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An Empirical Method for the Estimation of Towing Resistance of a Life Raft in various Sea States

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ABSTRACT

Current IMO regulations require life rafts to be tow tested only in calm water. In real evacuation situations, life rafts are deployed in the prevailing environmental conditions, with wind and waves. Added wave resistance is small at low wave heights but increases nonlinearly with increased wave height. If life rafts are to be towed in moderate seas (up to 4 m significant wave height), tow force estimates based only on calm water tow resistance become less reliable. Tow patches, towline, towing craft etc. also need to be designed to withstand dynamic wave loading in addition to mean load. Therefore, mean tow force, tow force variation and maximum tow force are important.

A full-scale 16-person, commercially available, SOLAS approved life raft was towed in the tank, in upwind, head seas with significant wave height of 0.5 m. The measured tow force showed that it could be treated as a linear system with wave amplitude, by demonstrating that tow force is mainly inertial and follows a Rayleigh distribution. Therefore, extreme-value statistics used for waves can be applied to developing equations for predicting tow force.

A method is proposed to predict life raft tow force at different tow speeds and in various sea states, with waves and wind. The method involved using tank experiments to obtain tow force response for one sea state. The information can then be used to predict life raft tow force in wind and waves for different sea states.

Three equations are proposed to demonstrate that a simple tank experiment could provide valuable information necessary to empirically estimate the mean tow force, tow force variation and maximum tow force for a specific life raft in different sea states. The equations are developed for upwind, head seas.

These equations were extensively validated using tow force measured in the tank. They were partially validated with limited sea trial data, by towing the same 16-person life raft and a 42-person life raft in upwind, head seas with significant wave height of 1.3 m. The equations were able to predict maximum tow forces to within 15% of the measured.

INTRODUCTION

Inflatable life rafts are commonly used on oil installations, merchant ships, cruise ships, ferries, military vessels and small vessels for evacuation. Large passenger ships, such as ferries, are typically equipped with dedicated motor crafts to tow the life rafts to safety, away from hazards such as fires, explosions, collisions and sinking vessels.

Currently IMO regulations require life rafts to be tow tested only in calm water. However, in real evacuation situations, life rafts are deployed in the prevailing environmental conditions, with wind and waves. Literatures reviewed by Mak et el. (2005) indicated that both environmental variables and life raft variables affect life raft stability and motion. Therefore, it is important to assess life raft towing performance in waves and wind.

Furthermore, added resistance due to waves is small at low wave heights but increases nonlinearly with increased wave height. If life rafts are to be towed in moderate seas (up to 4 m significant wave height), tow force estimates based only on calm water tow resistance become less reliable. Tow patches, towline, towing craft etc. also need to be designed to withstand the dynamic loads caused by the waves, in addition to the mean load. Therefore, information of mean tow force and tow force variation about its mean in various sea states is an important component to consider.

Currently, data on life raft towing performance in waves and wind are very limited. A comprehensive life raft tow test program composed of a full-scale tank test, a model-scale tank test and a sea trial was designed to address the knowledge gap. The combined data will provide needed information to address how different variables affect 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.

Mak et el. (2005, 2006) presented the results of tow tests of a full-scale life raft in waves, conducted in the tow tank of National Research Council Canada (NRC), Institute for Ocean Technology (IOT). The results indicated that:

- The type of ballast used is very important. The tests demonstrated that manikin ballast results in higher mean tow force and tow force variation than water bag ballast.
- There was very good agreement between the comparison of life raft Response amplitude operators (RAO) (in surge, heave, pitch and tow force variation) in regular and irregular waves. Irregular waves can be used effectively to determine the motion response RAOs of the life raft, without running individual regular waves.
- Irregular waves mean tow force is 20% higher than that in calm water, for the relatively mild sea condition tested (significant wave height 0.5 m), which is roughly equivalent to sea state 2 without wind.
- Mean tow force and raft heave increase with floor inflation, drogue deployment, even weight distribution and increased tow speed. Floor inflation also increases tow force variation. Raft heave tends to decrease with tow speed.
- Even weight distribution and drogue deployment increase raft surge, while floor inflation decreases raft surge.
- The measured occupant heave acceleration (from instrumented manikin) was about the same as the measured raft heave acceleration, indicating that the occupants would experience similar heave motions to those of the raft heave.
- The motion sickness dose value predicts that 20% of occupants would vomit after 20 hours in the life raft, for the relatively mild sea state tested (significant wave height = 0.5 m). The percentage of occupants vomiting is slightly lower at high tow speed.

