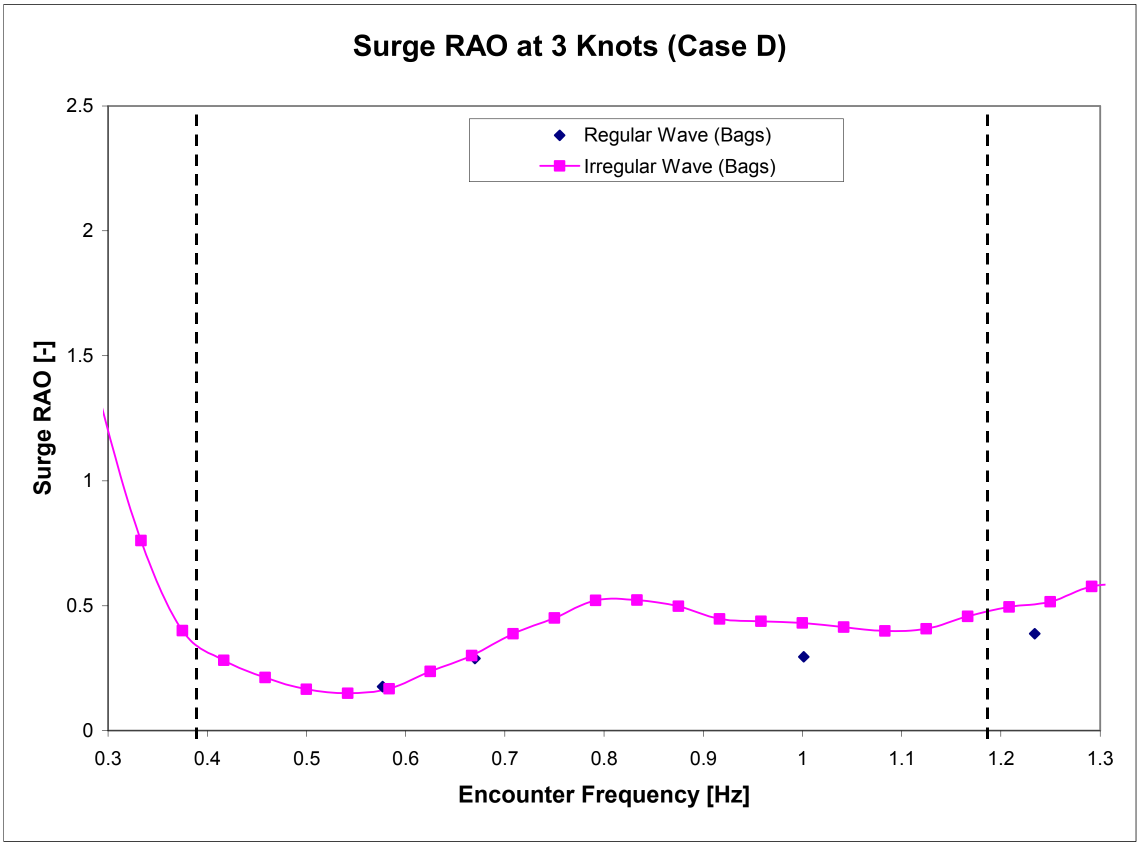

Tow Force RAO at 1 Knot (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]


Tow Force RAO at 2 Knots (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

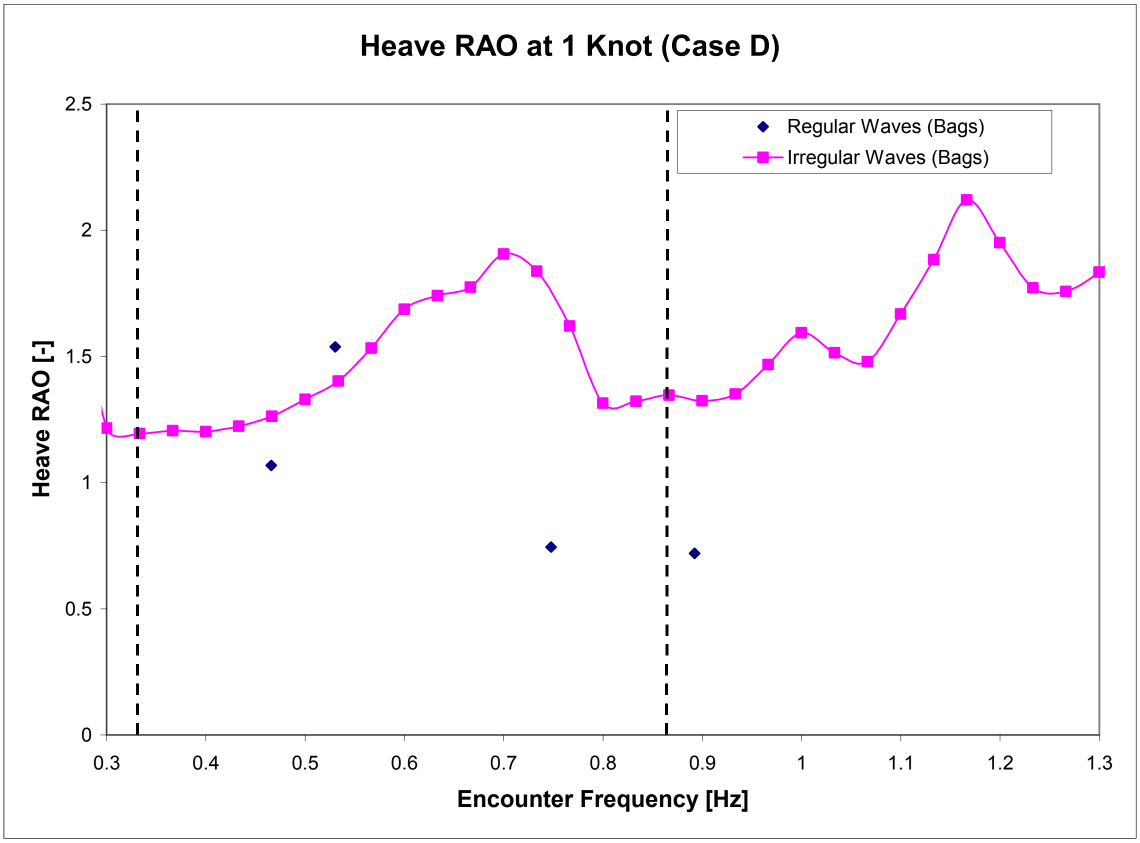

Tow Force RAO at 3 Knots (Case C)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]


Surge RAO at 1 Knot (Case D)
Surge RAO [-]
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

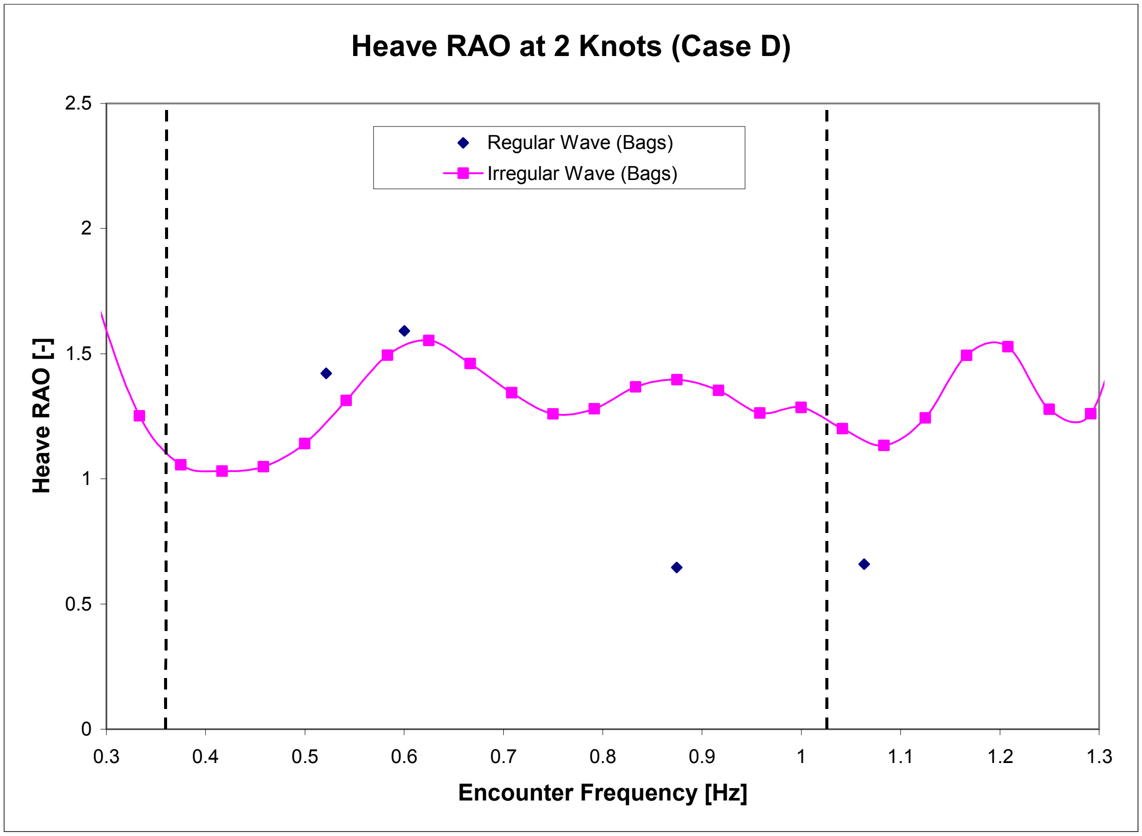

Surge RAO at 2 Knots (Case D)
Surge RAO [-]
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

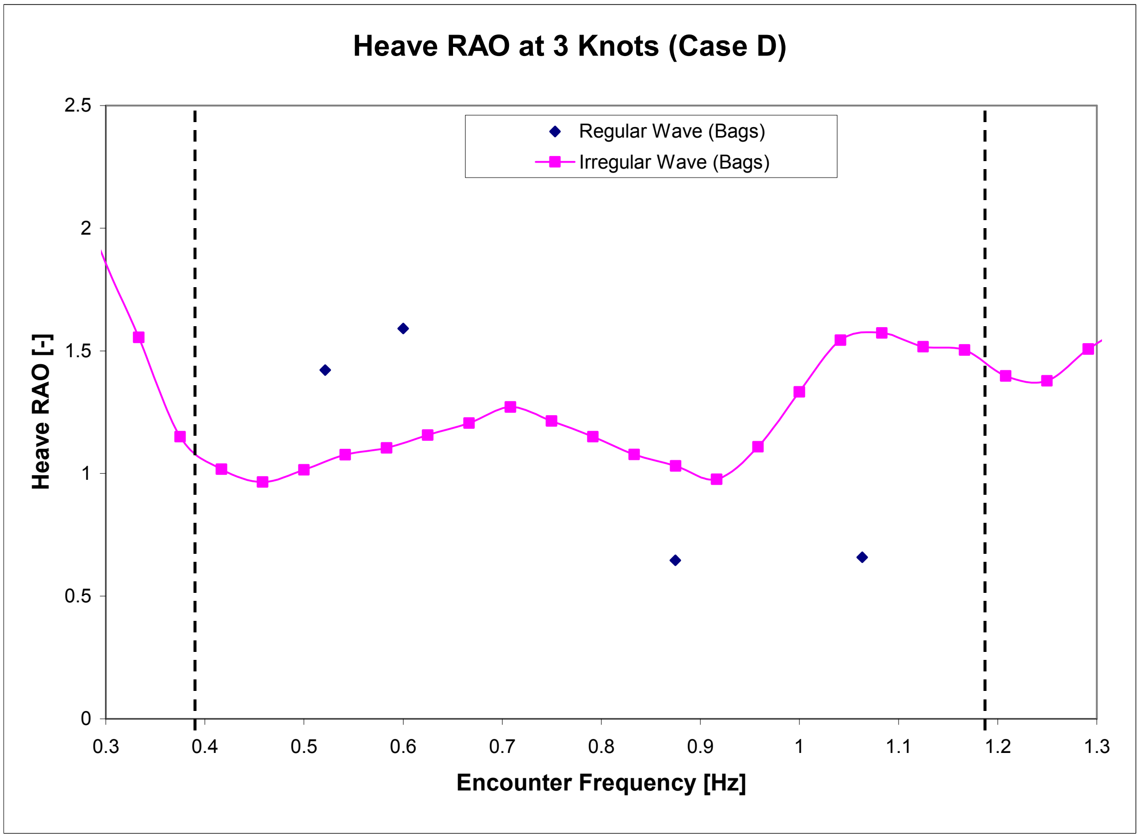


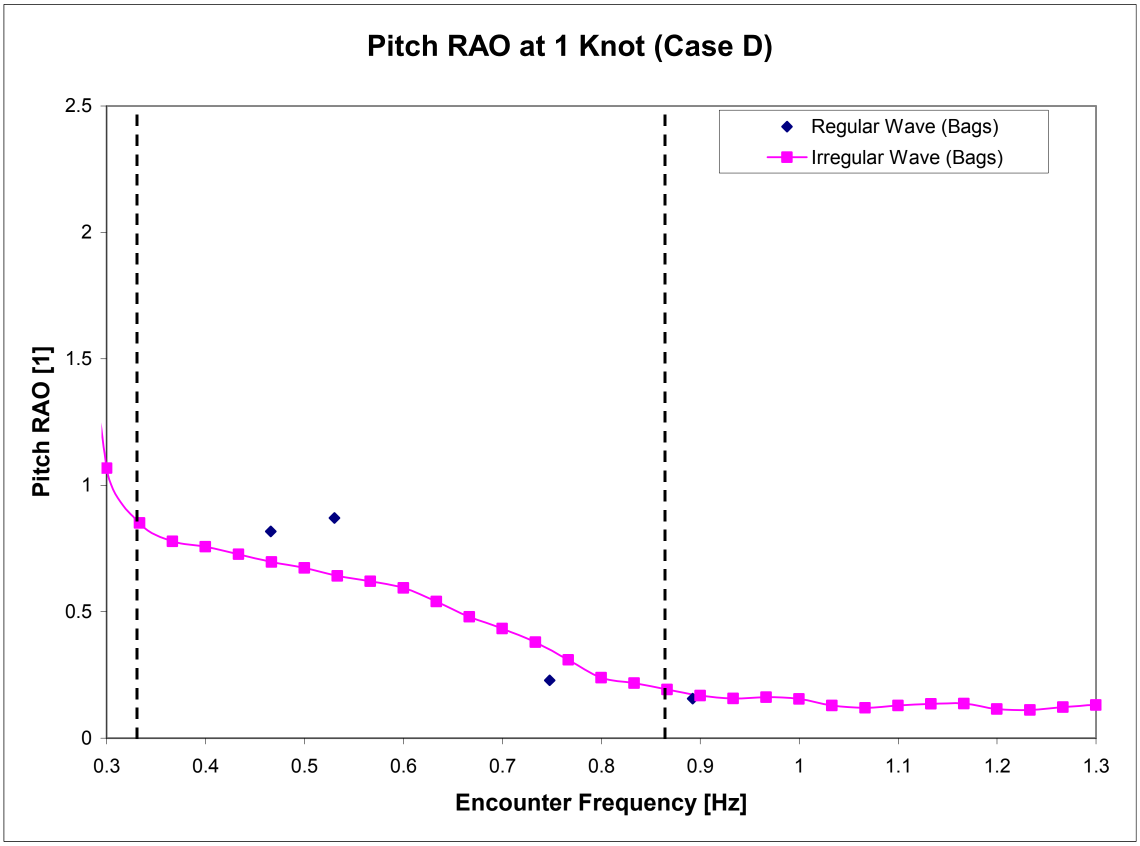
Surge RAO at 3 Knots (Case D)

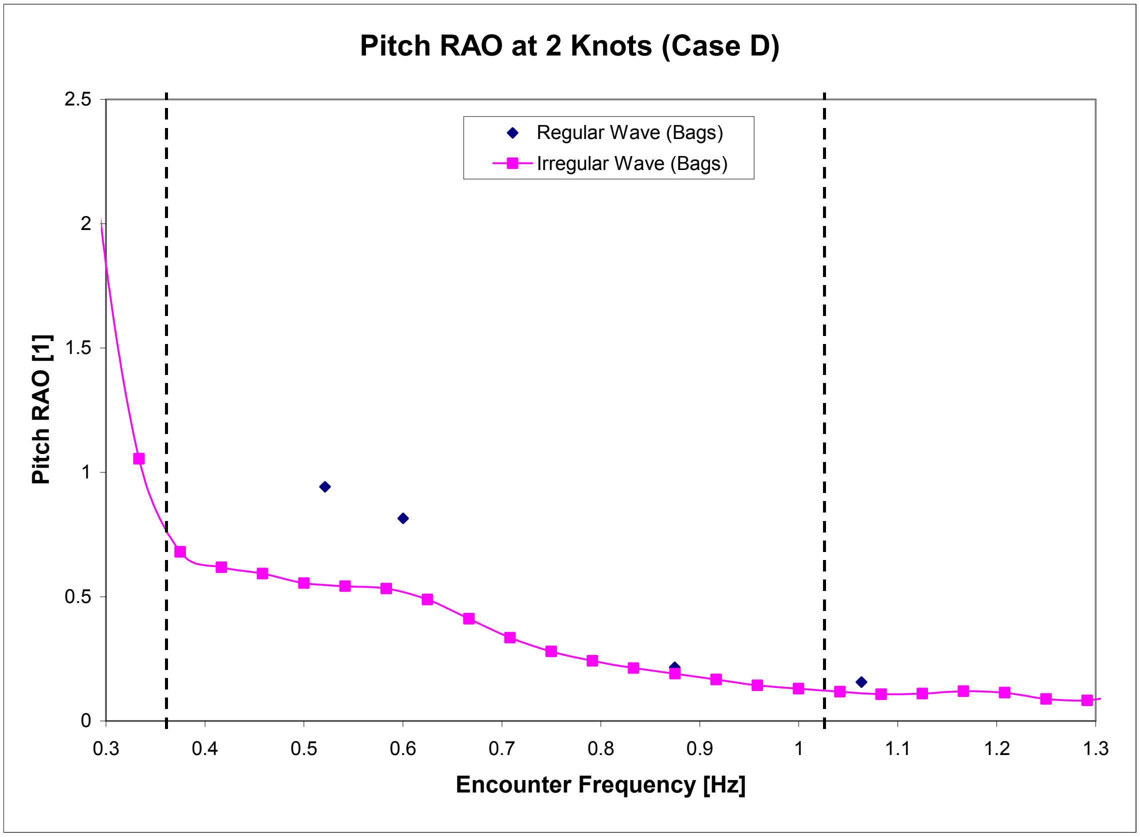


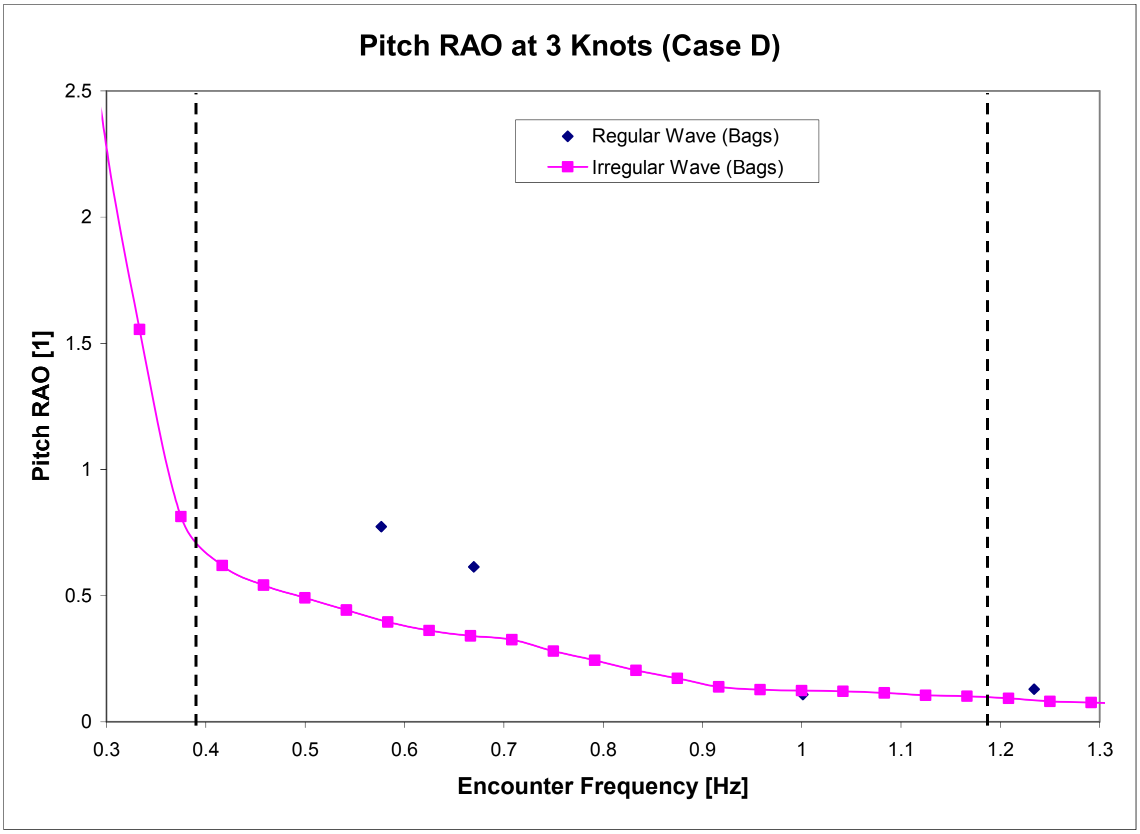
Heave RAO at 1 Knot (Case D)

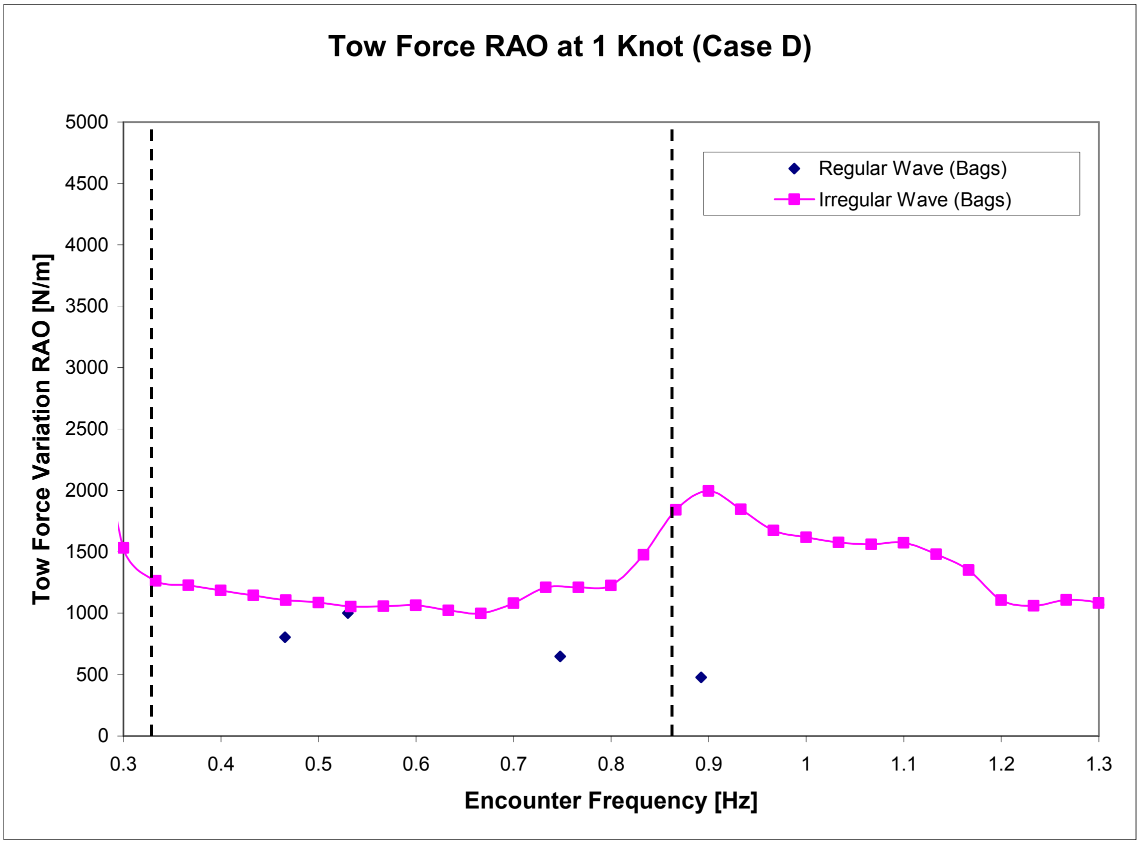

Heave RAO at 2 Knots (Case D)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

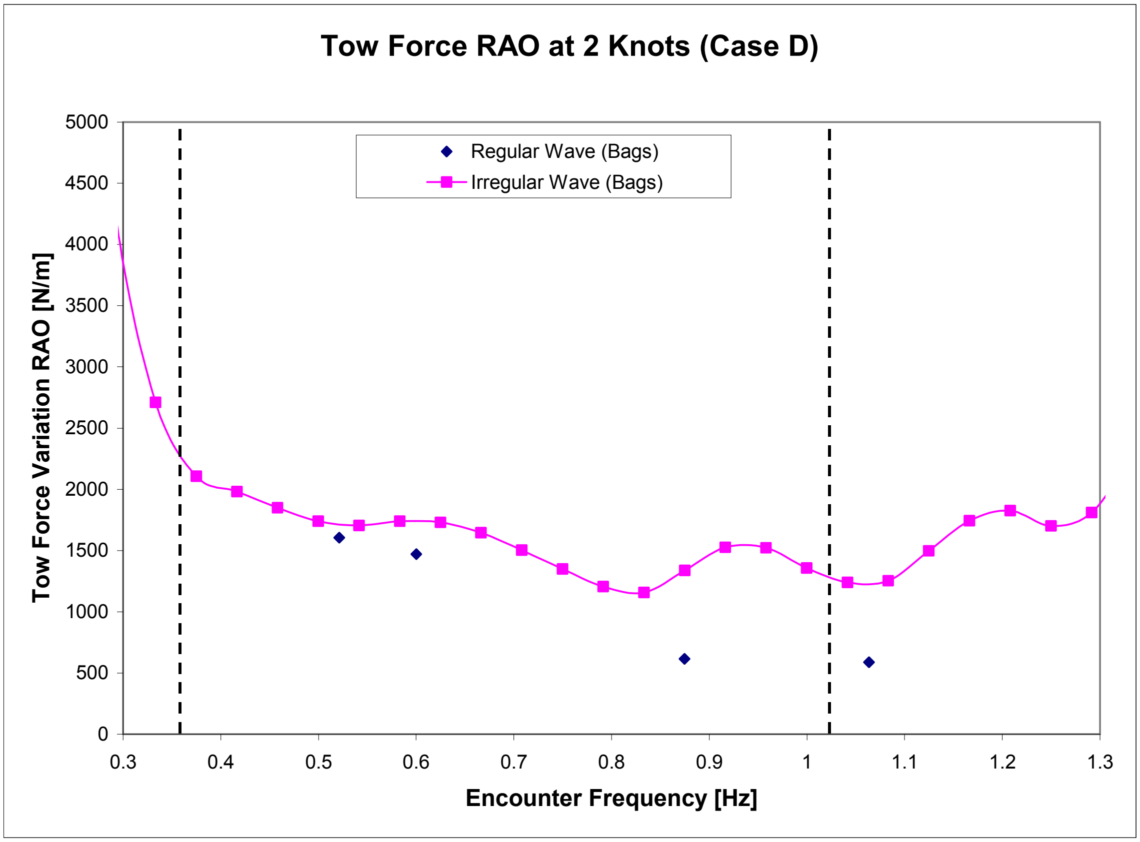

Heave RAO at 3 Knots (Case D)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