Further advancement of this work to develop and validate a test method, which can be applied to different life rafts, to estimate the tow force in different sea states, is presented in this paper.

OBJECTIVES

The objectives of this project are:

1. To design a method that can be applied to different life rafts, to predict tow force at different tow speed and in various sea states, with waves and wind.
2. To validate the method and to prove the concept, using the data measured in towing a full-scale life raft in the tow tank and at sea.
3. To assess if added wave resistance and added wind resistance in moderate seas can increase the tow force significantly.
4. To propose formulae that will help regulators, training providers and manufacturers to determine the design load.

The scope of the project will be limited to predicting tow force in low to moderate seas, where it is possible for a well trained and experienced crew to tow a life raft and where there might not be too many breaking waves to cause significant nonlinear effects.

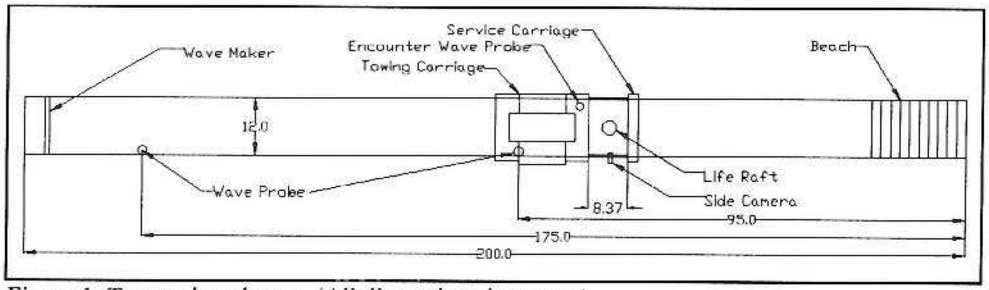

Figure 1. Tow tank and setup (All dimensions in meters)

TEST SETUP

The measured tow force from towing a full-scale 16-person, commercially available SOLAS approved life raft, in a tow tank and at sea, are used in the present study to validate the method. The results of these tests are documented in Mak et al. (2005, 2006) and Simões Ré et al. (2006) respectively.

The tank test was conducted in the Tow Tank at National Research Council Canada, Institute for Ocean Technology. The Tow Tank is 200 m long, 12 m wide and 7 m deep (see Figure 1). A dual-flap wave maker at one end of the tank is capable of generating regular and irregular uni-directional waves. 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. A distributed client/server system is used for data acquisition.

A SOLAS approved, commercially available, 16-person life raft was used in the test program. In the test program, the tow carriage was connected to the service carriage via two aluminium truss-like structures, which allowed the two carriages to move as a unit. The life raft was set up between the tow carriage and the service carriage (see Figure 2).

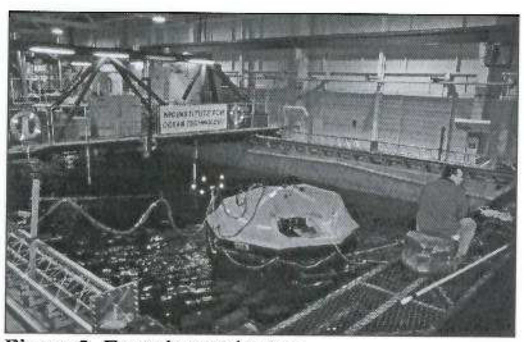
Figure 2. Experimental setup

During the experiments, the tow carriage towed the life raft into the waves, from the beach end to the wave maker end of the tank. The towline was 21 m long. After each experiment, the tow 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 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. To prevent the drogue from sinking to the bottom of the tank, especially during low speed tow test, a float was attached approximately midway on the drogue line.