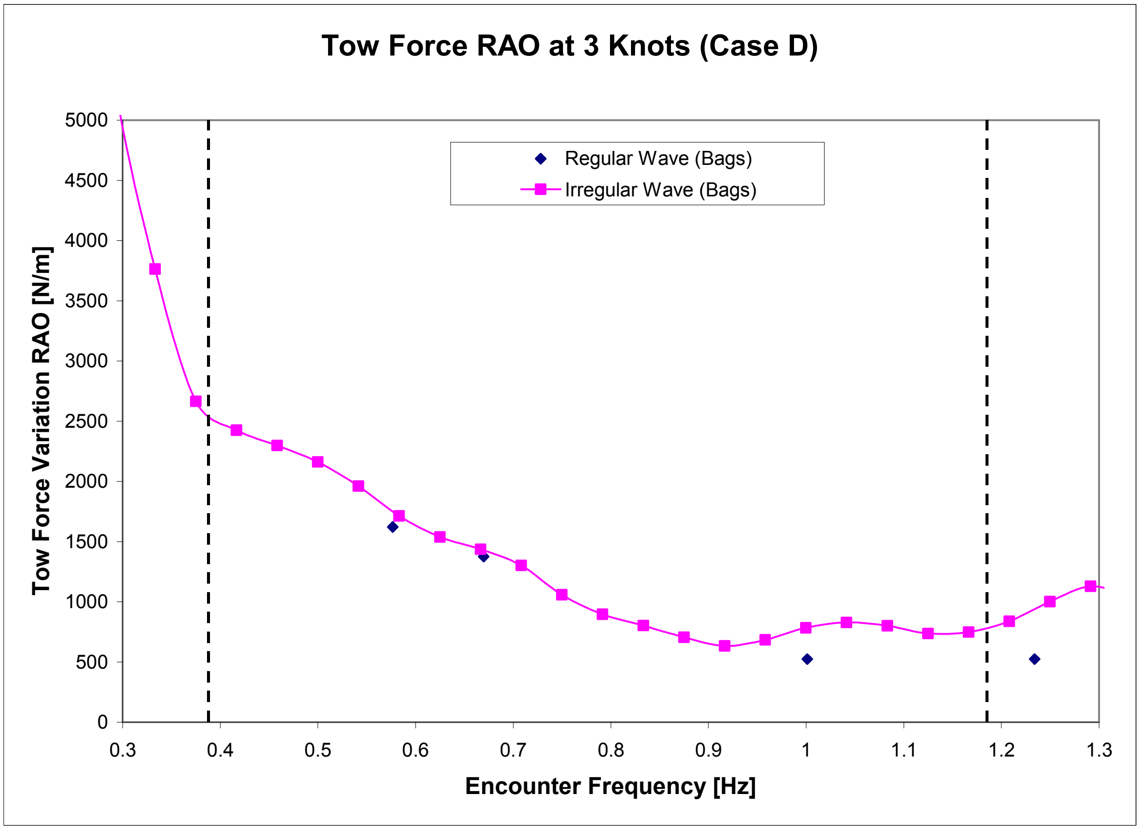

Pitch RAO at 1 Knot (Case D)
Pitch RAO [1]
Encounter Frequency [Hz]
◆ Regular Wave (Bags)
Irregular Wave (Bags)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

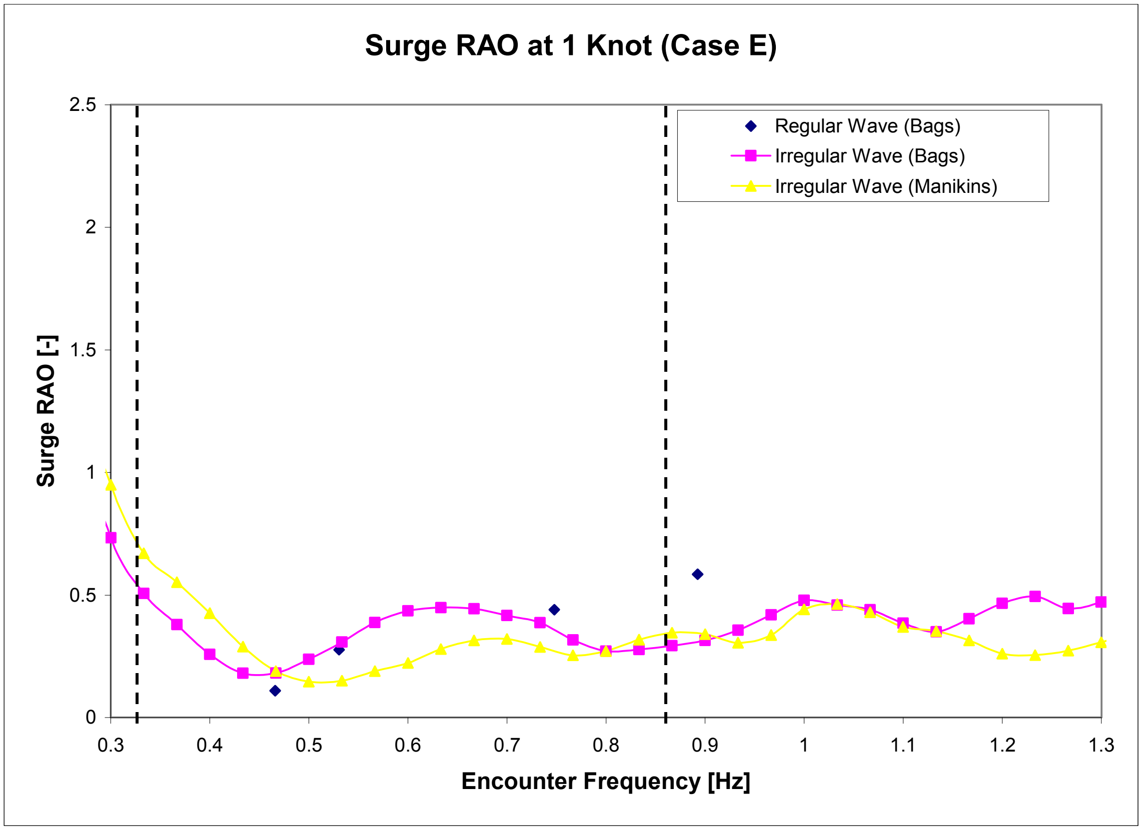

Pitch RAO at 2 Knots (Case D)
Pitch RAO [1]
Encounter Frequency [Hz]
◆ Regular Wave (Bags)
Irregular Wave (Bags)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

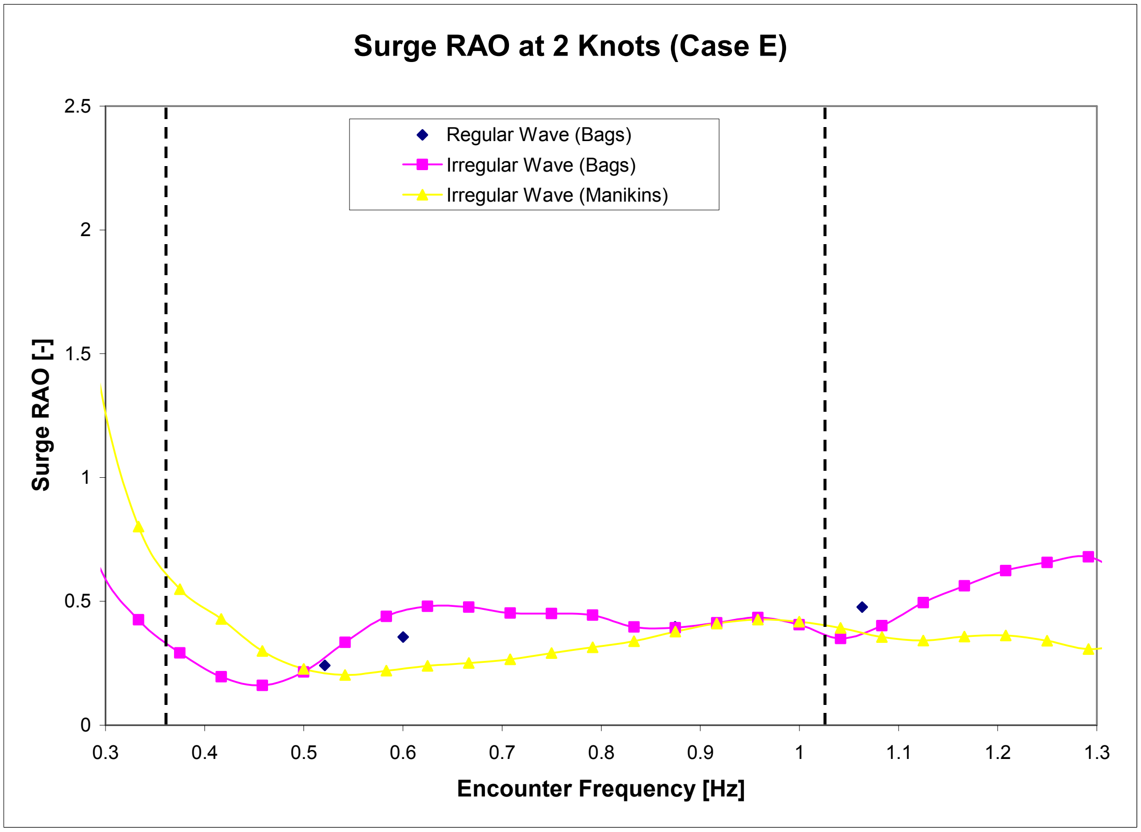

Pitch RAO at 3 Knots (Case D)
Regular Wave (Bags)
Irregular Wave (Bags)
Pitch RAO [1]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

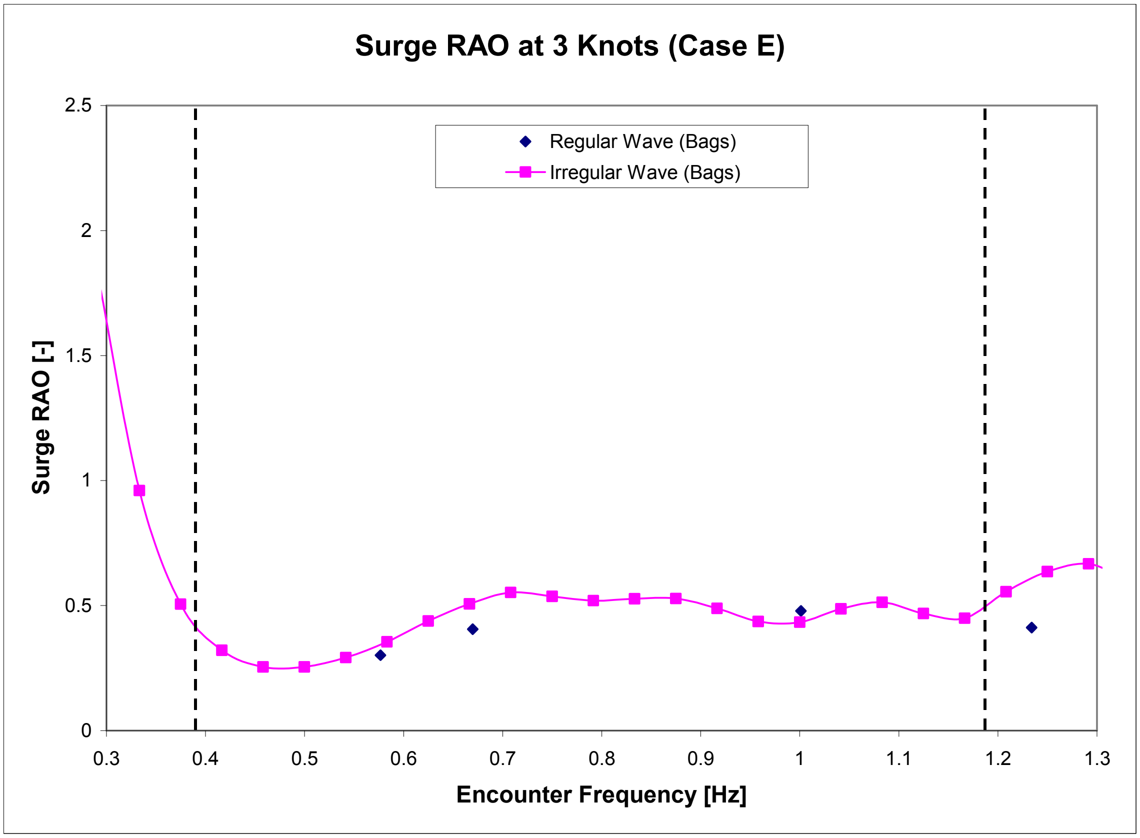

Tow Force RAO at 1 Knot (Case D)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

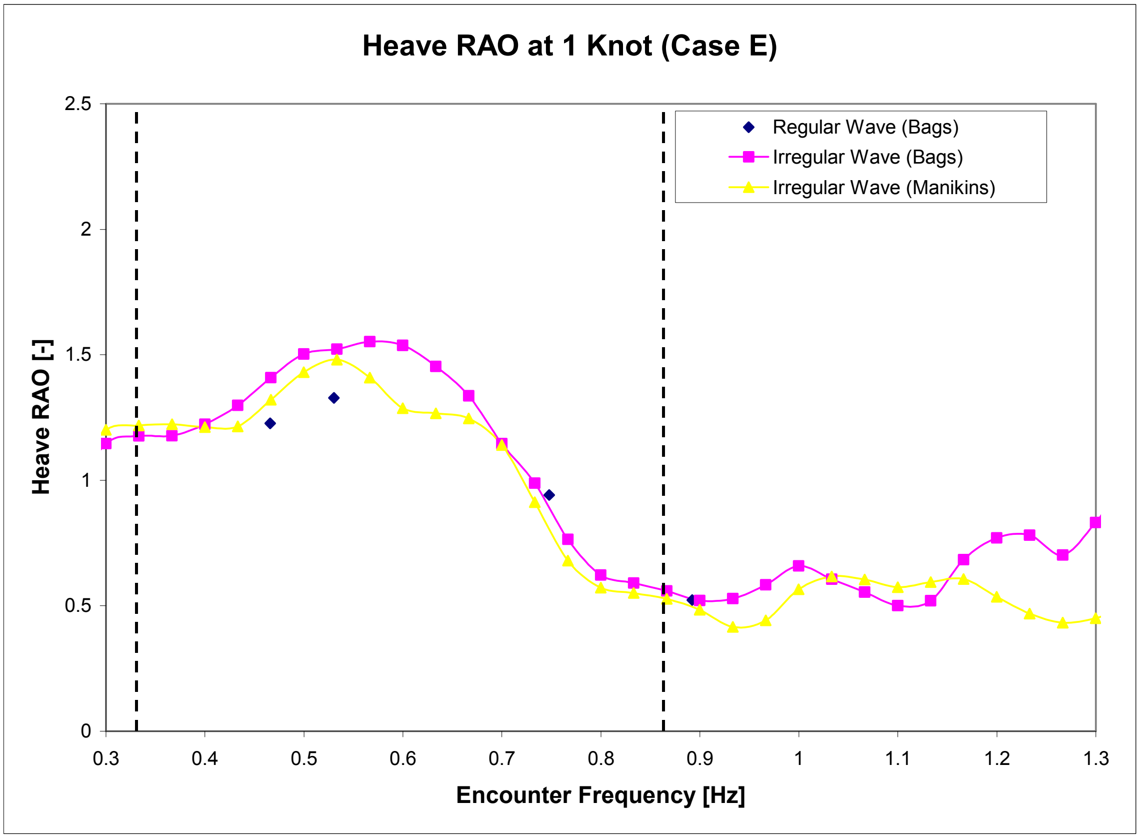

Tow Force RAO at 2 Knots (Case D)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

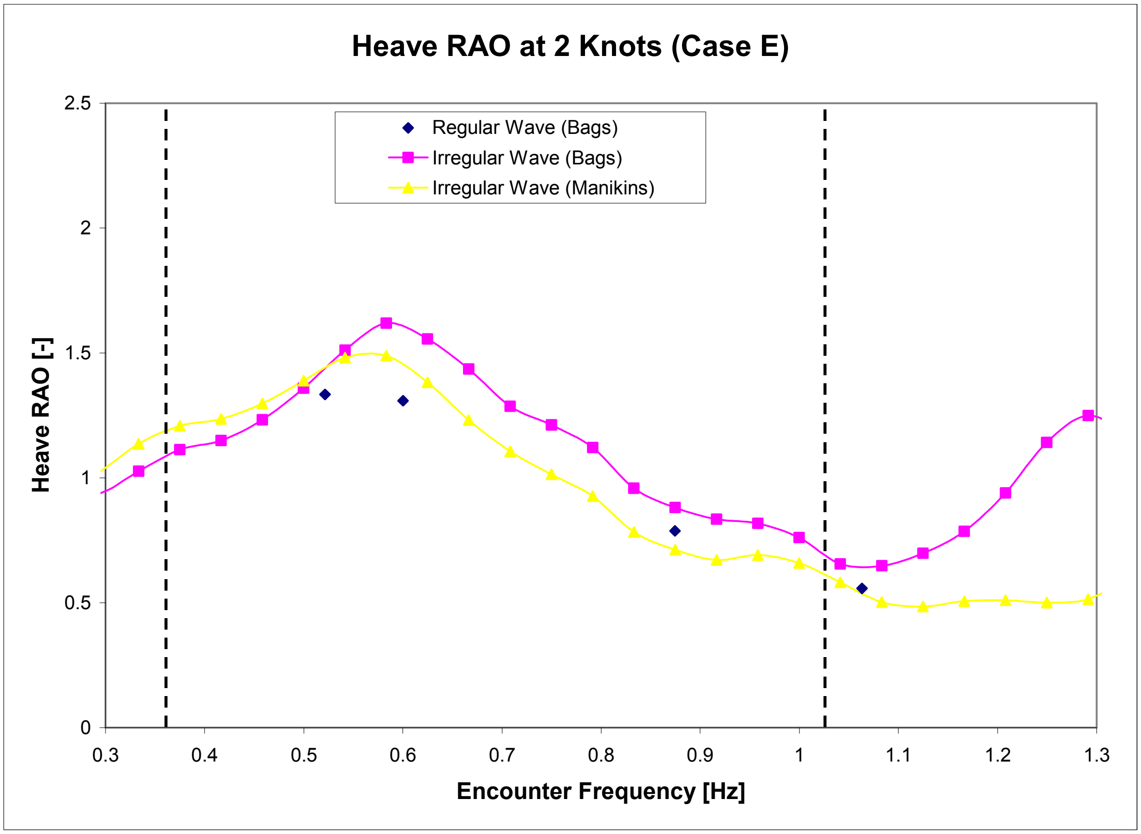

Tow Force RAO at 3 Knots (Case D)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

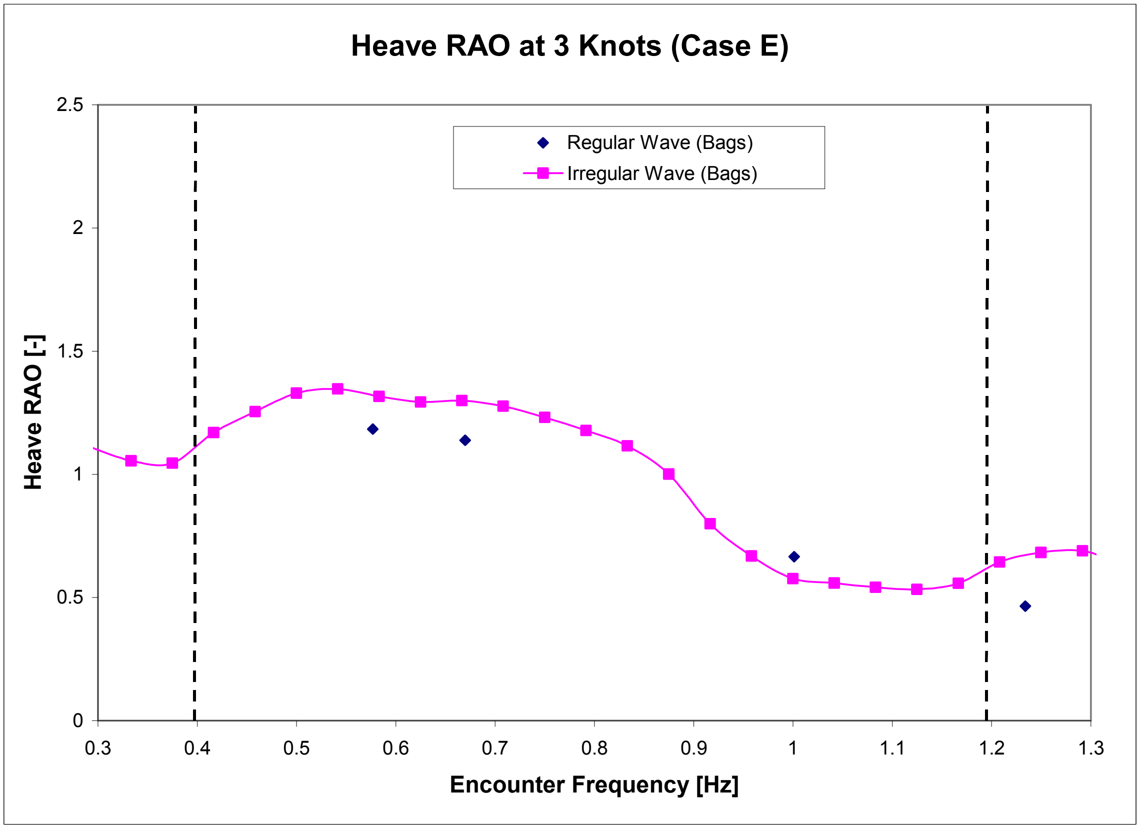

Surge RAO at 1 Knot (Case E)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)

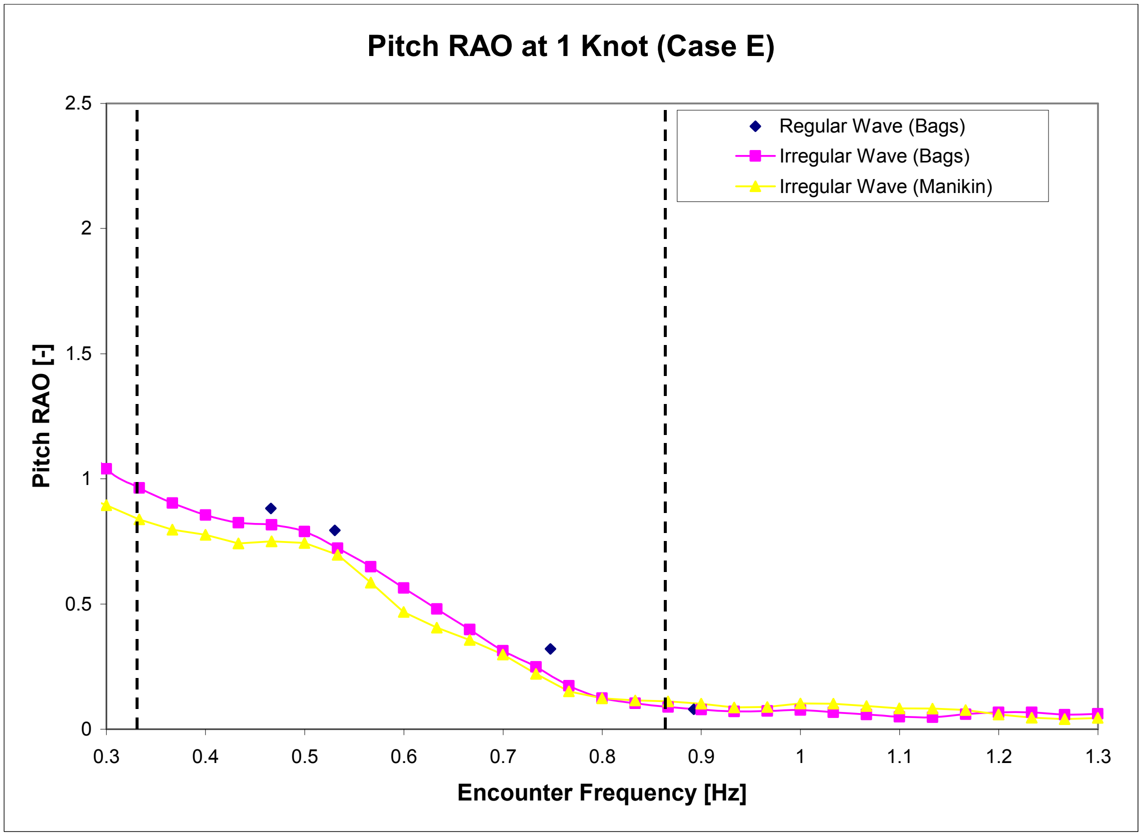

Surge RAO at 2 Knots (Case E)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)

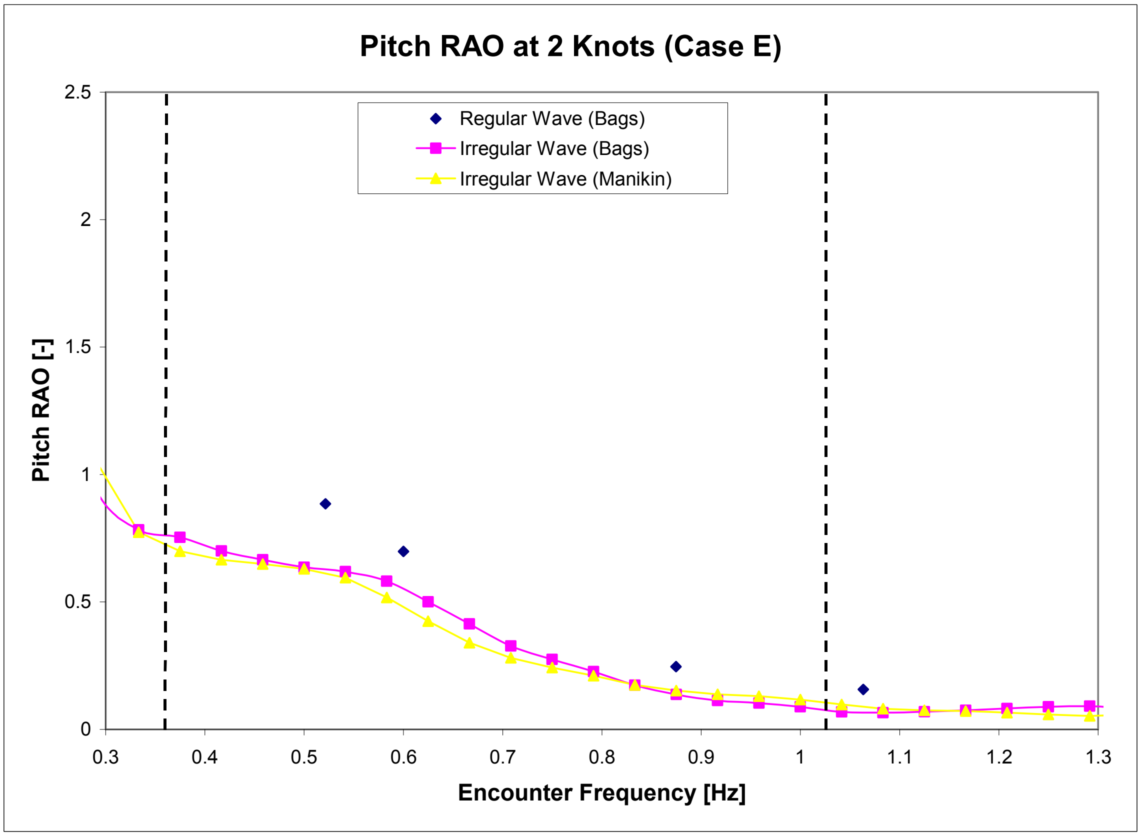

Surge RAO at 3 Knots (Case E)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

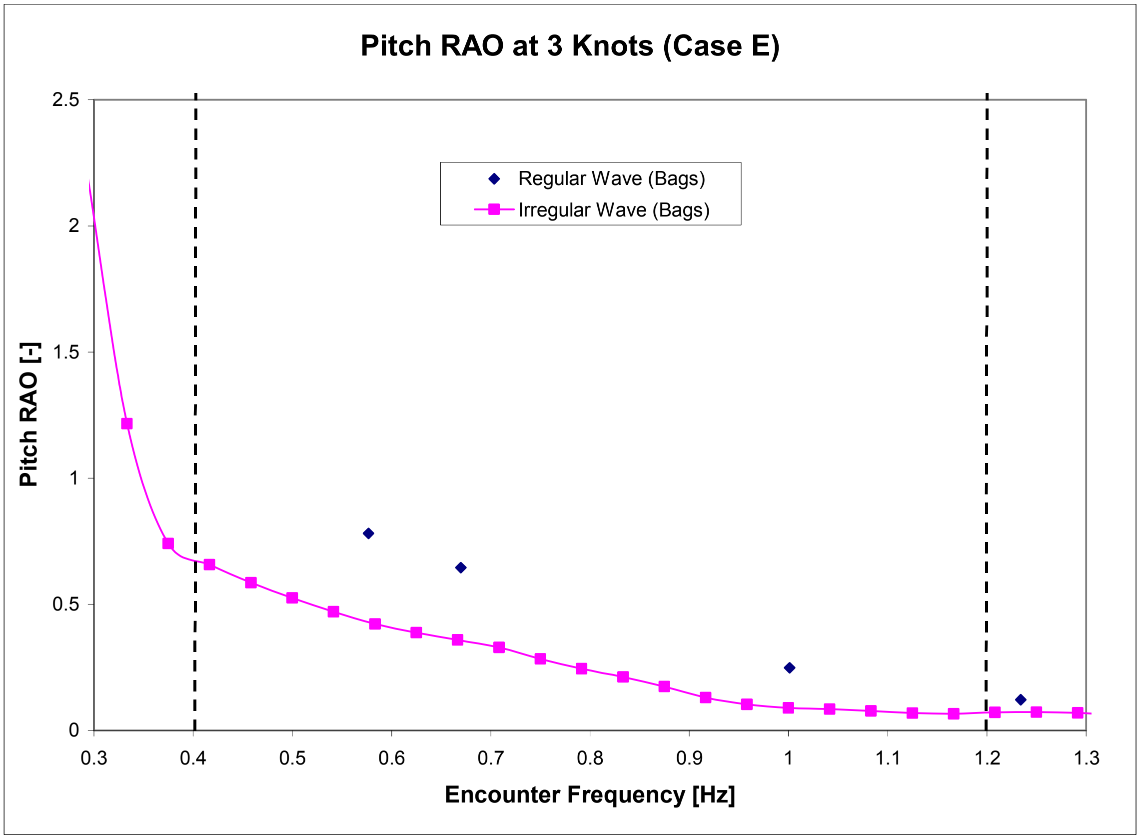

Heave RAO at 1 Knot (Case E)
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

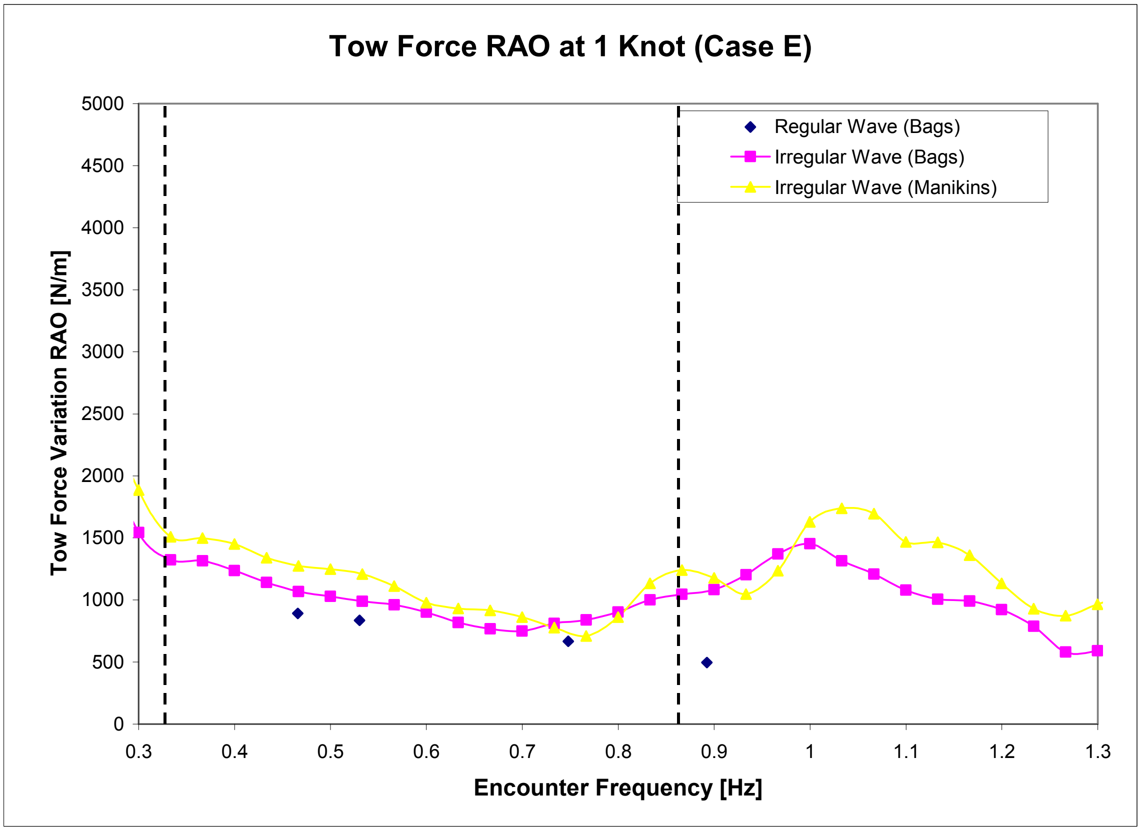

Heave RAO at 2 Knots (Case E)
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

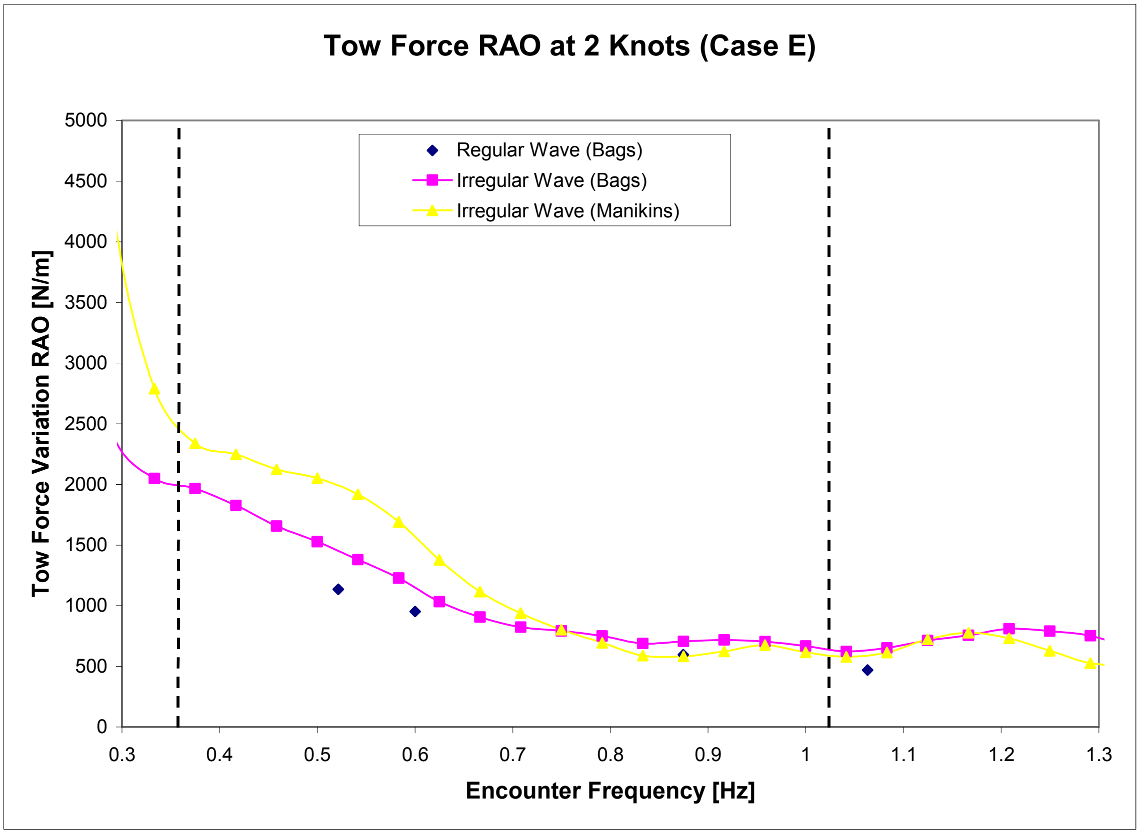

Heave RAO at 3 Knots (Case E)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

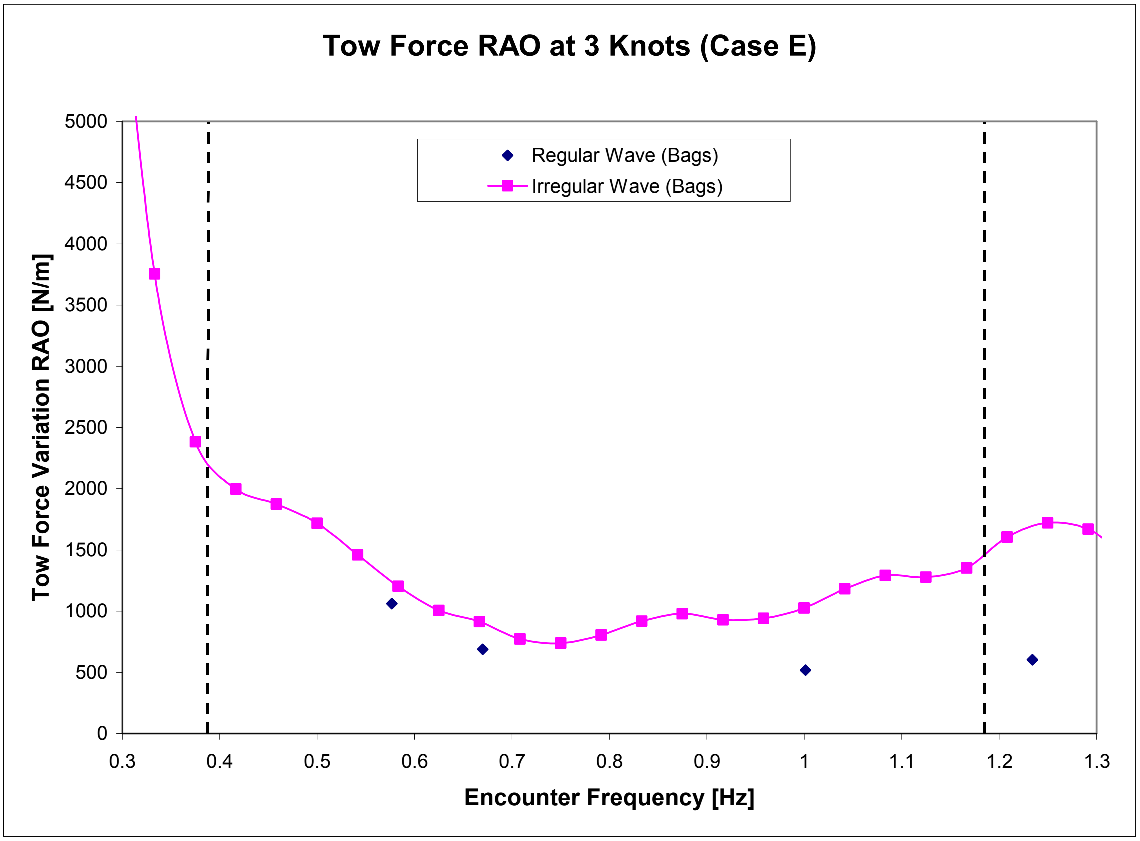

Pitch RAO at 1 Knot (Case E)
Pitch RAO [-]
Encounter Frequency [Hz]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikin)

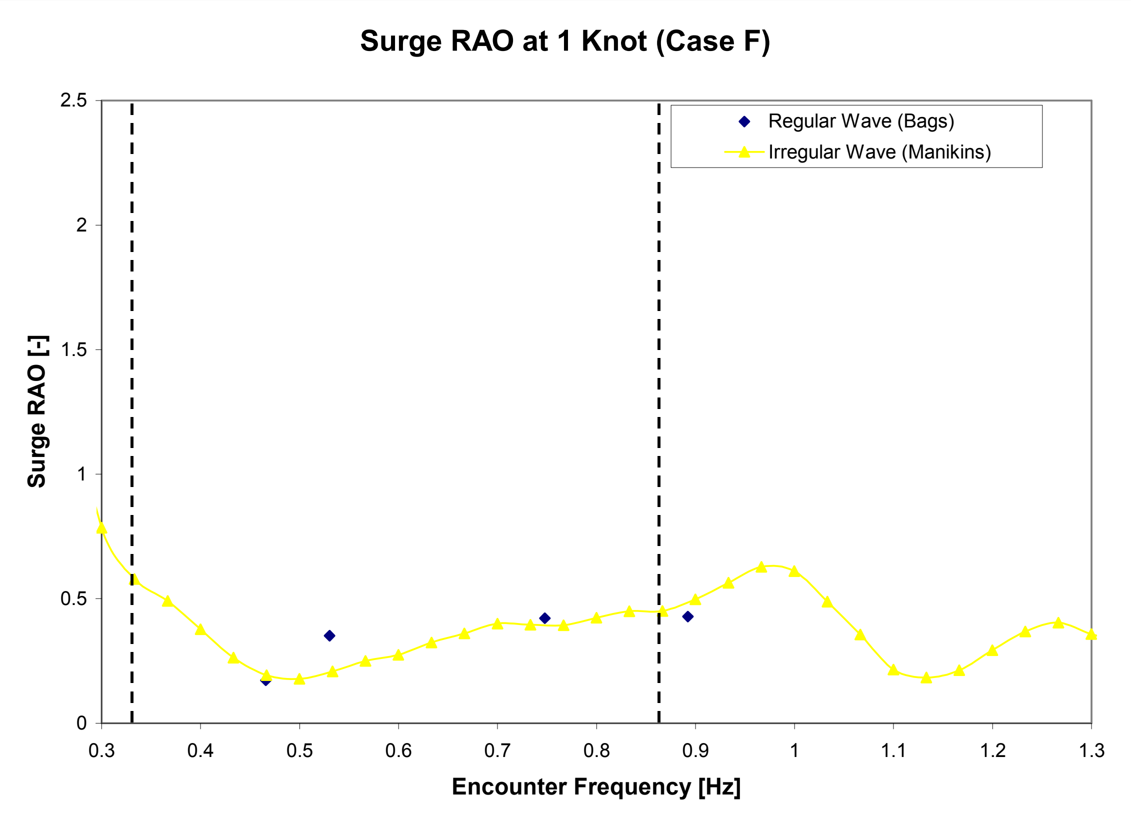

Pitch RAO at 2 Knots (Case E)
Pitch RAO [-]
Encounter Frequency [Hz]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikin)


Pitch RAO at 3 Knots (Case E)
Regular Wave (Bags)
Irregular Wave (Bags)
Pitch RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

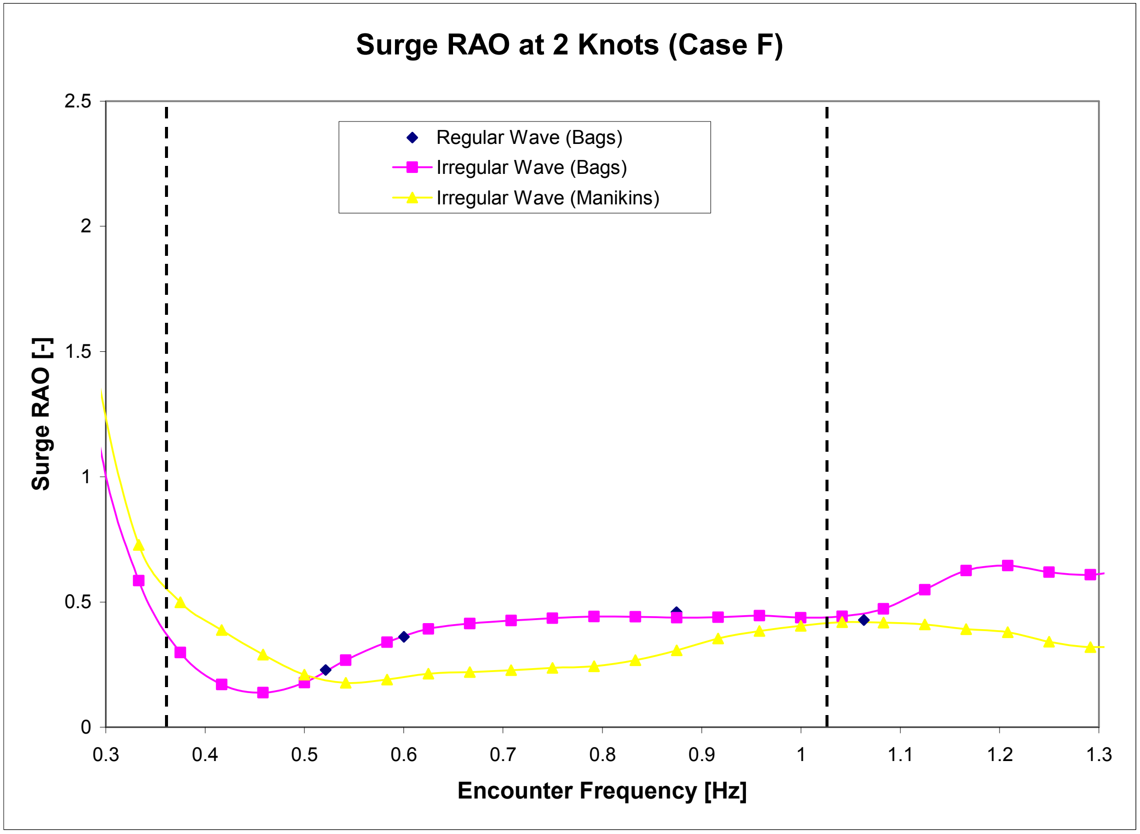

Tow Force RAO at 1 Knot (Case E)
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
Tow Force Variation RAO [N/m]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]


Tow Force RAO at 2 Knots (Case E)
Tow Force Variation RAO [N/m]
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

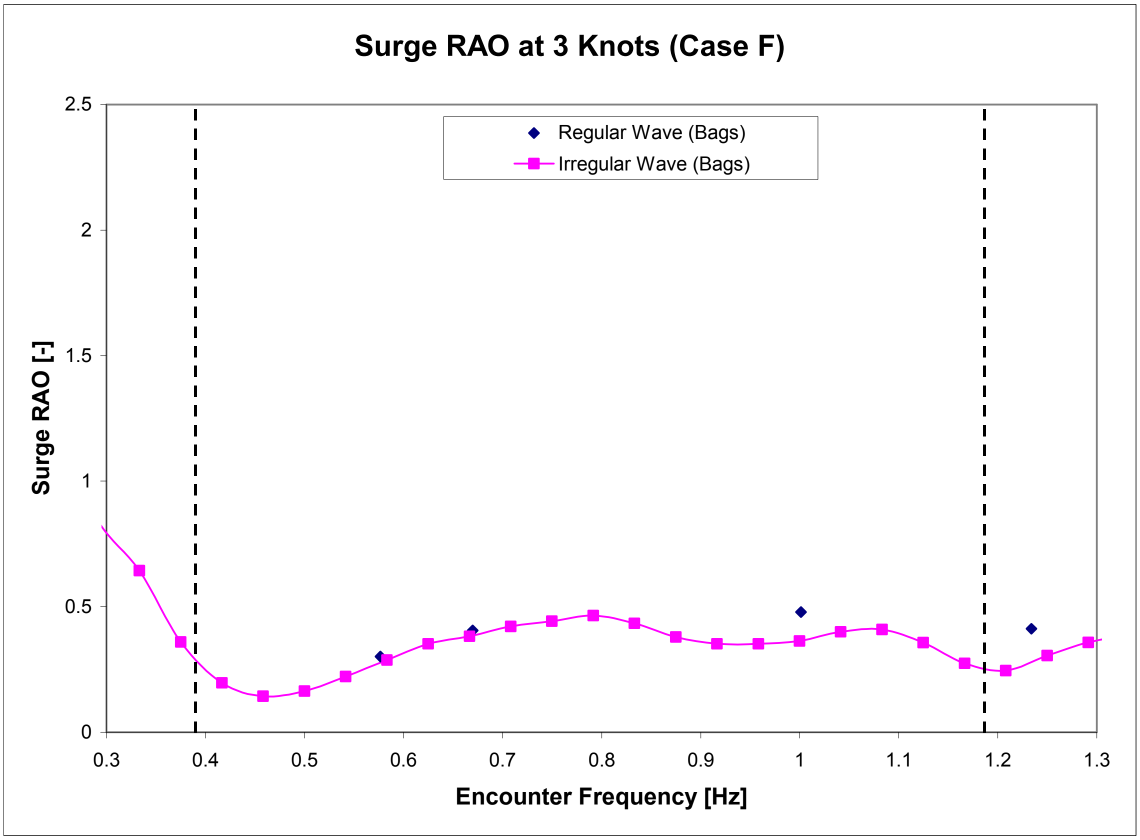

Tow Force RAO at 3 Knots (Case E)
Tow Force Variation RAO [N/m]
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

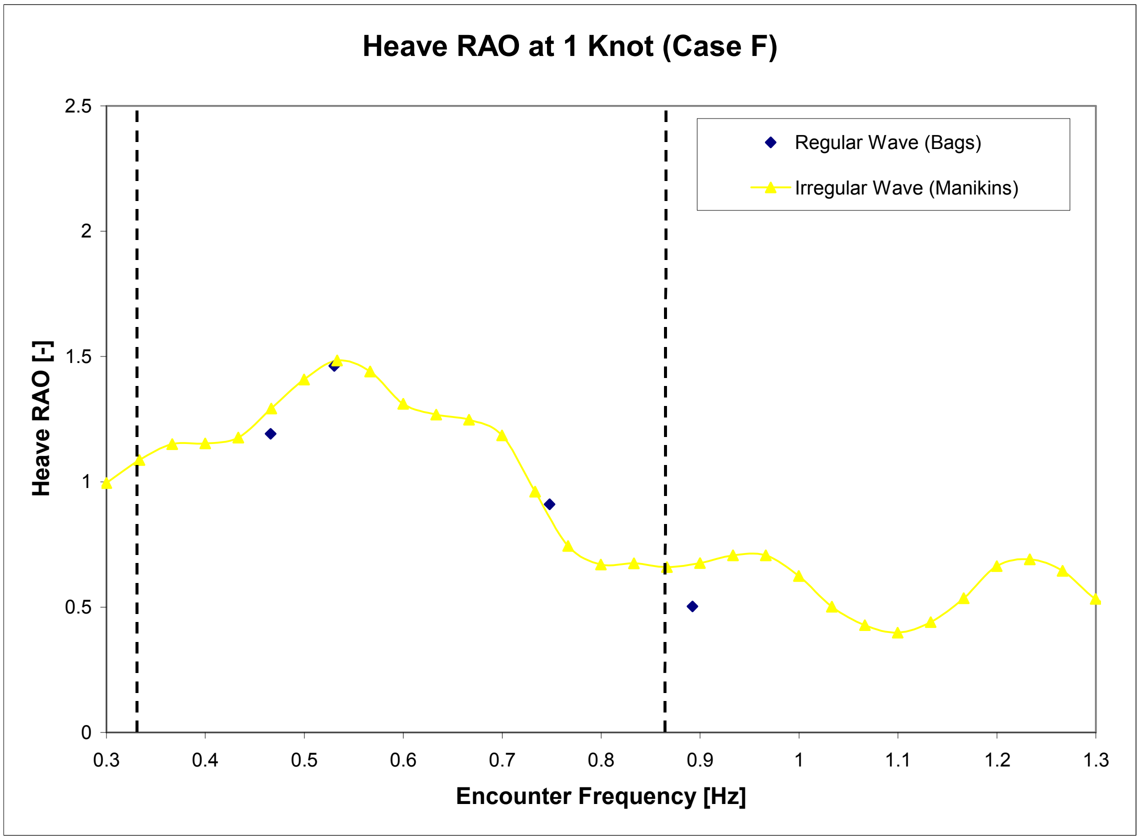


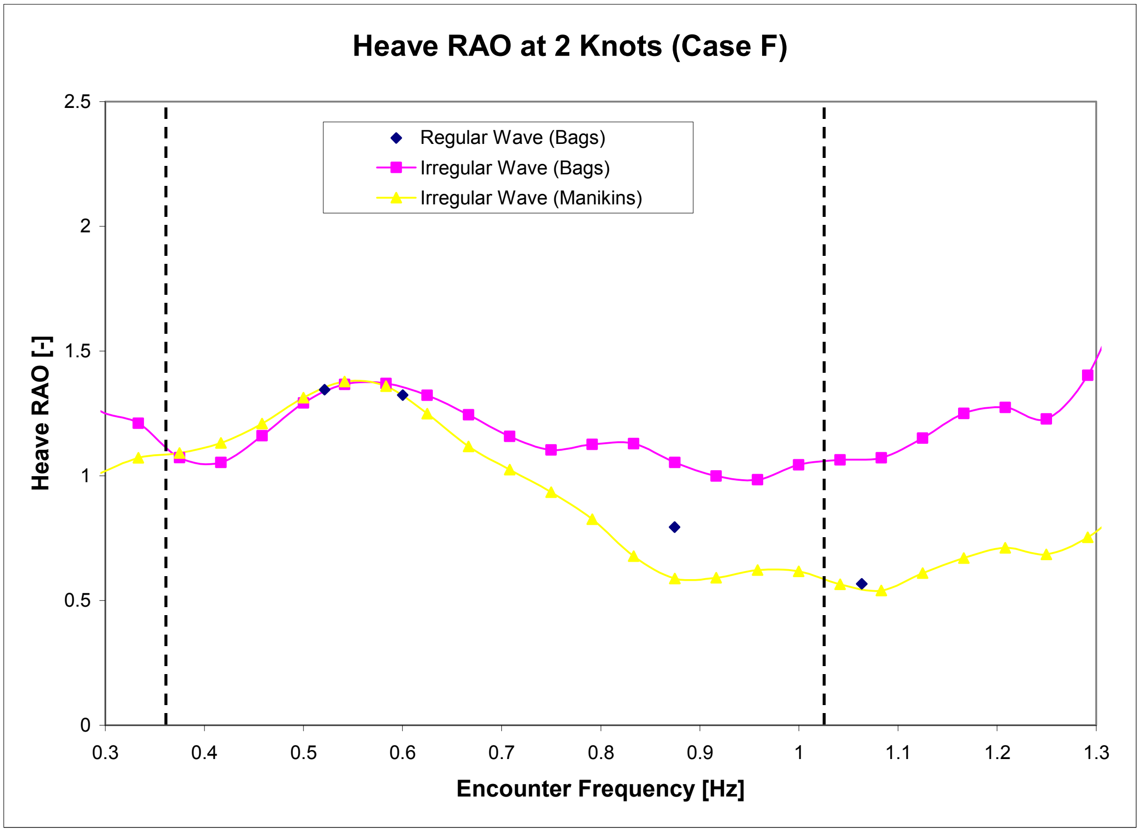
Surge RAO at 1 Knot (Case F)
Regular Wave (Bags)
Irregular Wave (Manikins)
Surge RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