TEST PROGRAM

The test matrix for these tests is shown in Table 1.

				Calm Water		Regular Waves		Irregular Waves	
				Ballast Type					
Case	Weight Distribution	Floor Inflated	Drogue	Manikins	Bags	Manikins	Bags	Manikins	Bags
A	Even	Y	Y	Y	Y	Y		Y	Y
B	Even	Y	N		Y		Y		Y
C	Even	N	N		Y		Y		Y
D	Uneven	Y	N		Y		Y		Y
E	Uneven	N	Y	Y	Y	Y	Y	Y	Y
F	Uneven	N	N	Y	Y		Y	Y	Y

Table 1. Test matrix

In the tow tank, the life raft was towed at 1, 2 and 3 knots, with both water bag ballast and manikin ballast. For regular waves, the wave frequencies varied from 0.36 Hz to 0.88 Hz. The ratio of wave height to wavelength was 1:15. For irregular wave, a Jonswap spectrum with significant wave height of 0.5 m, peak frequency of 0.392 Hz and repeat period of 120 seconds was used. The wave is roughly equivalent to sea state 2 with no wind. 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.

At sea, the life raft was towed at various speeds, with water bag ballast only. The waves had various significant heights.

PROPOSED METHOD AND FORMULAE

The proposed method to estimate life raft tow force in wind and waves is to use tank experiments to obtain tow force response for one sea state. This information will be used to formulate equations that can be applied to predict life raft tow force in wind and waves for different sea states.

Three formulae are proposed to demonstrate that a simple tank experiment, such as the one described in Mak et al. (2005, 2006), could provide valuable information necessary to empirically predict the mean tow force, tow force variation and maximum tow force for a specific life raft in different sea states. All formulae were developed for upwind, head seas, which we believe is potentially the worst-case scenario. These formulae predict towing by a large vessel. In the next section, the difference between towing by a large vessel and a Rigid Hull Inflatable Boat (RIB) is discussed. Also, detailed discussion of these equations, how they are applied and comparison of predicted and measured data are presented.

The first formula is used to predict mean tow force for different sea states. The tow resistance is expressed as the sum of calm water resistance, added wave resistance and added wind resistance. Calm water resistance is developed empirically using the data measured in the tow tank. The added wave resistance is estimated with the same method developed for large ships. The response function, R_{AW}/ζ_a^2, is computed from regular wave tow test data in the tank (Bhattacharyya 1978). It is raft specific and tow speed dependent. Added wind resistance is estimated for the raft with wind speed, tow speed, air density, projected area of the raft and drag coefficient (Lloyd 1989).

$$F_{mean} = R_{Calm} + R_{\substack{Added\ Wave \\ Resistance}} + R_{\substack{Added\ Wind \\ Resistance}}$$
$$= 0.5\rho\, S_m\, C_{TM}\, V^2$$
$$+ 2\int \frac{R_{AW}}{\zeta_a^2}(f)\, S_e(f)df$$
$$+ 0.5C_d\rho(V_w^2 + 2VV_w)A \qquad (1)$$

Where

F_{mean}	Mean tow force in irregular waves, head seas [N]
S_m	Wetted surface [m^2]
C_{TM}	Total resistance coefficient
V	Tow speed [m/s]
R_{AW}	Added resistance measured in regular wave tow tests [N]
ζ_a	Regular wave amplitude [m]
$S_e(f)$	Encounter wave spectrum [m^2/Hz]
V_w	Wind velocity [m/s]
A	Projected area of the raft [m^2]
ρ	Density of air [kg/m^3]
C_d	Drag coefficient

The second formula is used to predict the significant or average of the one-third highest tow force variations about its mean, due to waves, for different sea states.