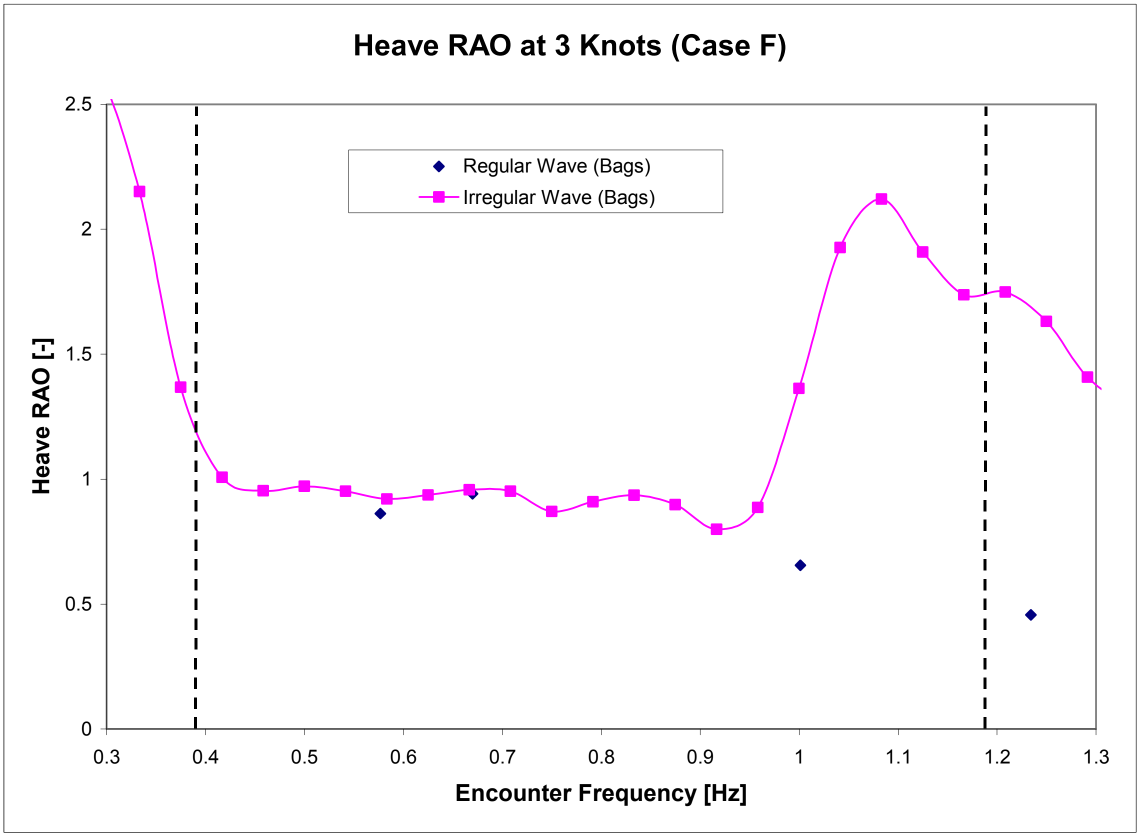


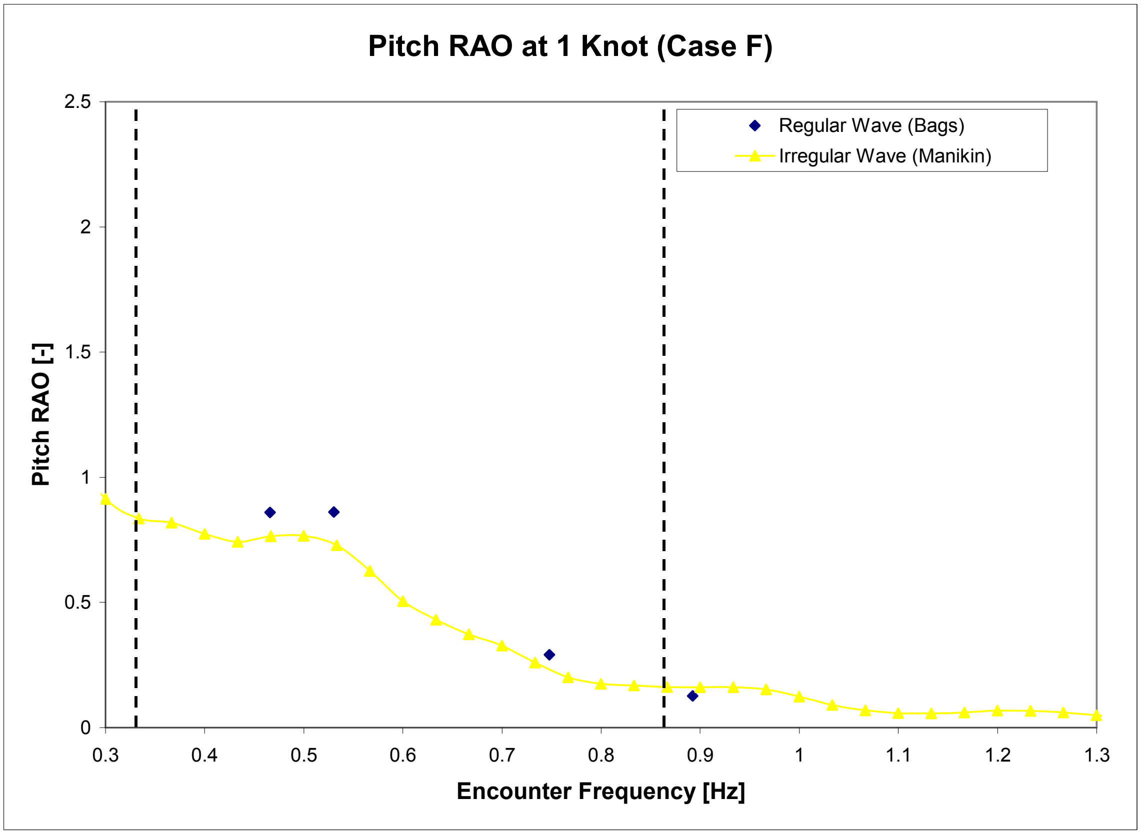
Surge RAO at 2 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
Surge RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

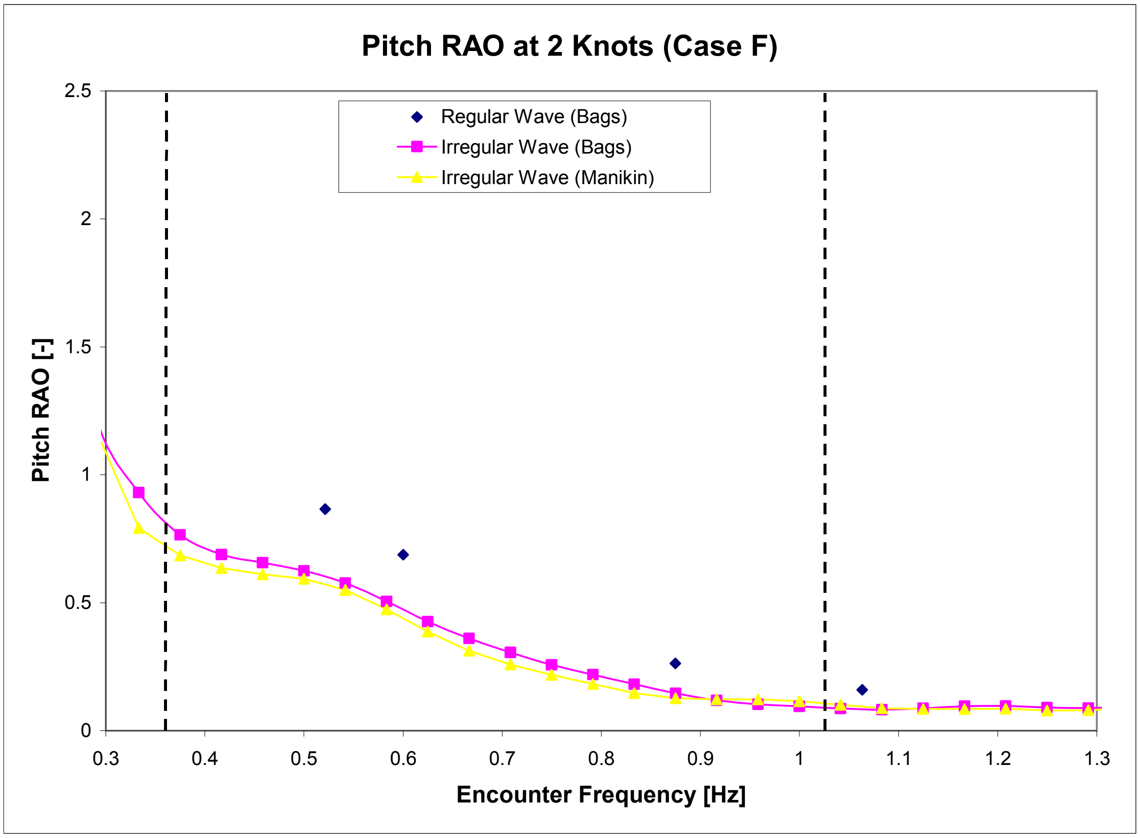

Surge RAO at 3 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

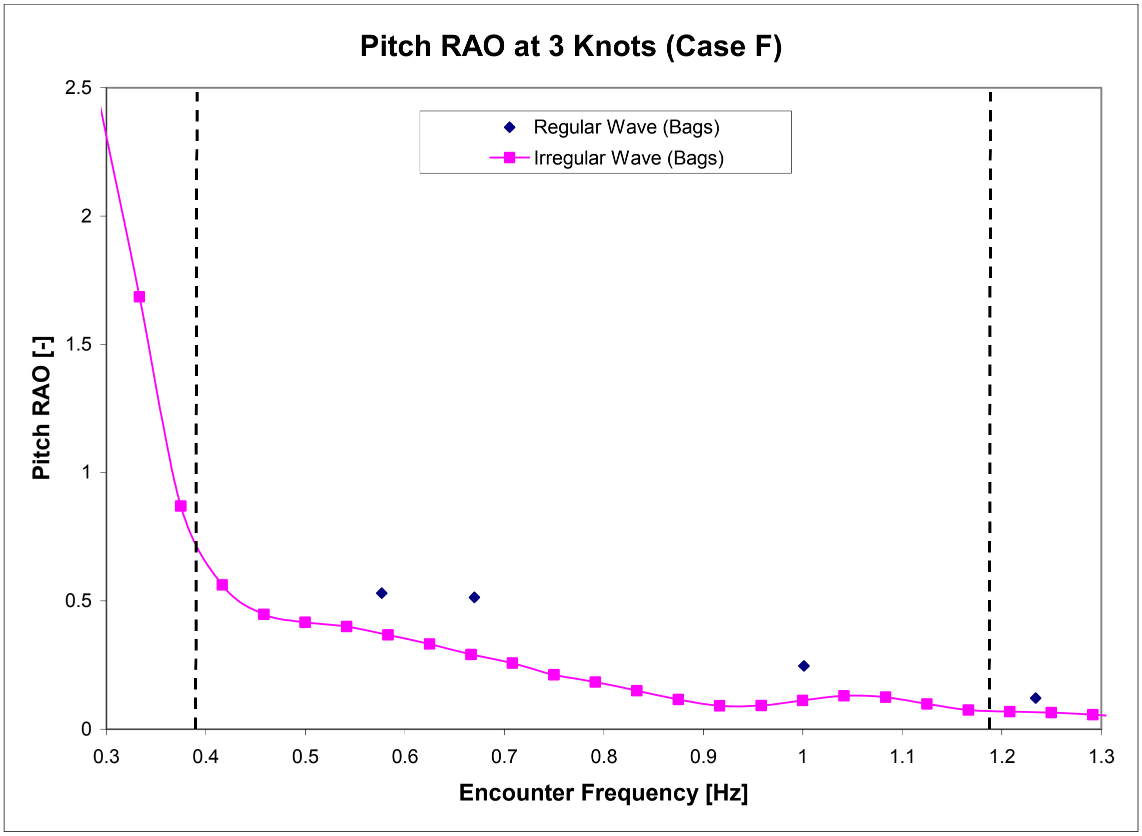

Heave RAO at 1 Knot (Case F)
Regular Wave (Bags)
Irregular Wave (Manikins)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

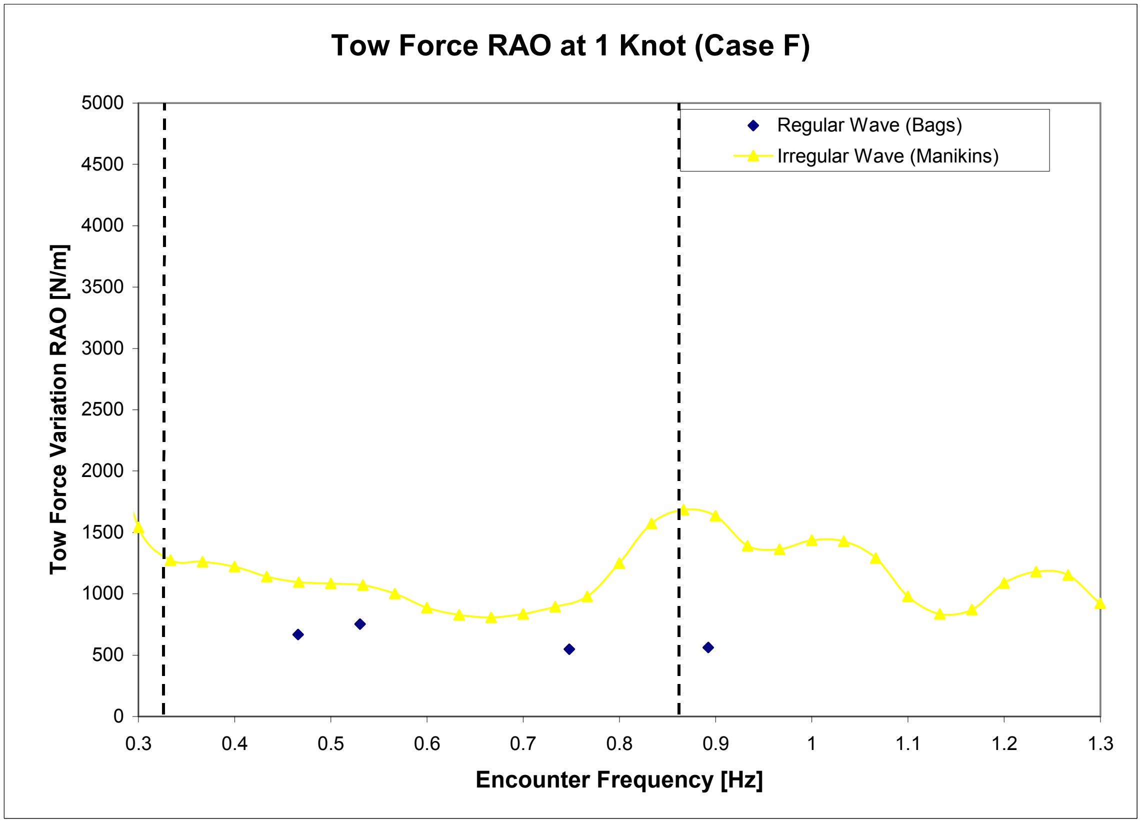

Heave RAO at 2 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

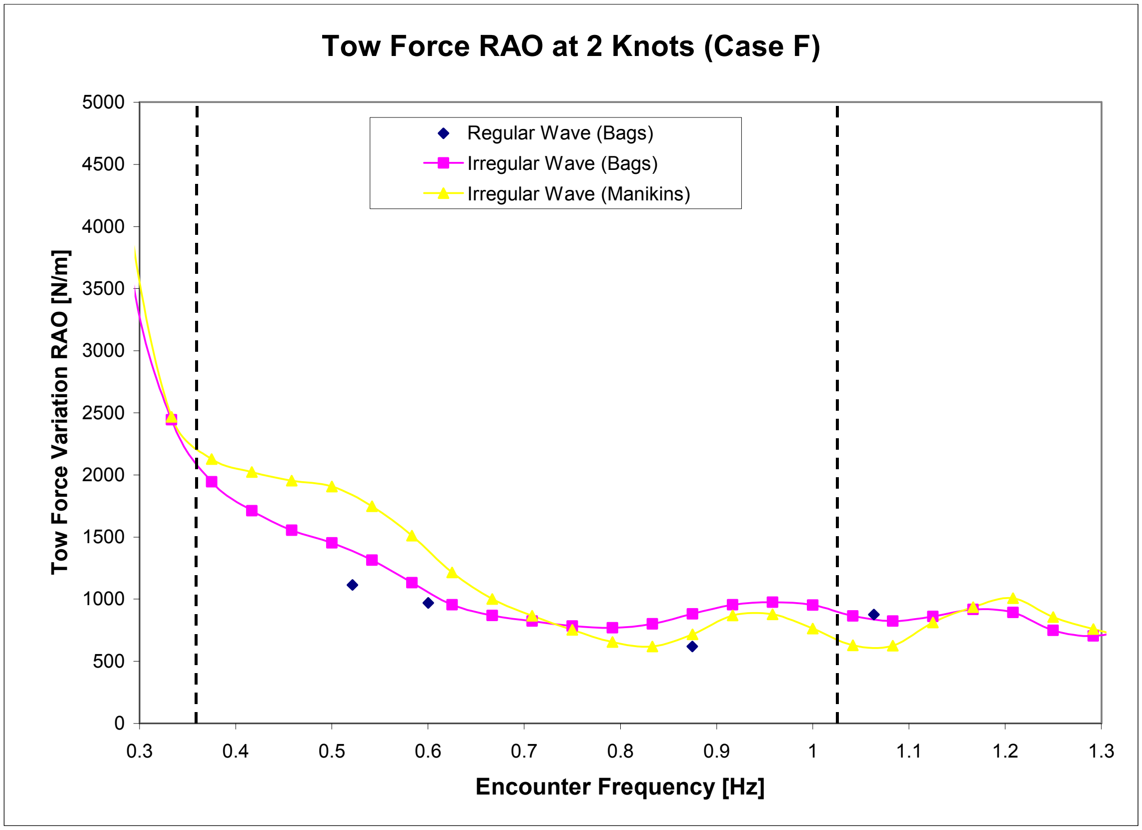

Heave RAO at 3 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

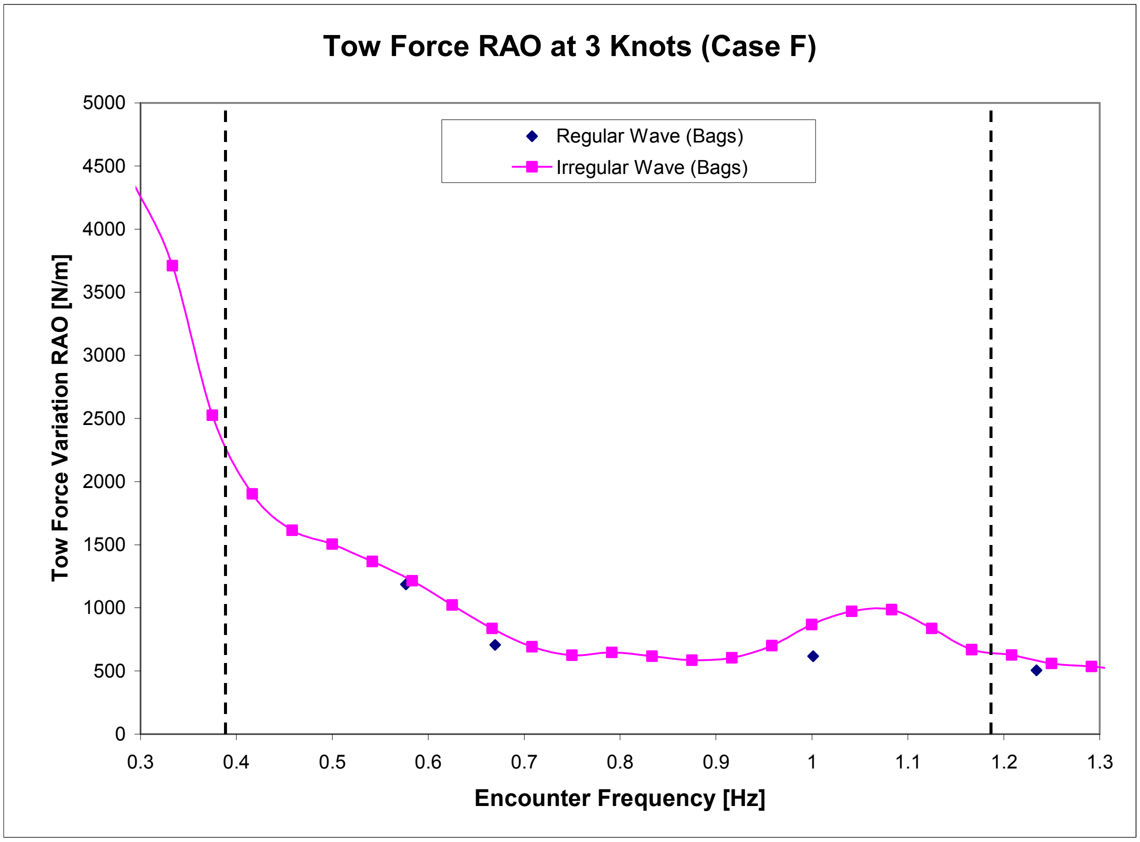

Pitch RAO at 1 Knot (Case F)
Pitch RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Manikin)


Pitch RAO at 2 Knots (Case F)
Pitch RAO [-]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikin)


Pitch RAO at 3 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

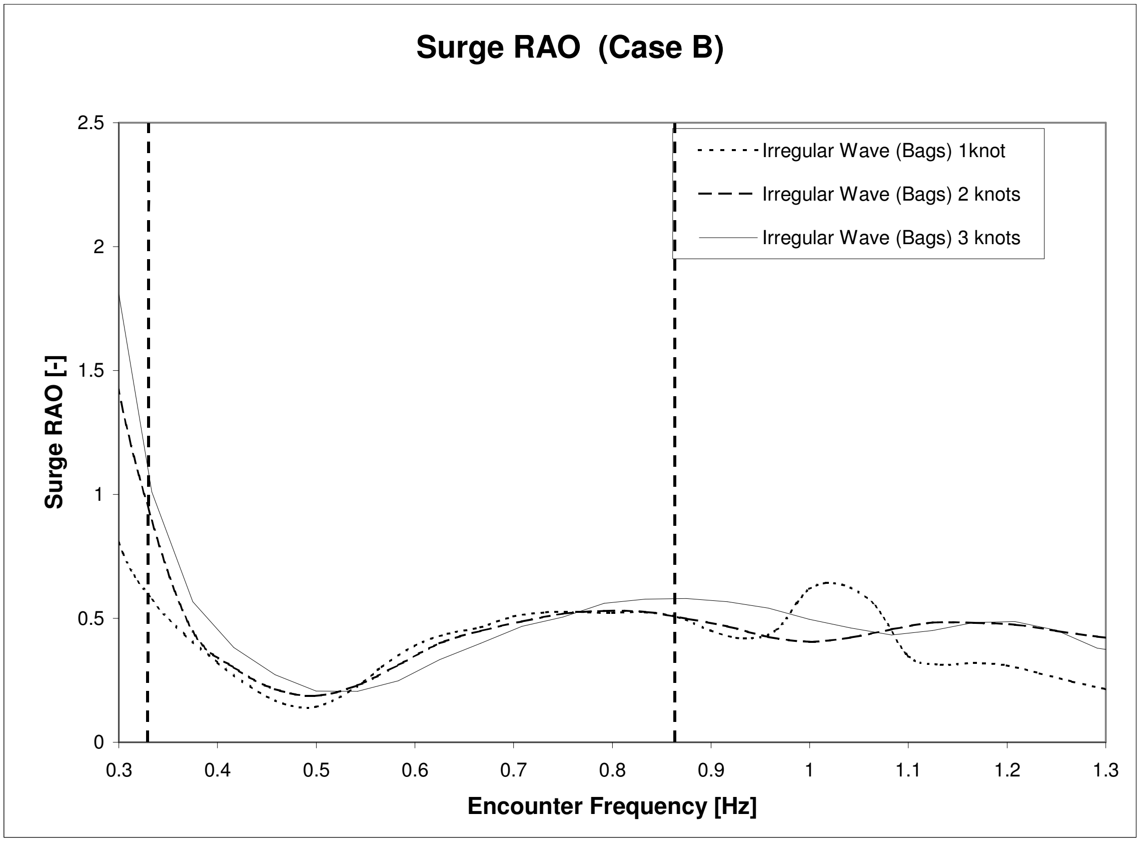

Tow Force RAO at 1 Knot (Case F)
Regular Wave (Bags)
Irregular Wave (Manikins)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

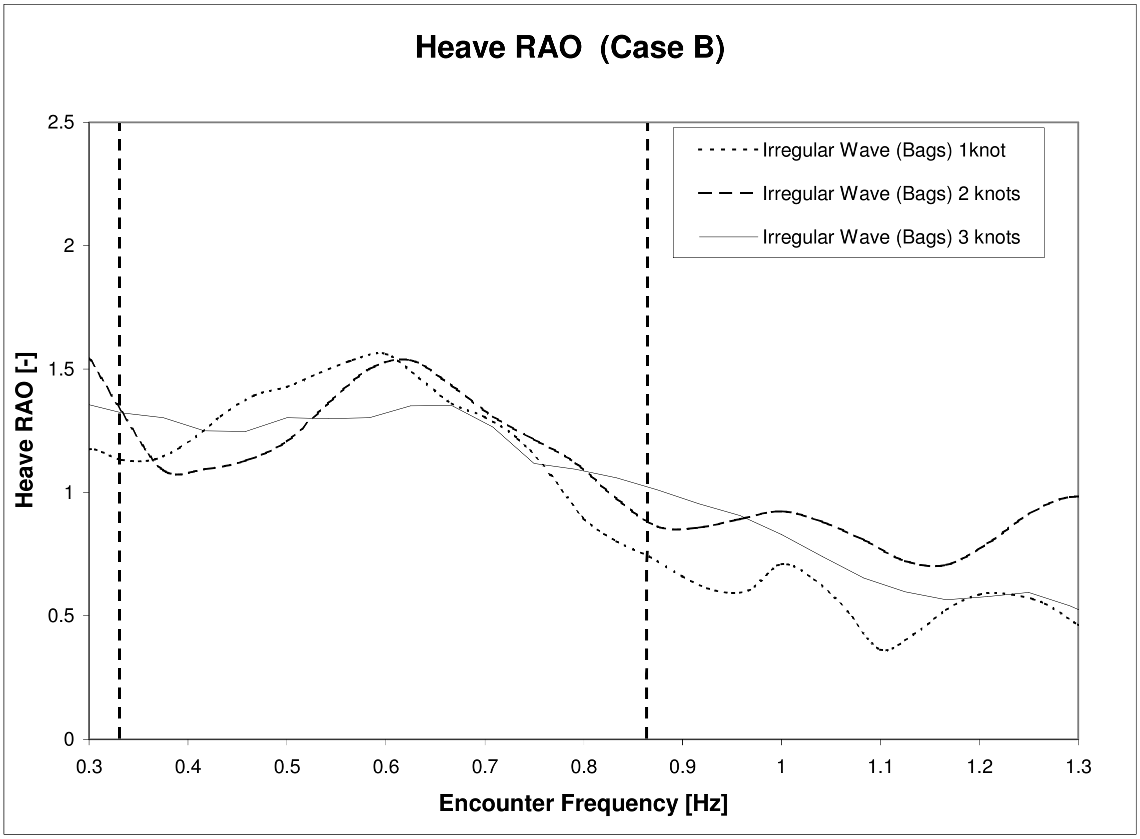

Tow Force RAO at 2 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Irregular Wave (Manikins)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

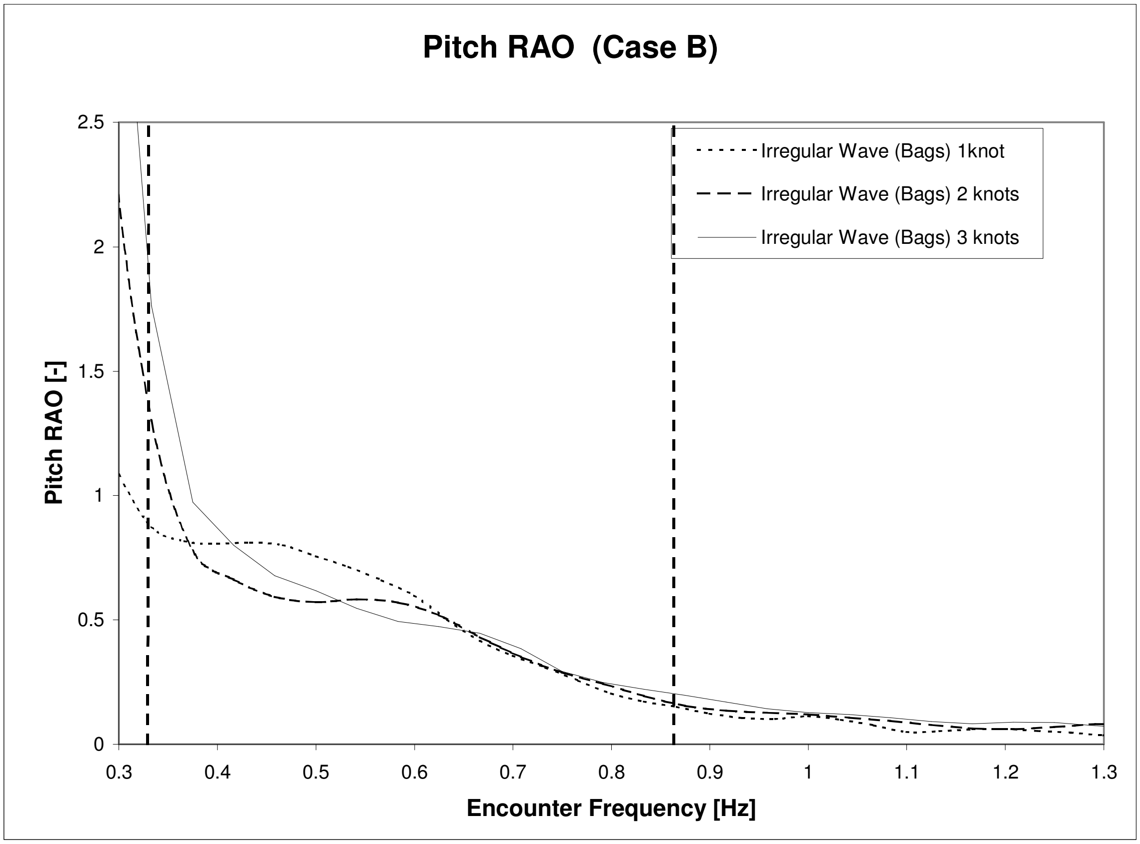

Tow Force RAO at 3 Knots (Case F)
Regular Wave (Bags)
Irregular Wave (Bags)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

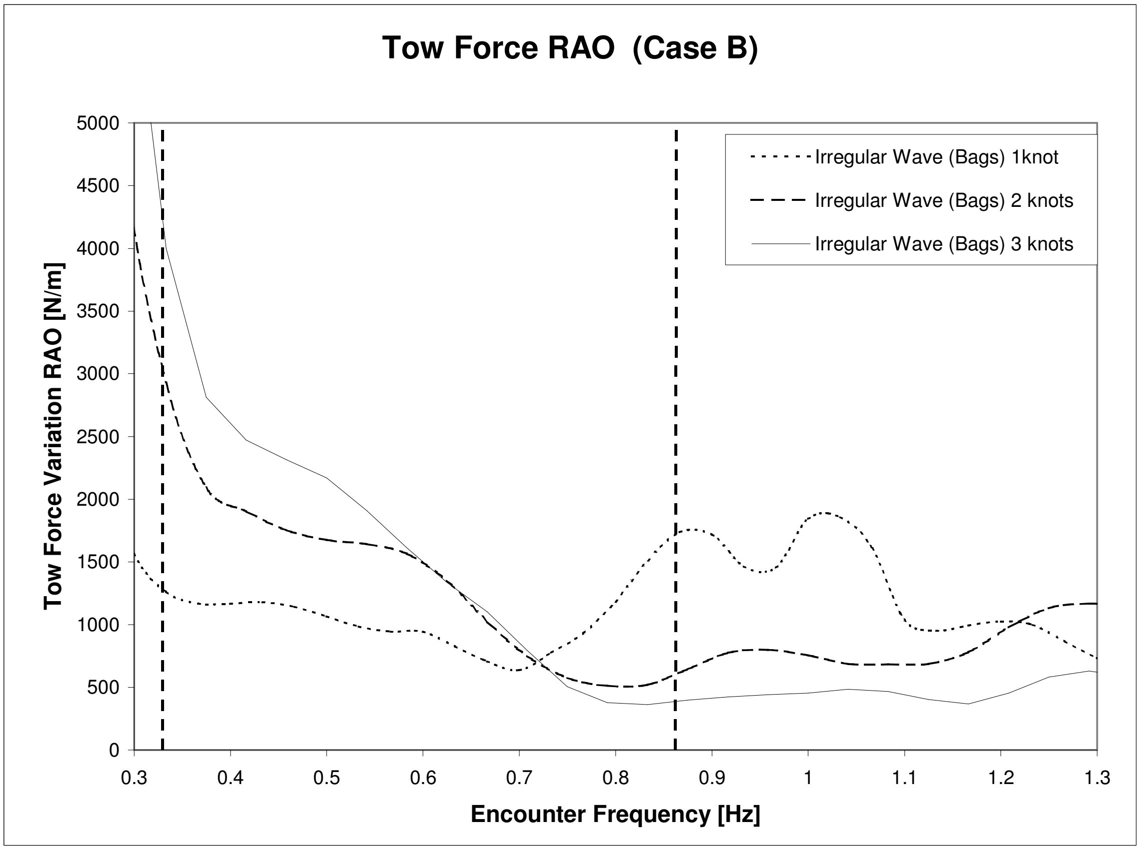
Appendix C

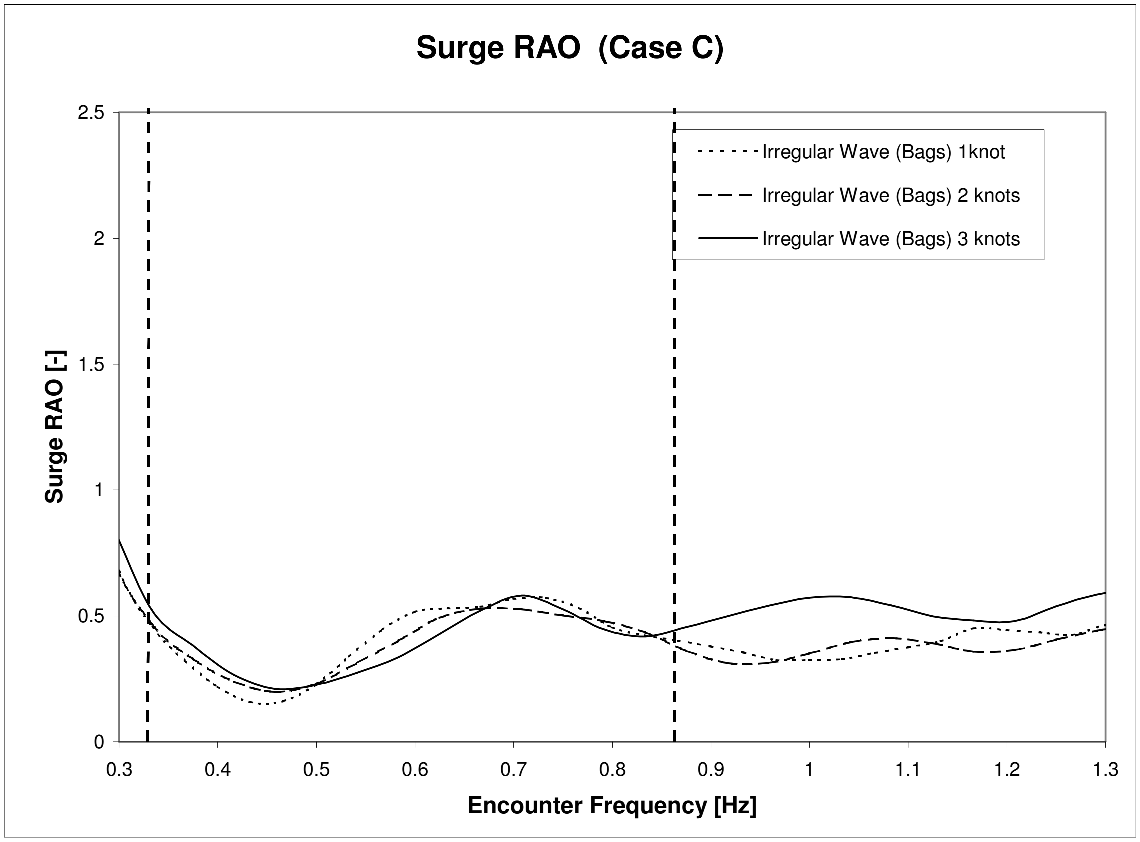
Effect of tow speeds on life raft motion and tow force RAO.

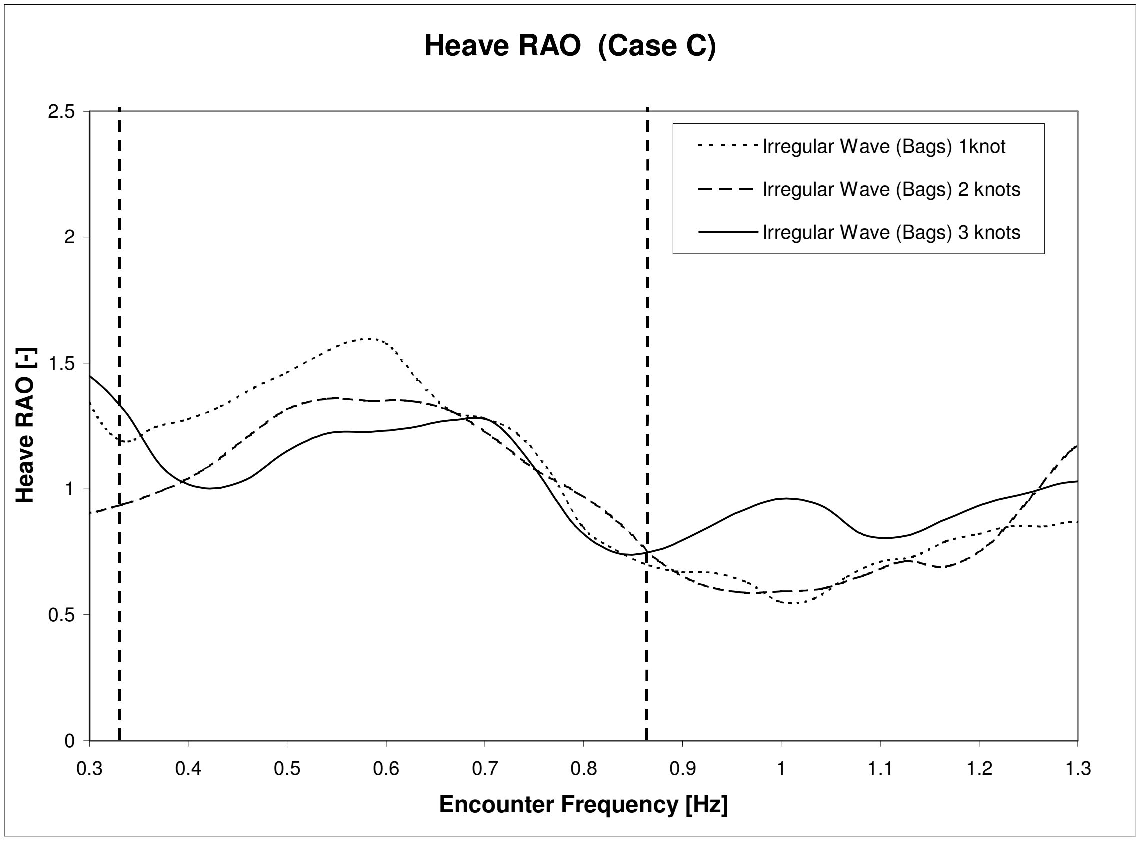

Surge RAO (Case B)
2.5
2
1.5
1
0.5
0
Surge RAO [-]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

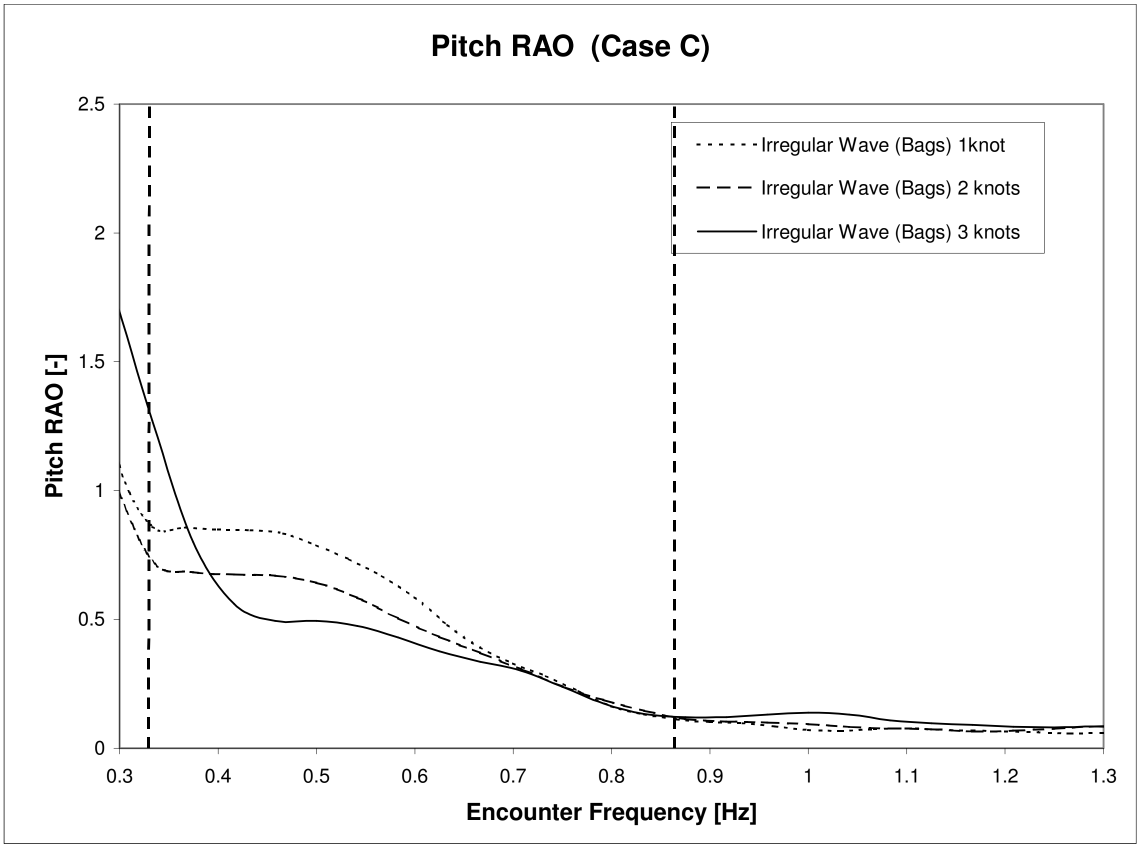

Heave RAO (Case B)
2.5
2
1.5
1
0.5
0
Heave RAO [-]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

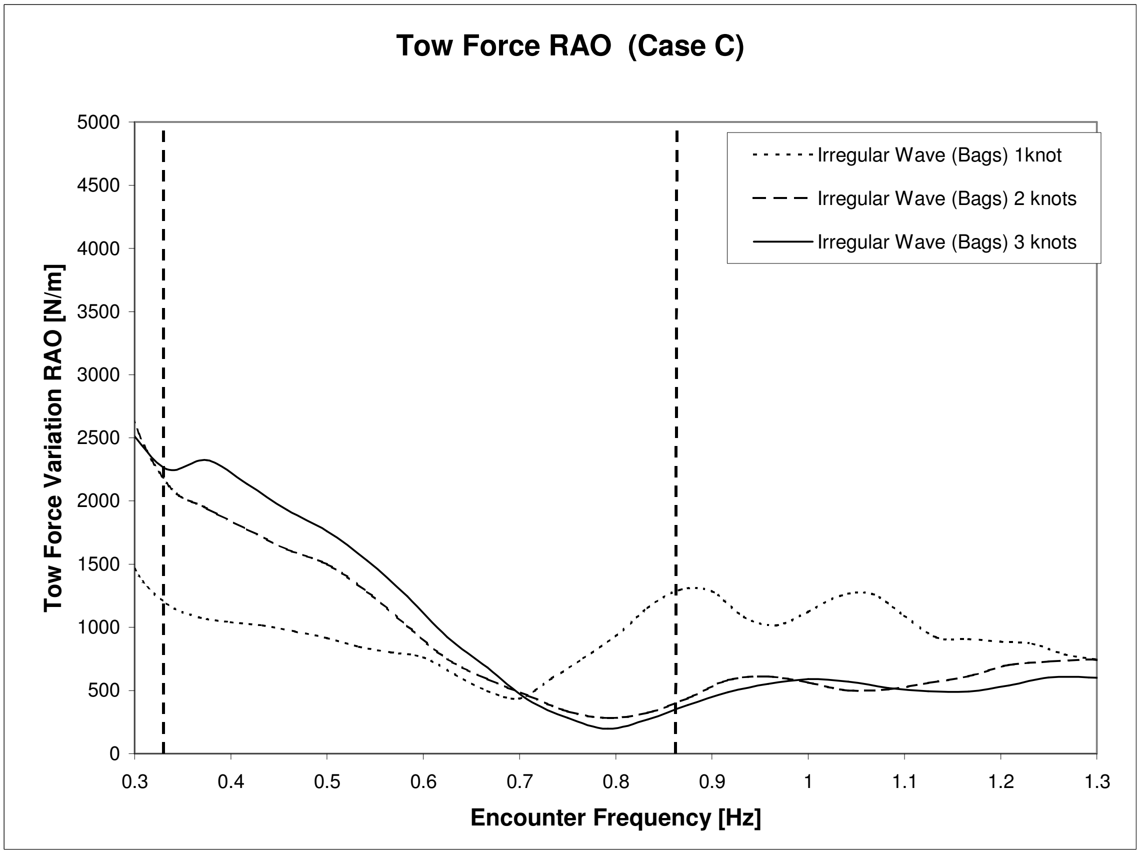

Pitch RAO (Case B)
Pitch RAO [-]
Encounter Frequency [Hz]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

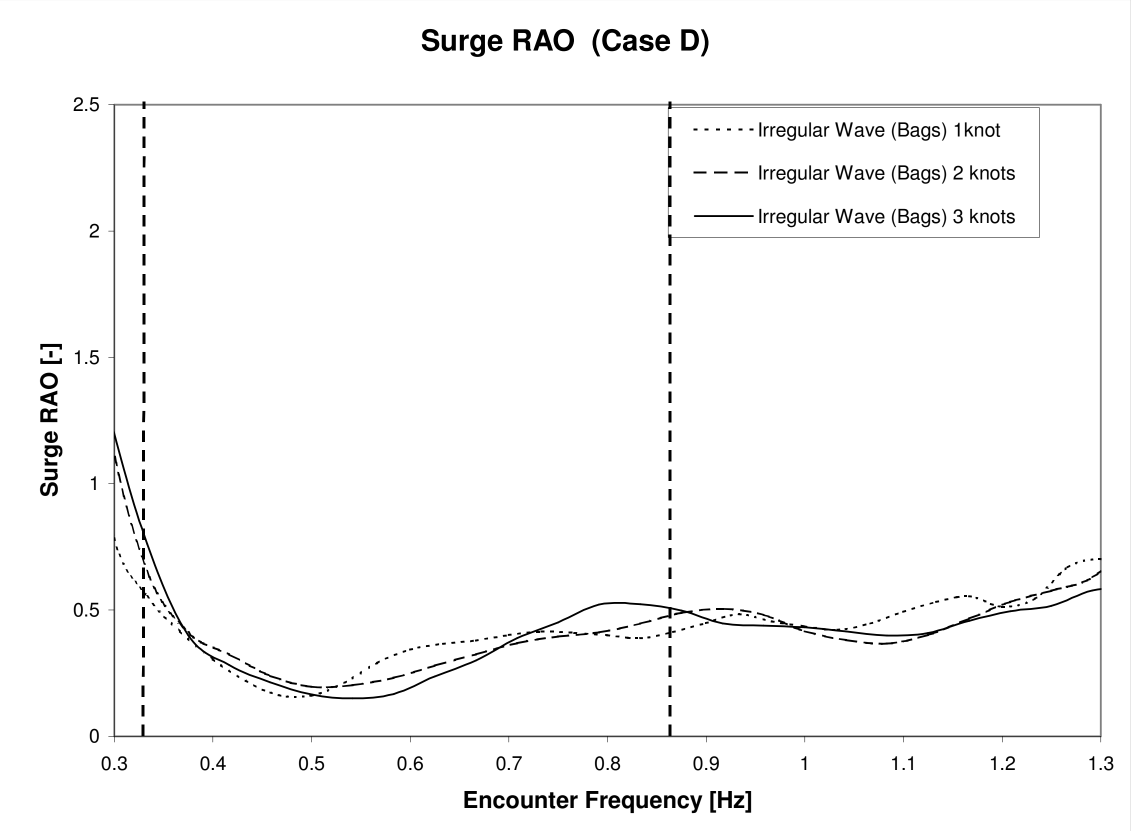

Tow Force RAO (Case B)
Tow Force Variation RAO [N/m]
Encounter Frequency [Hz]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