$$(F_{variation})_{1/3} = 4\times\sqrt{\int S_{raft}(f)df}$$
$$S_{raft}(f) = |\,RAO(f)\,|^2 \times S_e(f) \qquad (2)$$

Where

$(F_{variation})_{1/3}$	Significant or average of the one-third highest tow force variation about its mean, head seas [N]
$S_{raft}(f)$	Raft tow force variation response spectrum [N^2/Hz]
$RAO(f)$	Raft tow force variation response amplitude operator computed from irregular waves tow tests [N/m]
$S_e(f)$	Encounter wave spectrum [m^2/Hz]

The third formula is used to predict the maximum tow force, using results obtained from Equations 1 and 2.

$$F_{max} = F_{mean} + [(F_{variation})_{1/3} \times C_{waves} \times C_{skewness}] \qquad (3)$$

Where

F_{max}	Maximum tow force [N]
F_{mean}	Mean tow force in irregular waves, head seas [N]
$(F_{variation})_{1/3}$	Average of one-third highest tow force variation about its mean, head seas [N]
C_{waves}	Ratio of most probable maximum wave height to significant wave height as proposed by Goda (2000) and Chakrabarti (1987). Tow force is shown to be a linear system with wave height.
$C_{skewness}$	Skewness factor to account for the fact that tow force response is unevenly distributed about its mean. If a response is symmetric about its mean, the skewness factor is $\frac{1}{2}$. A typical tow force response is asymmetric, with very sharp peak. A skewness factor of $\frac{2}{3}$ is used in this report.

RESULTS AND DISCUSSIONS

Tow force distribution and short-term response statistics

To show that the tow force response is mostly inertial, the Keulegan-Carpenter number, KC, (KC = UT/D) was computed for different wave height, wave period and water depth for a 16-person and a 42-person life raft. According to Sarpkaya and Isaacson (1981), when KC is smaller than 10, inertia force is more important. It was found that inertial force predominates in both sizes of life rafts. Inertial force predominates more in the large raft than in the small raft. Charkrabarti (1987) stated that generally inertial forces are linear with the wave amplitude, for example, the inertia part of Morison's equation, Froude-Krylov force and total force by diffraction theory. To simplify the formulation of prediction equations, it was assumed that tow force response is linearly related to wave amplitude.

Also, under the assumption that the wave spectrum is narrow banded (wave elevation is a stationary and ergodic random process following the Gaussian distribution and wave heights follow the Rayleigh distribution) and force is mainly inertial, it can be shown that the force amplitudes follow the Rayleigh distribution. If Rayleigh distribution applies to the force amplitudes, then all of the extreme-value statistics shown for the waves are equally applicable to the force (Chakrabarti, 1987 and Lloyd, 1989).

Figure 3 shows (a) a typical time series of measured tow force at 2 knots, (b) a plot of probability density histogram with a fitted Rayleigh probability density function, and (c) a plot of the cumulative distribution function obtained by integrating the probability density histogram (CDH) with the cumulative distribution function of the fitted Rayleigh distribution (CDF).

A Chi-squared Goodness-of-fit test at the 0.05 level of significance is used to test the hypothesis that the tow force has a Rayleigh distribution. If the probability of exceedance associated with the Chi-square value is greater than 0.05, the hypothesis is accepted. The probability of exceedance is 0.9107 in Figure 3. This shows that the Rayleigh distribution can be used as a first approximation for tow force magnitude. The measured tow force magnitude for other tow speeds also follow a Rayleigh distribution.

These results form the basis of using extreme-value statistics used for waves in tow force and in the formulation of equations 1 to 3.

Development of mean tow force equation

a. Life raft calm water resistance

Calm water tow resistance tests were conducted in a tow tank with a full-scale, 16-person life raft, as described in Mak et al. 2005. The tow force was measured using an inline load cell. Figure 4 shows the correlation of calm water raft resistance versus tow speed squared. Figure 5 shows the total resistance coefficient, C_{TM} versus Froude number.