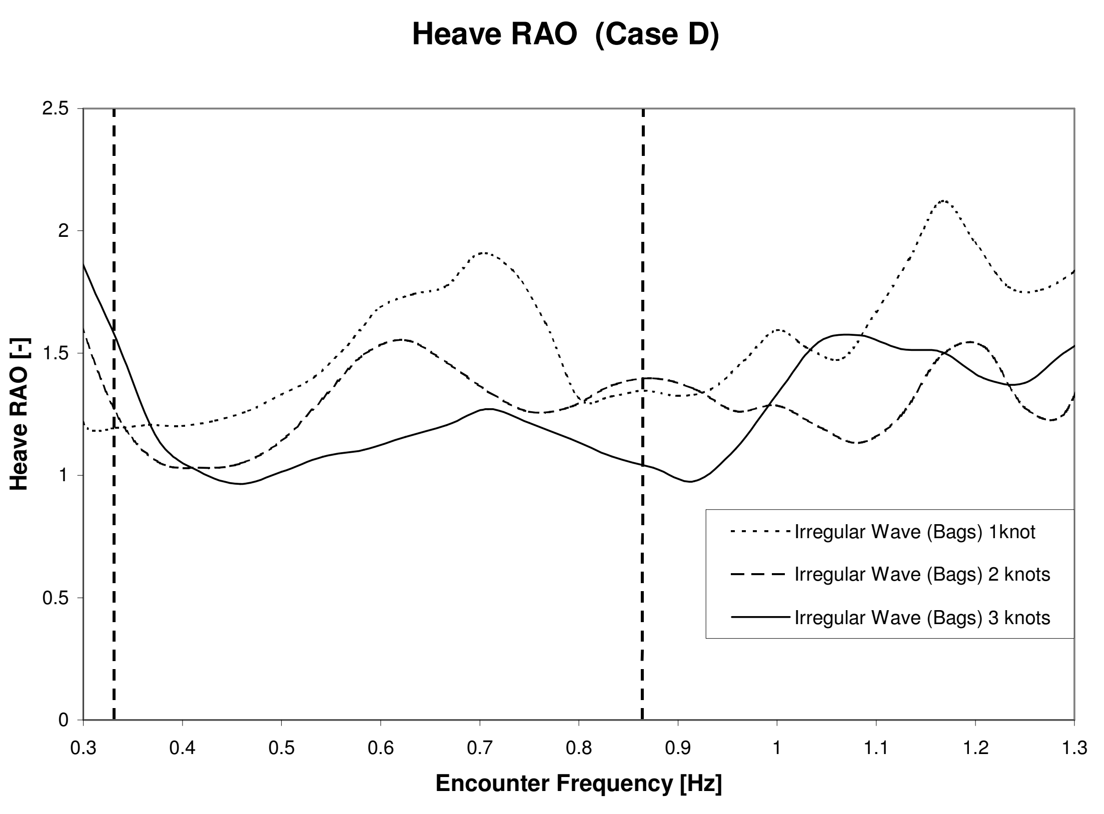

Surge RAO (Case C)
Surge RAO [-]
Encounter Frequency [Hz]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

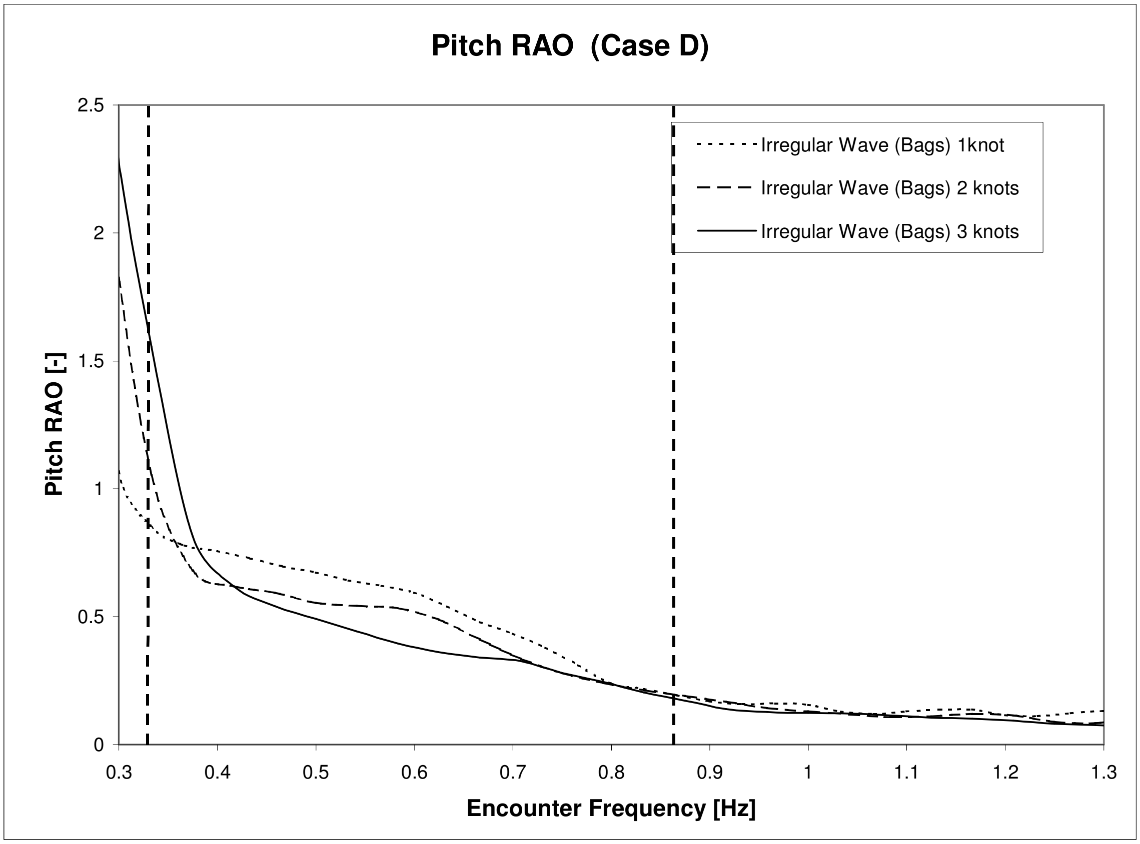

Heave RAO (Case C)
Heave RAO [-]
Encounter Frequency [Hz]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

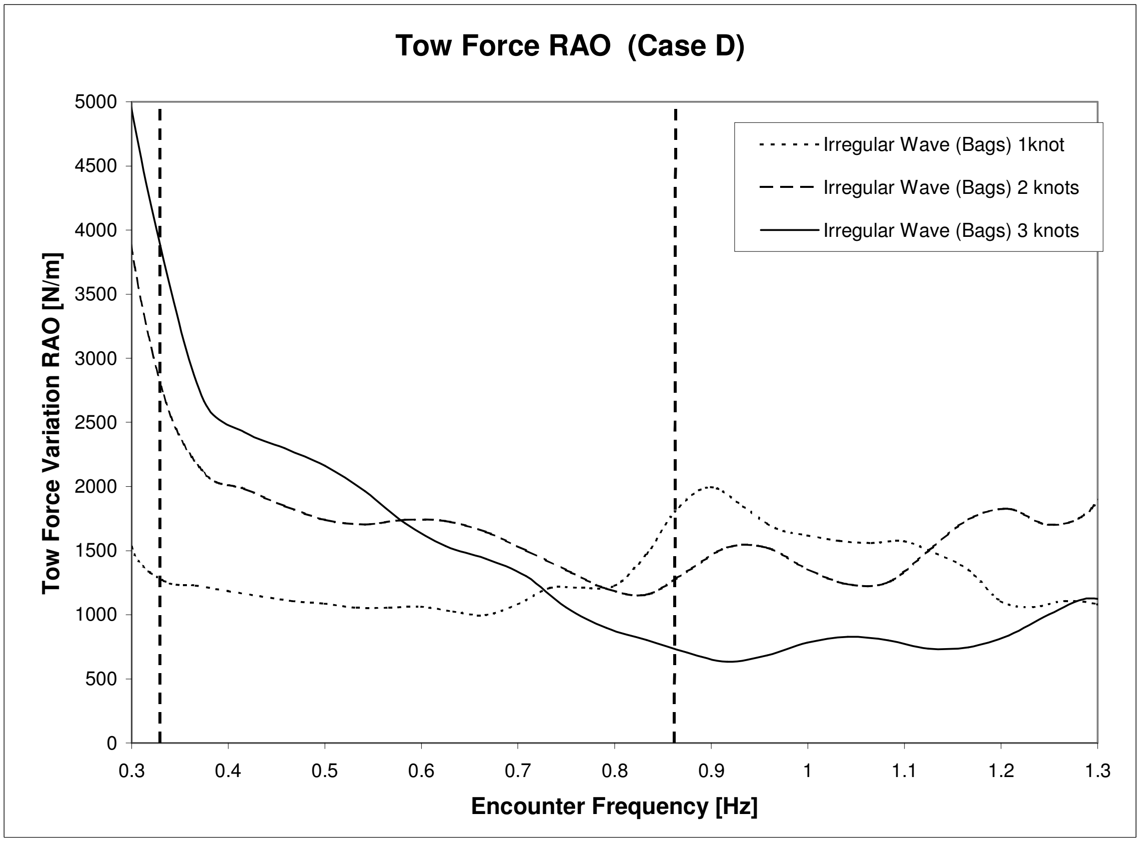

Pitch RAO (Case C)
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

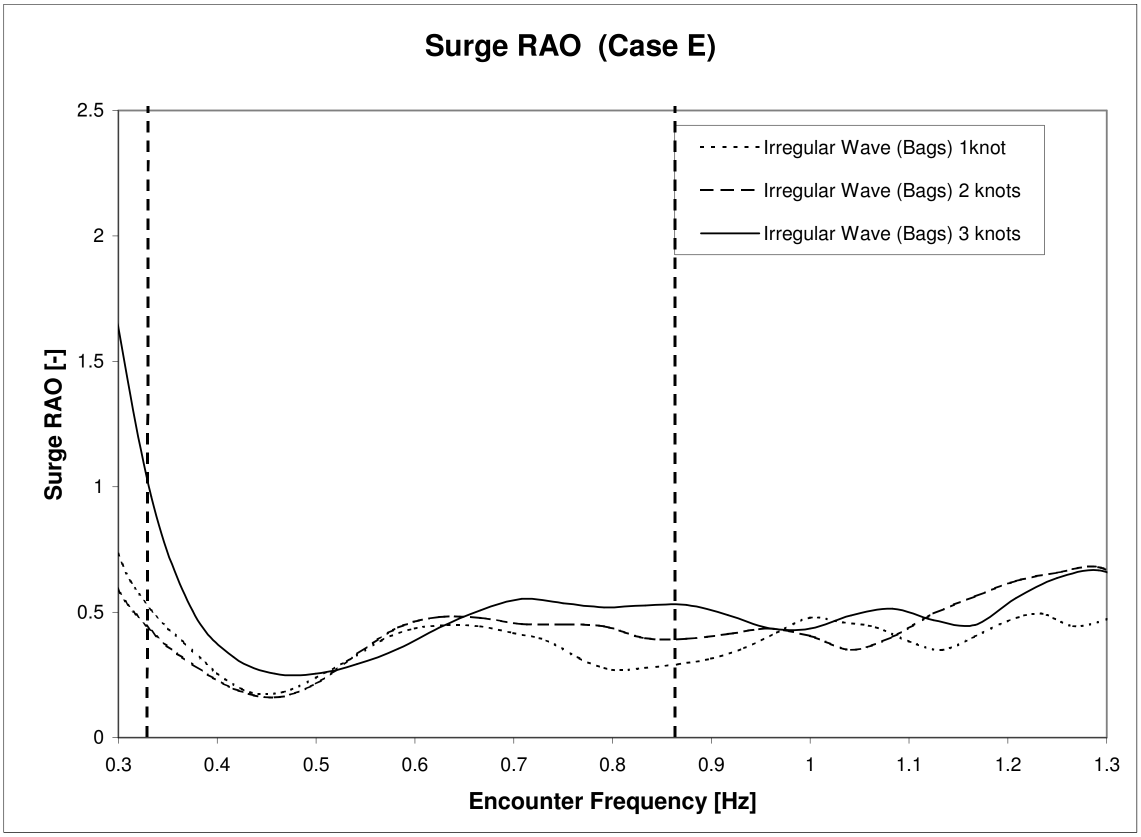

Tow Force RAO (Case C)
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

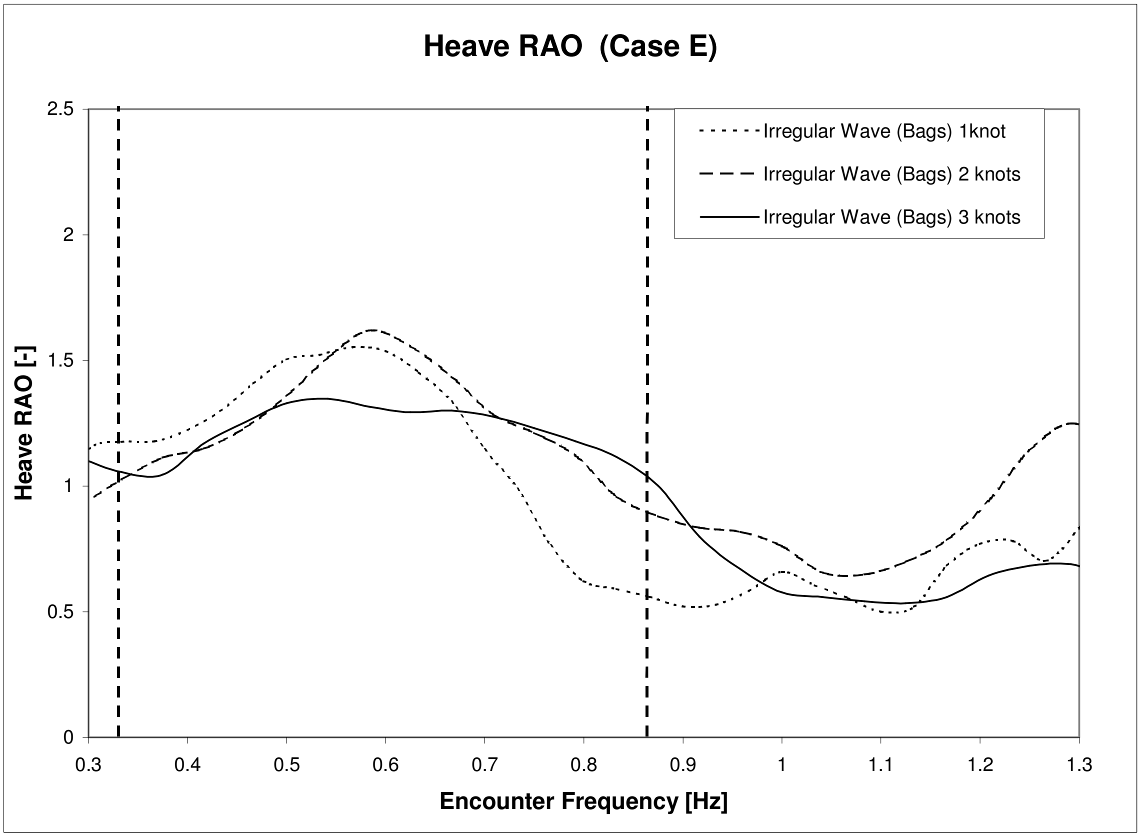

Surge RAO (Case D)
Surge RAO [-]
Encounter Frequency [Hz]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

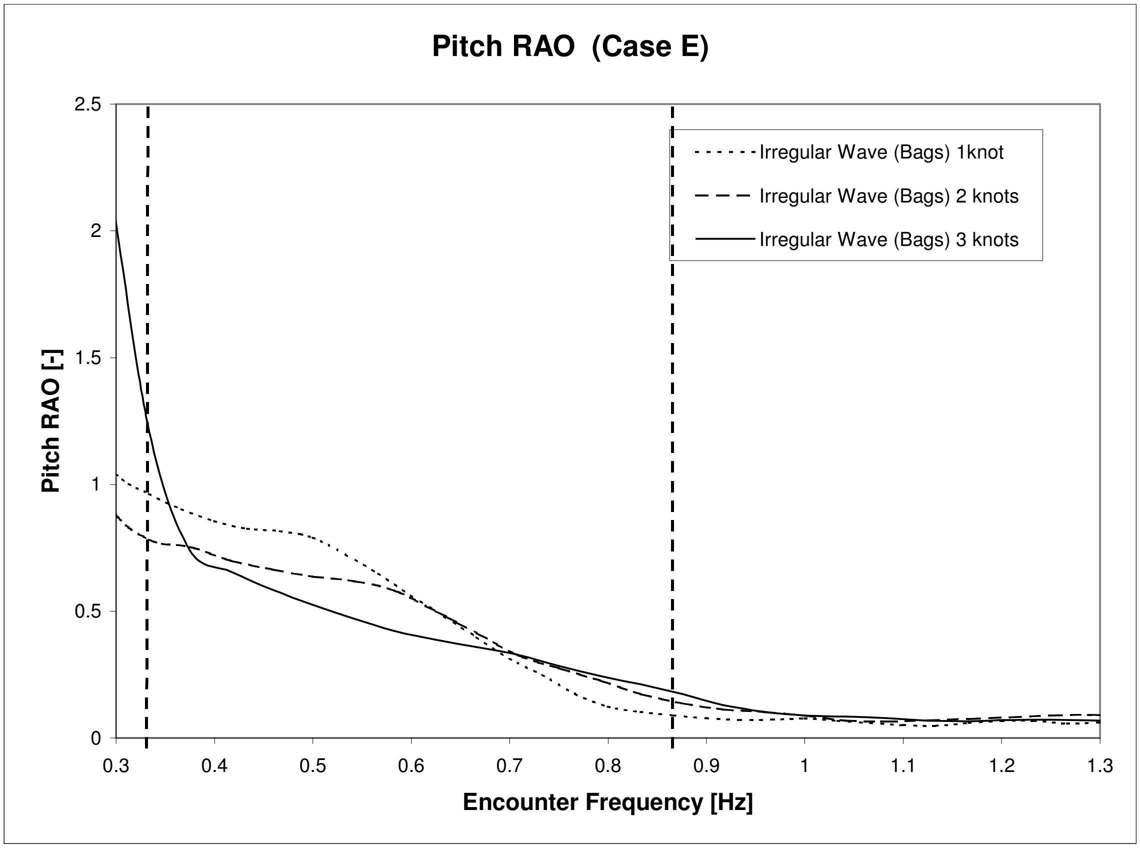

Heave RAO (Case D)
Heave RAO [-]
Encounter Frequency [Hz]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

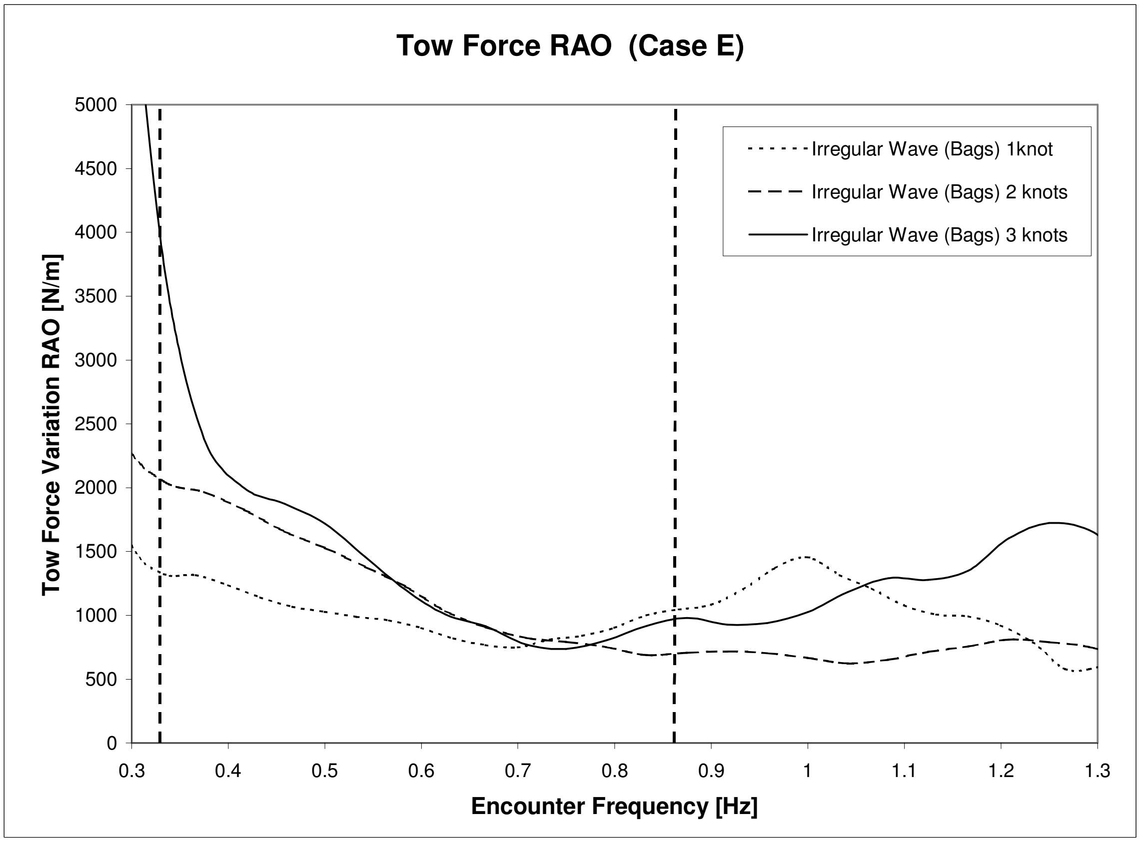

Pitch RAO (Case D)
Pitch RAO [-]
Encounter Frequency [Hz]
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

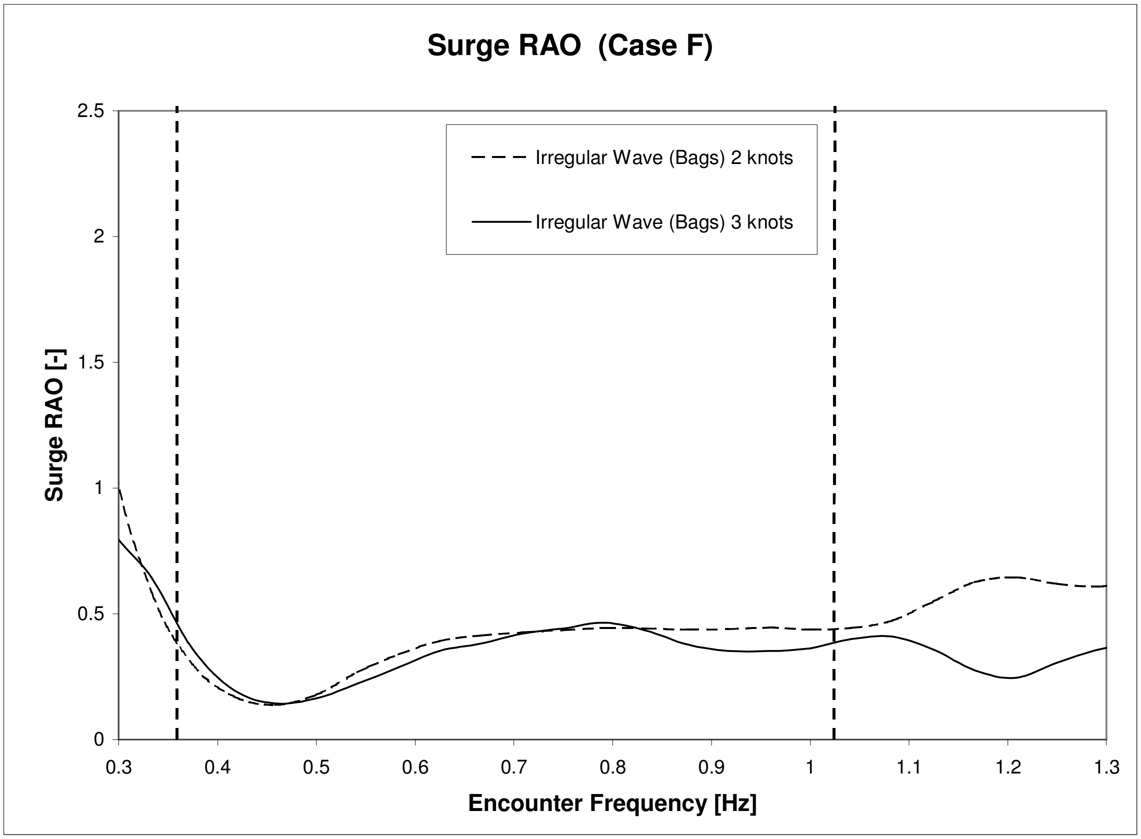

Tow Force RAO (Case D)
Tow Force Variation RAO [N/m]
Encounter Frequency [Hz]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots

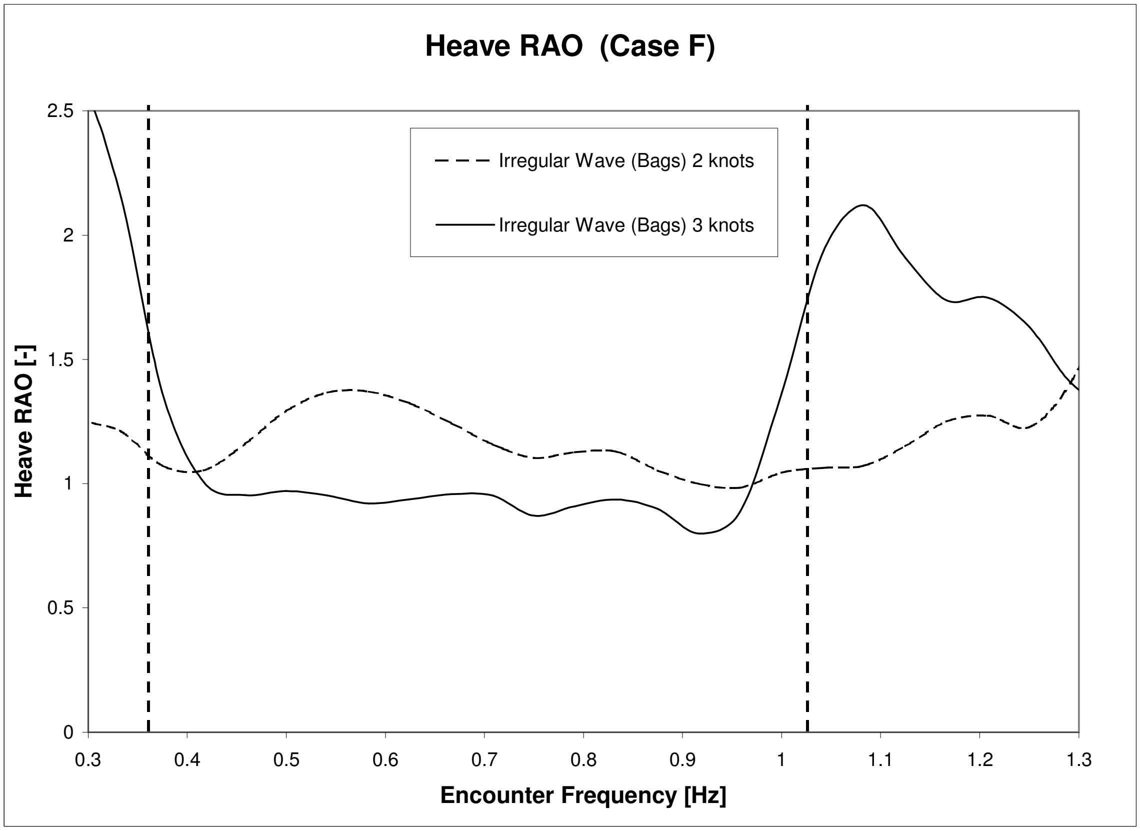

Surge RAO (Case E)
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

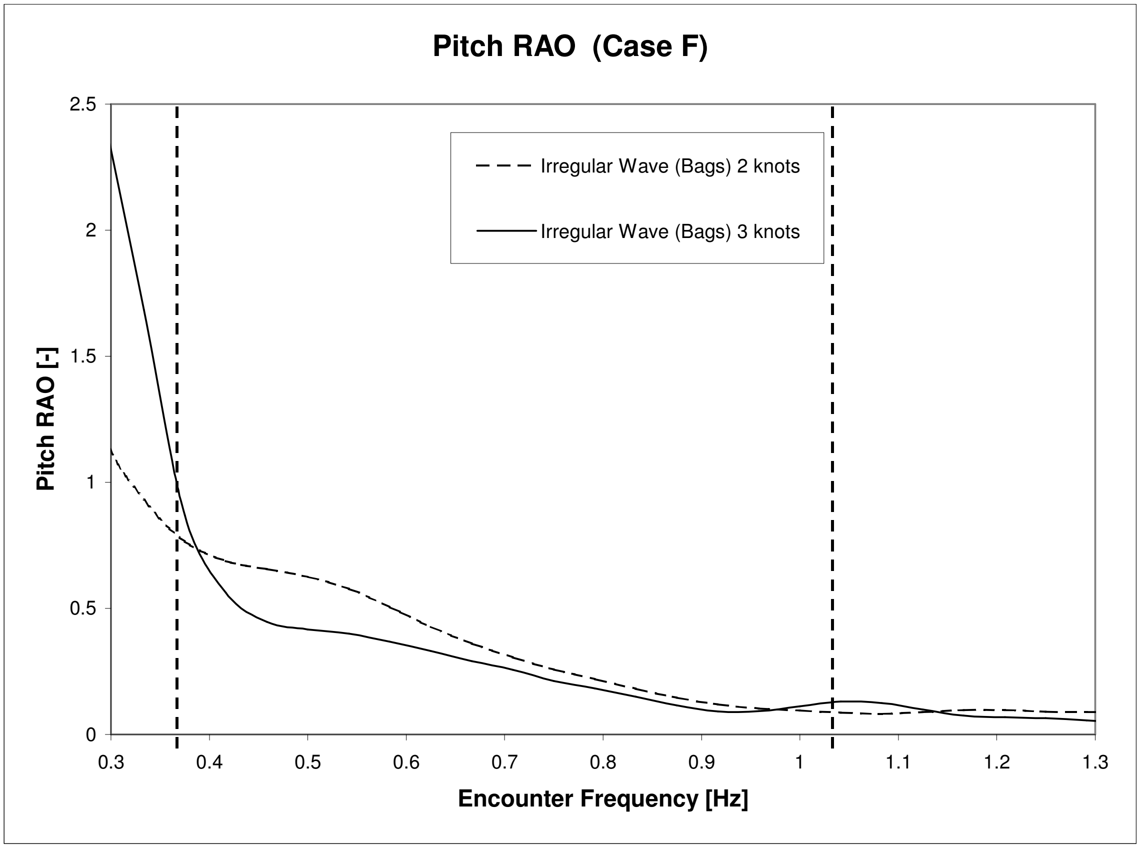

Heave RAO (Case E)
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

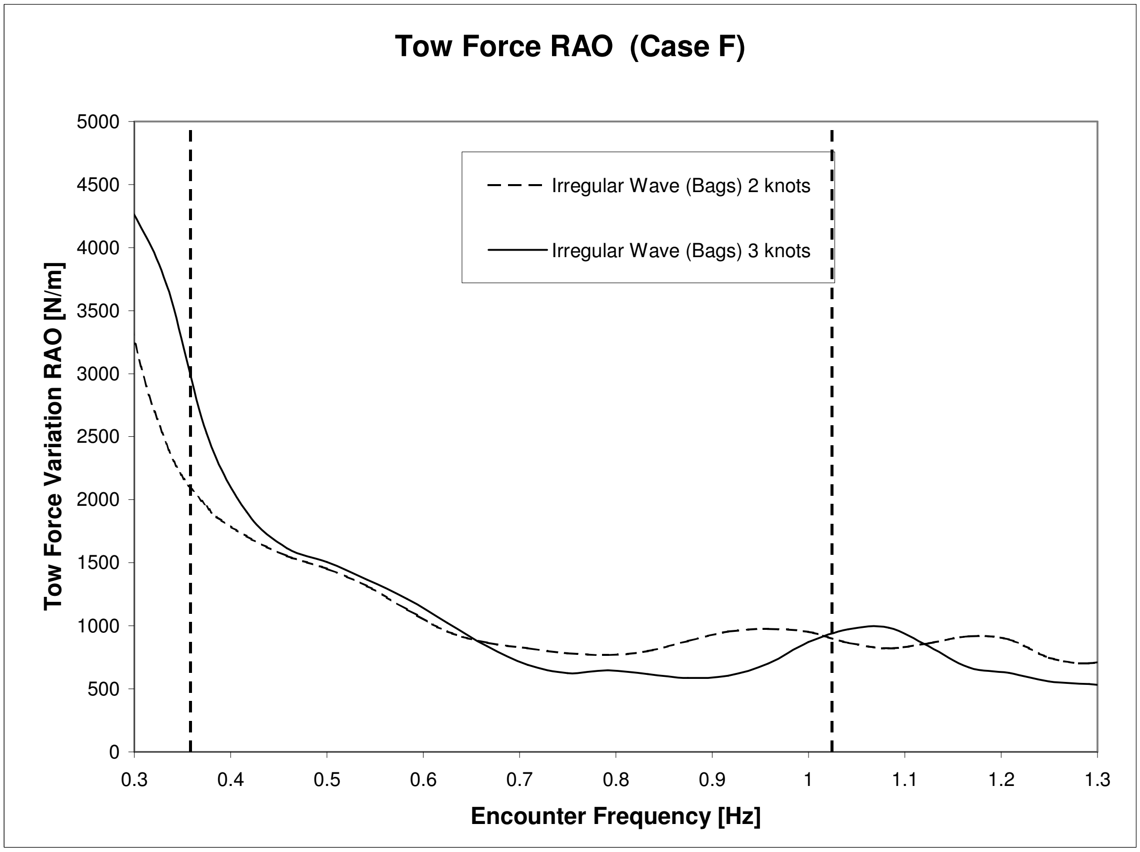

Pitch RAO (Case E)
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots


Tow Force RAO (Case E)
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]
Irregular Wave (Bags) 1knot
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots


Surge RAO (Case F)
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

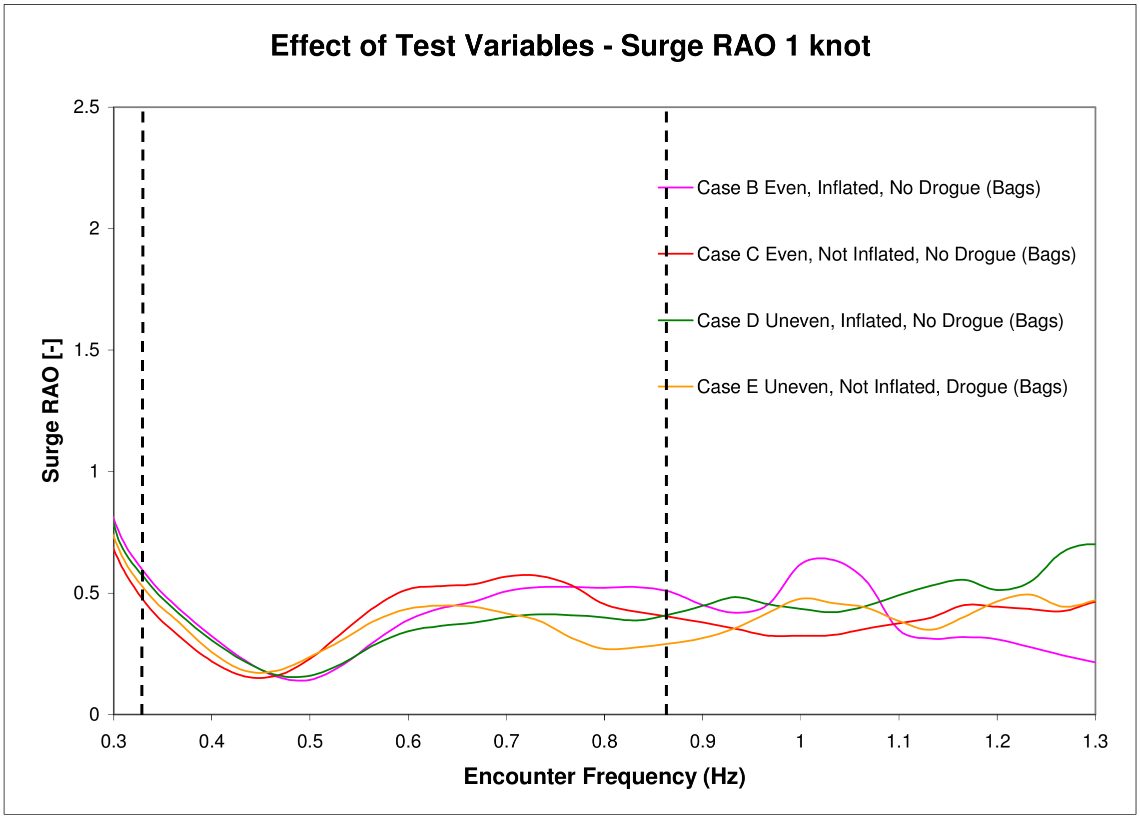

Heave RAO (Case F)
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Heave RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency [Hz]

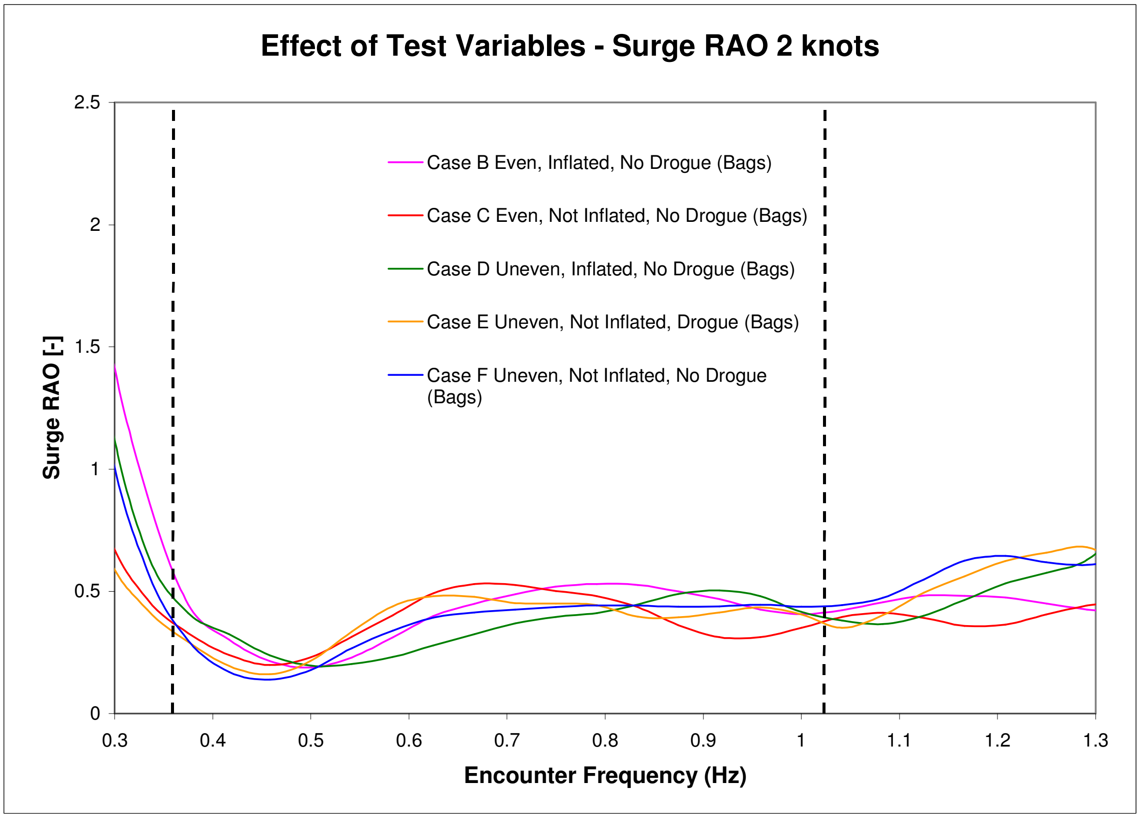

Pitch RAO (Case F)
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Pitch RAO [-]
0
0.5
1
1.5
2
2.5
Encounter Frequency [Hz]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

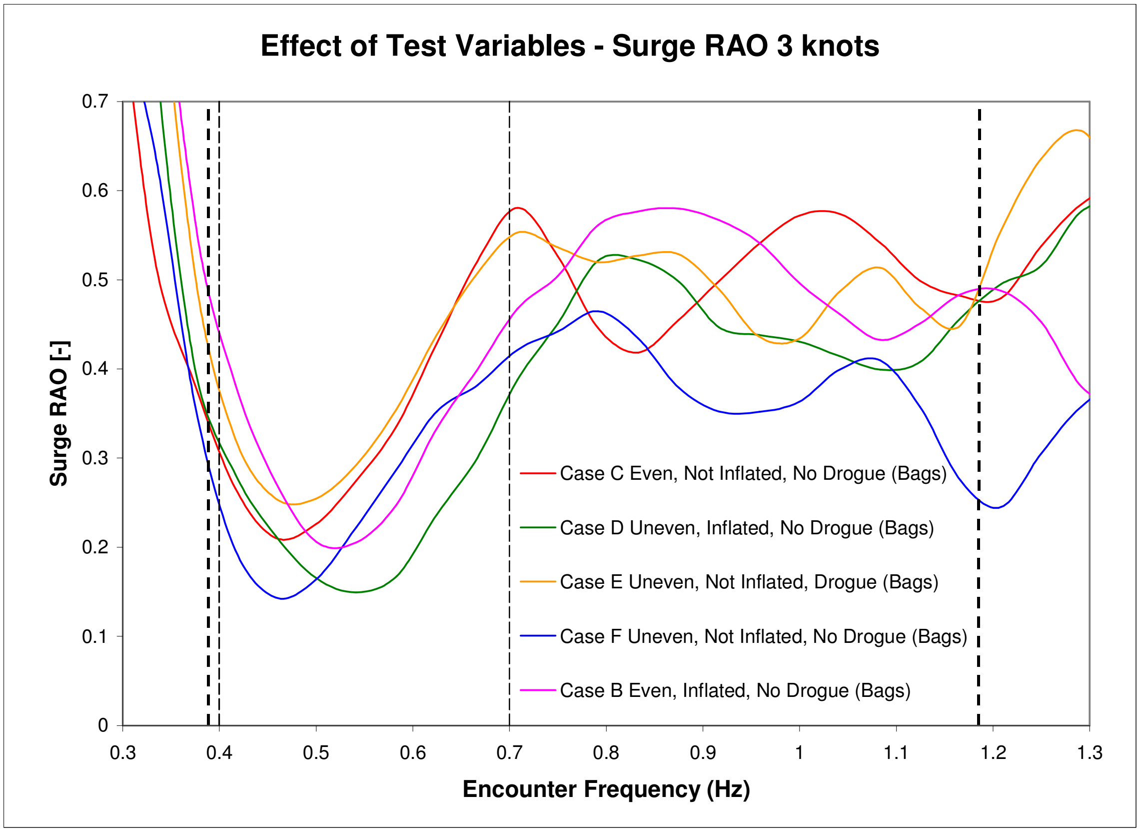

Tow Force RAO (Case F)
Irregular Wave (Bags) 2 knots
Irregular Wave (Bags) 3 knots
Tow Force Variation RAO [N/m]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Encounter Frequency [Hz]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3

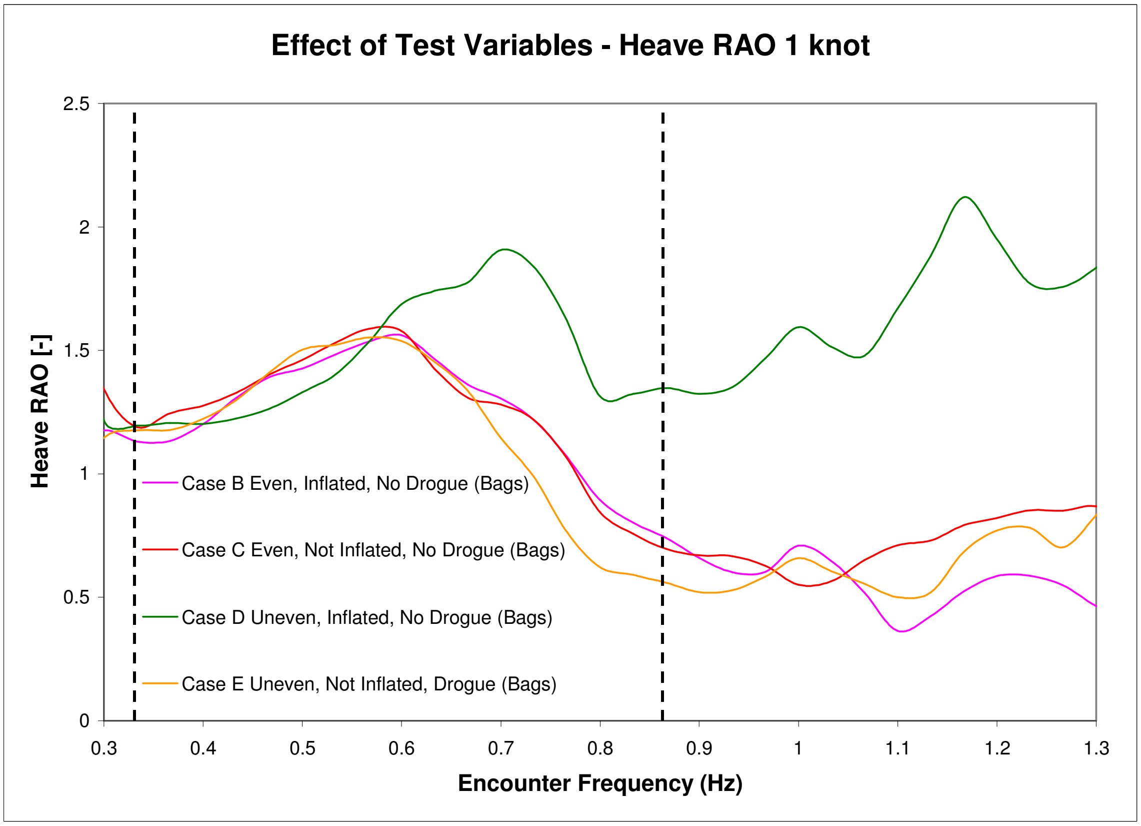
Appendix D

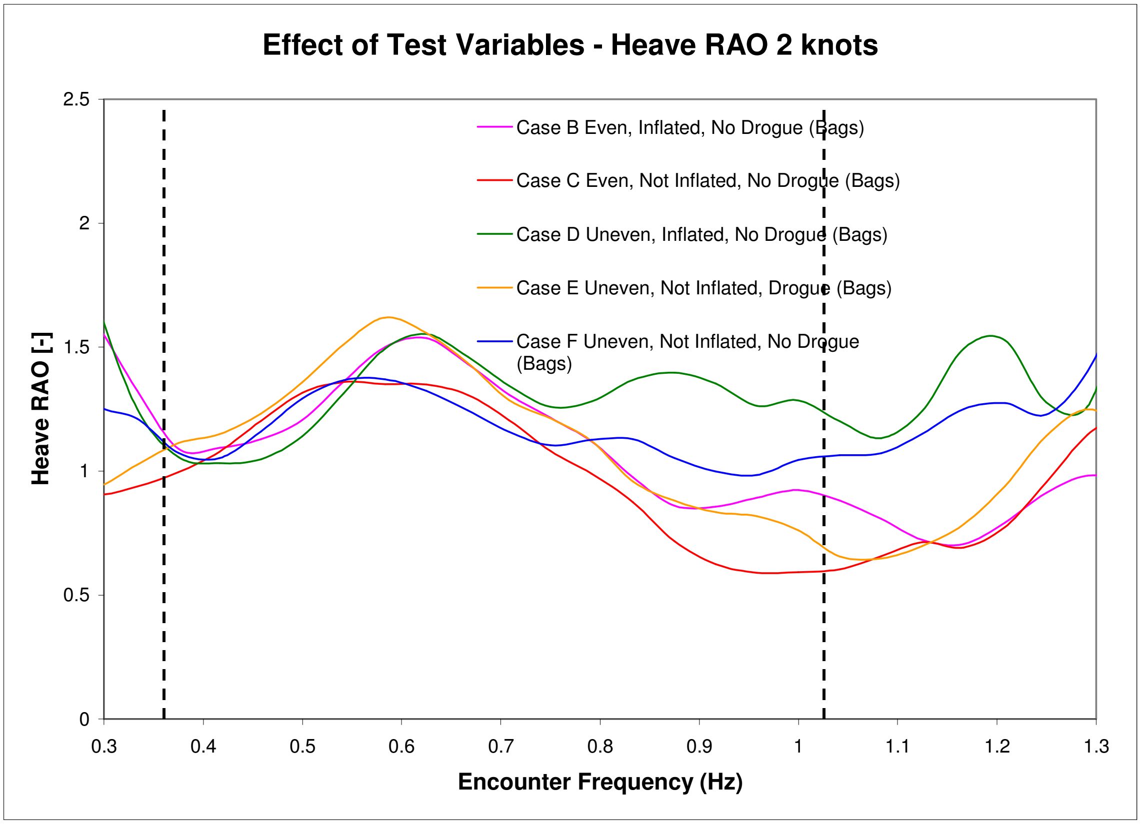
Effect of test variables on life raft motion and tow force RAO.

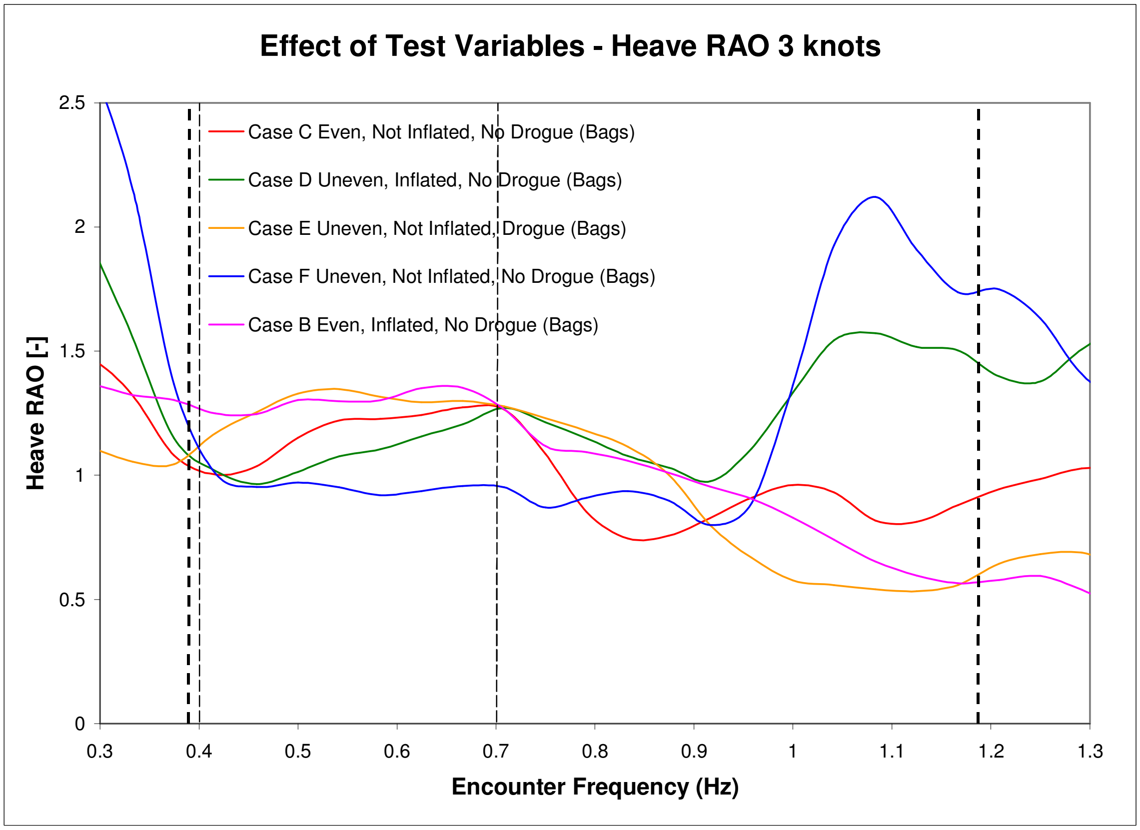

Effect of Test Variables - Surge RAO 1 knot
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency (Hz)
Case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)

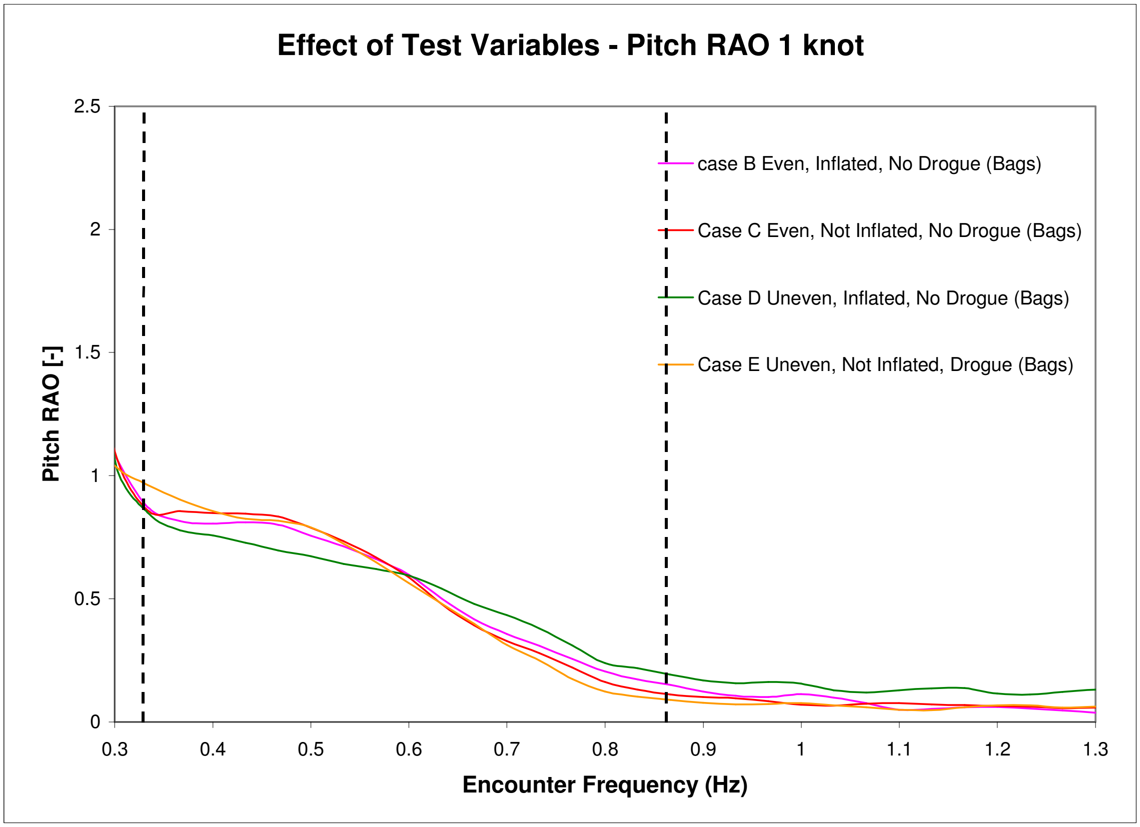

Effect of Test Variables - Surge RAO 2 knots
Surge RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency (Hz)
Case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)

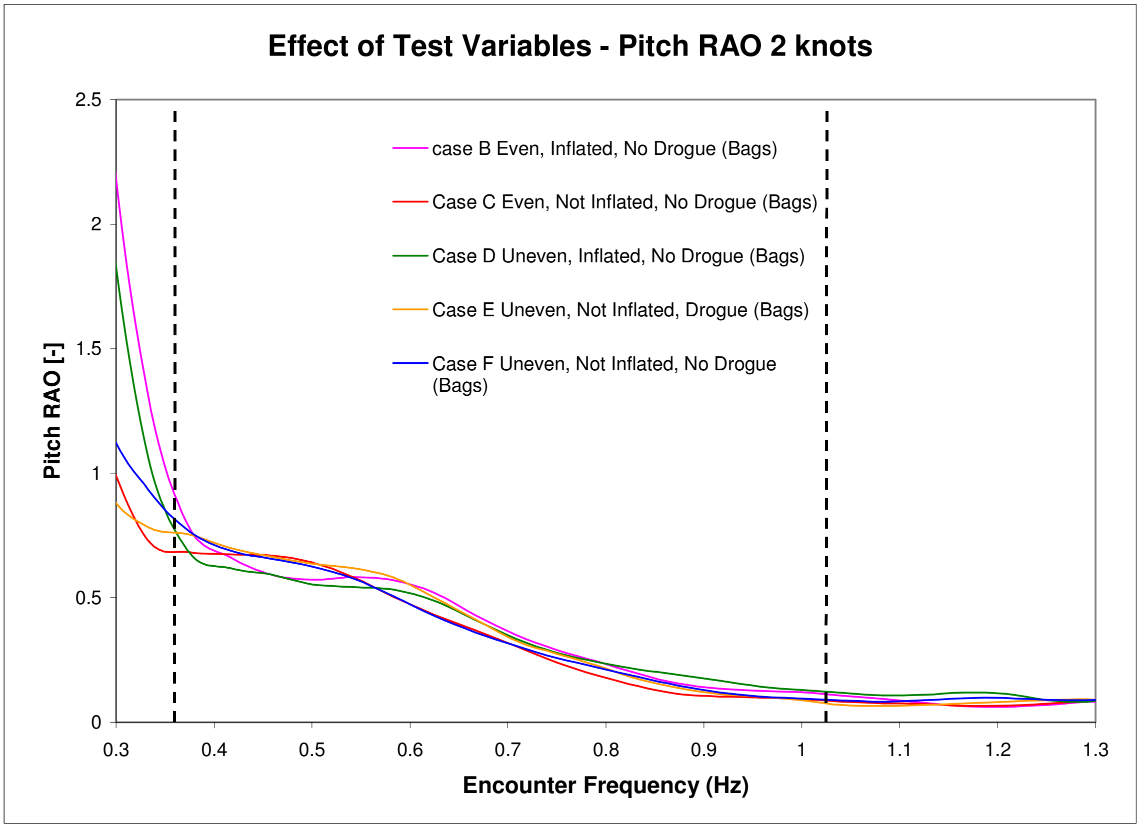

Effect of Test Variables - Surge RAO 3 knots

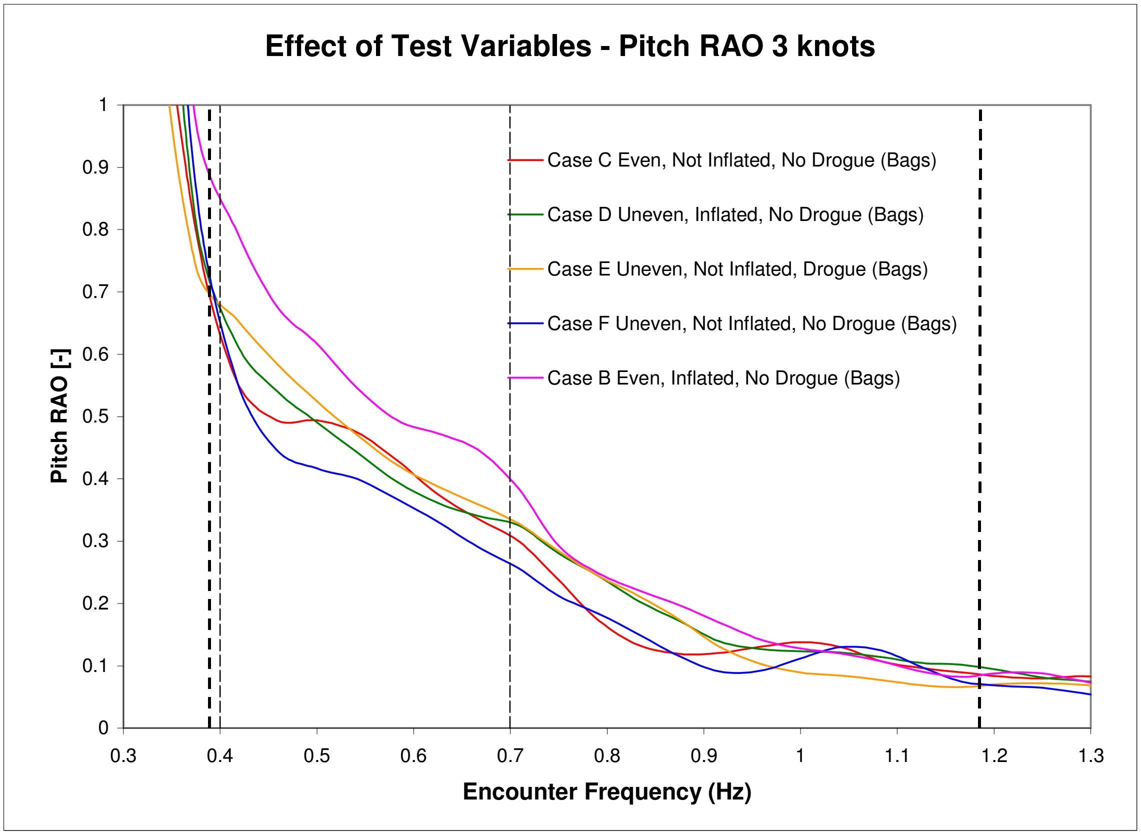

Effect of Test Variables - Heave RAO 1 knot

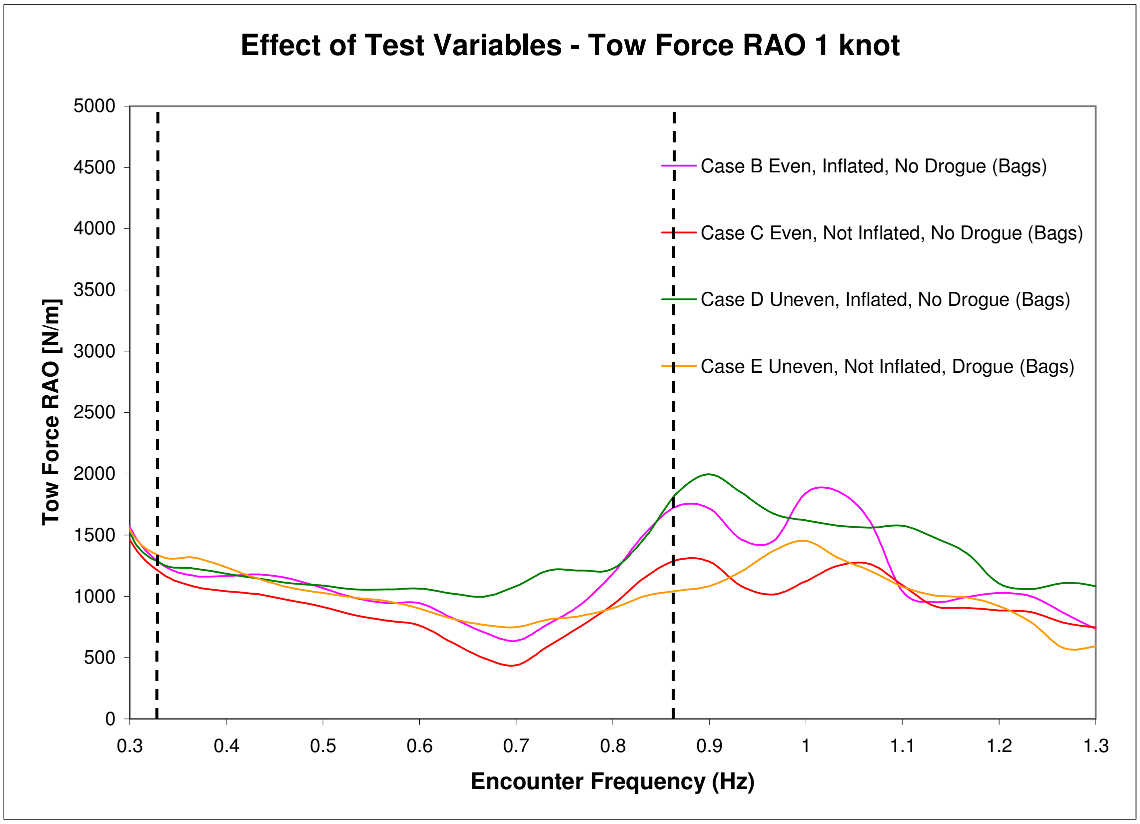

Effect of Test Variables - Heave RAO 2 knots
Heave RAO [-]
Encounter Frequency (Hz)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)

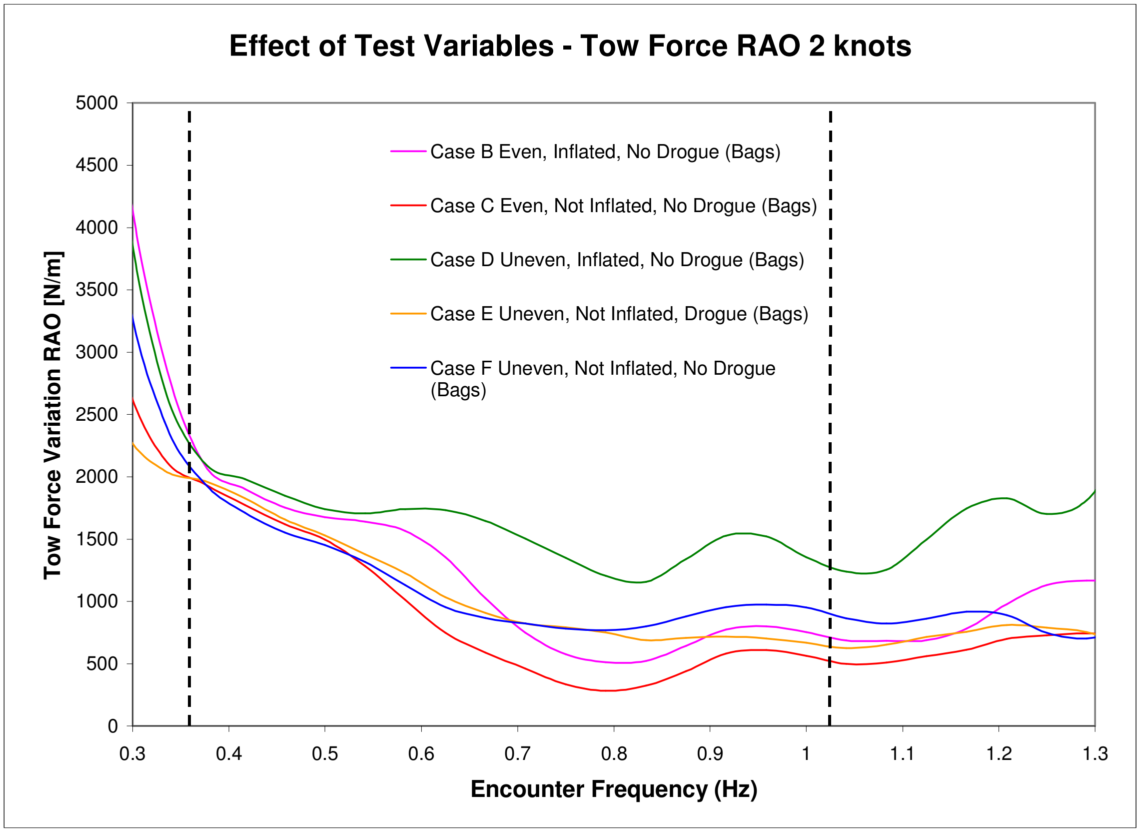

Effect of Test Variables - Heave RAO 3 knots
Heave RAO [-]
Encounter Frequency (Hz)
0
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)
Case B Even, Inflated, No Drogue (Bags)

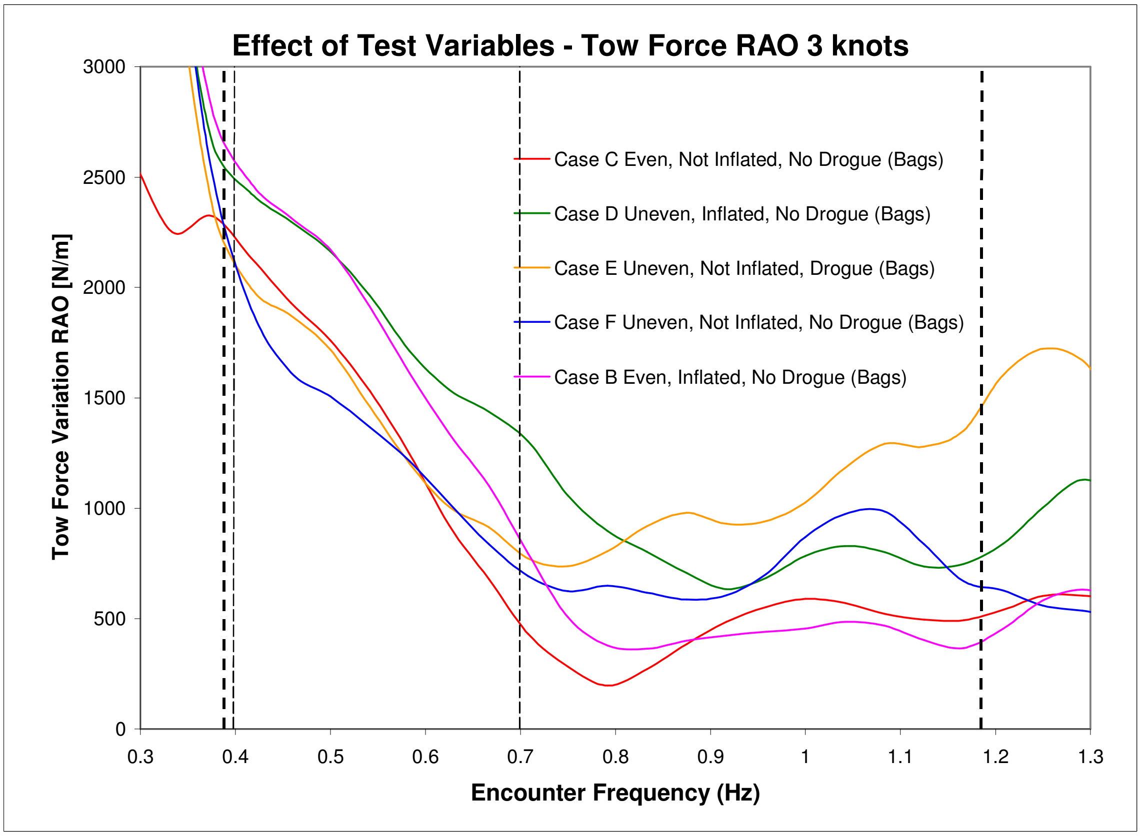

Effect of Test Variables - Pitch RAO 1 knot
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency (Hz)
case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)

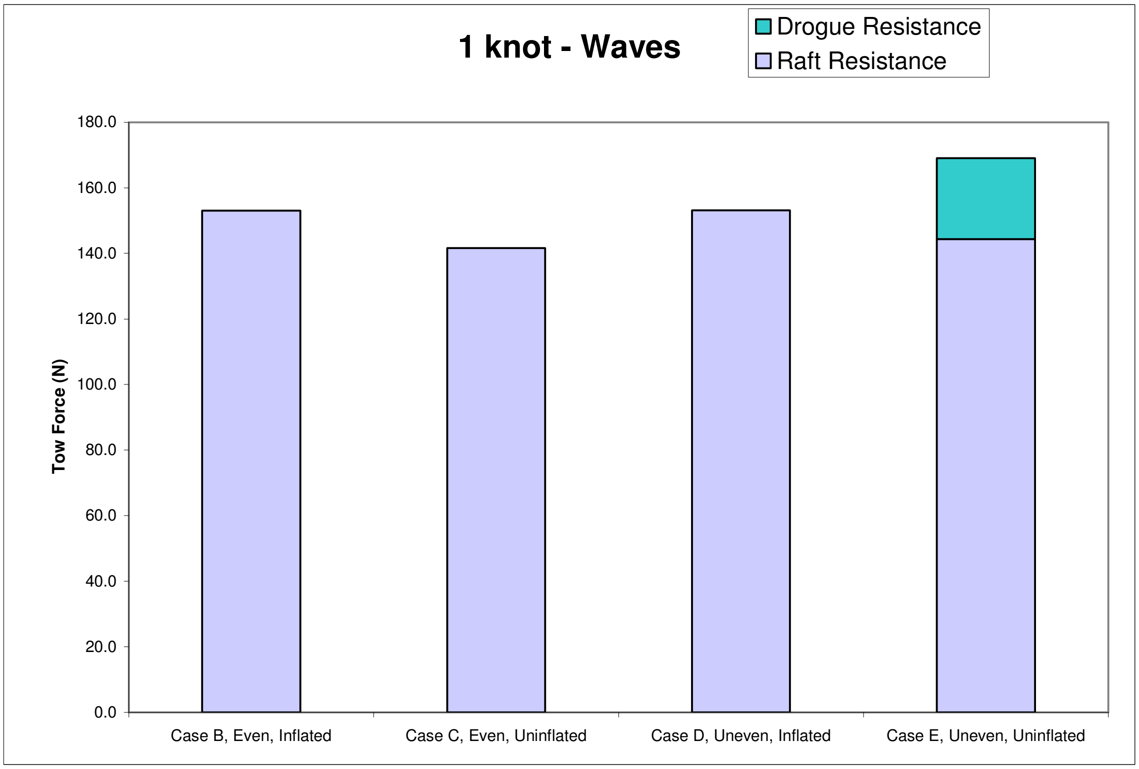

Effect of Test Variables - Pitch RAO 2 knots
Pitch RAO [-]
2.5
2
1.5
1
0.5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency (Hz)
case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)

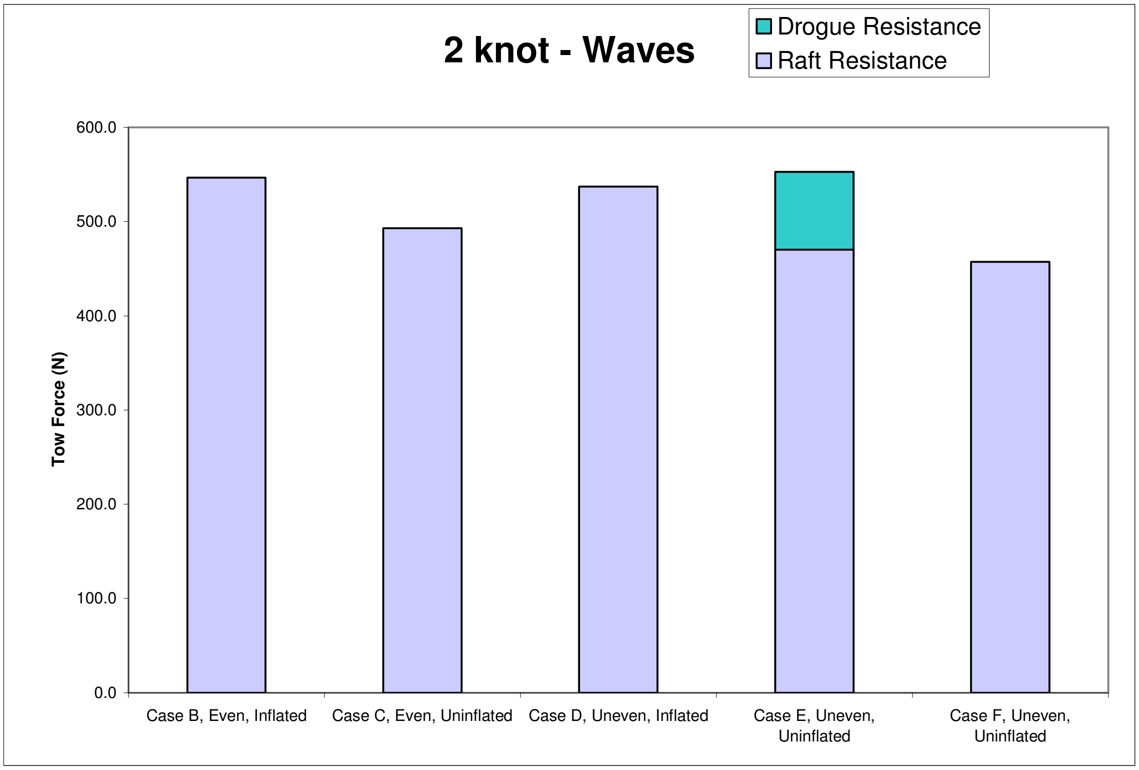

Effect of Test Variables - Pitch RAO 3 knots
Pitch RAO [-]
Encounter Frequency (Hz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)
Case B Even, Inflated, No Drogue (Bags)

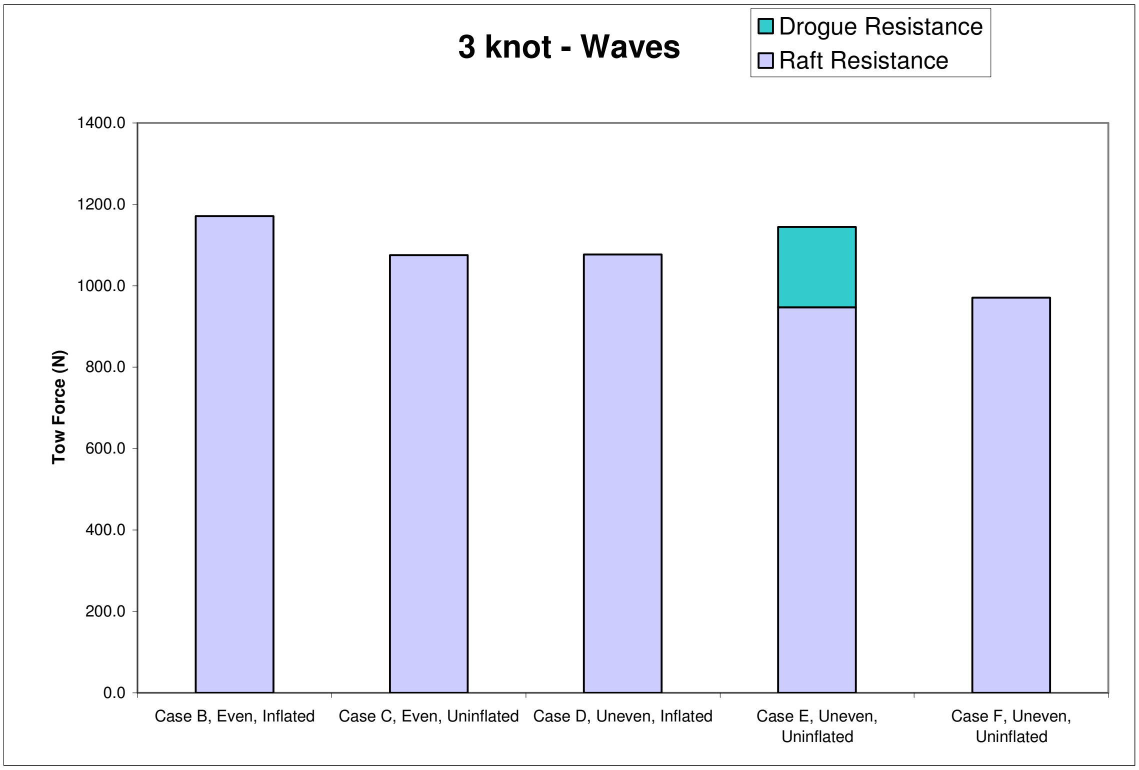

Effect of Test Variables - Tow Force RAO 1 knot
Tow Force RAO [N/m]
Encounter Frequency (Hz)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)


Effect of Test Variables - Tow Force RAO 2 knots
Tow Force Variation RAO [N/m]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency (Hz)
Case B Even, Inflated, No Drogue (Bags)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)


Effect of Test Variables - Tow Force RAO 3 knots
Tow Force Variation RAO [N/m]
3000
2500
2000
1500
1000
500
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Encounter Frequency (Hz)
Case C Even, Not Inflated, No Drogue (Bags)
Case D Uneven, Inflated, No Drogue (Bags)
Case E Uneven, Not Inflated, Drogue (Bags)
Case F Uneven, Not Inflated, No Drogue (Bags)
Case B Even, Inflated, No Drogue (Bags)


1 knot - Waves
Drogue Resistance
Raft Resistance
Tow Force (N)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Case B, Even, Inflated
Case C, Even, Uninflated
Case D, Uneven, Inflated
Case E, Uneven, Uninflated


2 knot - Waves
Drogue Resistance
Raft Resistance
Tow Force (N)
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Case B, Even, Inflated
Case C, Even, Uninflated
Case D, Uneven, Inflated
Case E, Uneven, Uninflated
Case F, Uneven, Uninflated


3 knot - Waves
Drogue Resistance
Raft Resistance
Tow Force (N)
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
Case B, Even, Inflated
Case C, Even, Uninflated
Case D, Uneven, Inflated
Case E, Uneven, Uninflated
Case F, Uneven, Uninflated