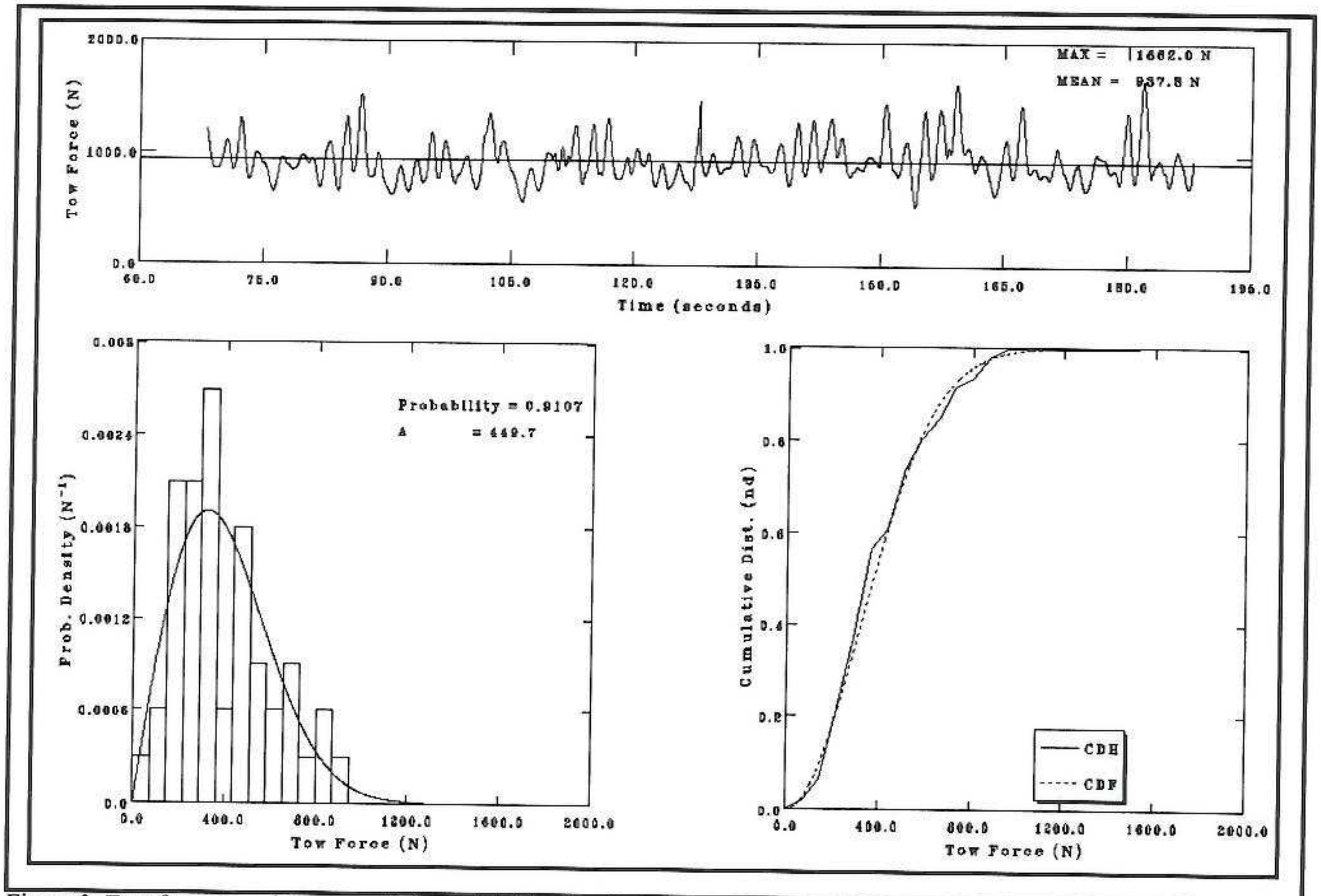

Figure 3. Tow force, tow force magnitude probability density and cumulative distribution

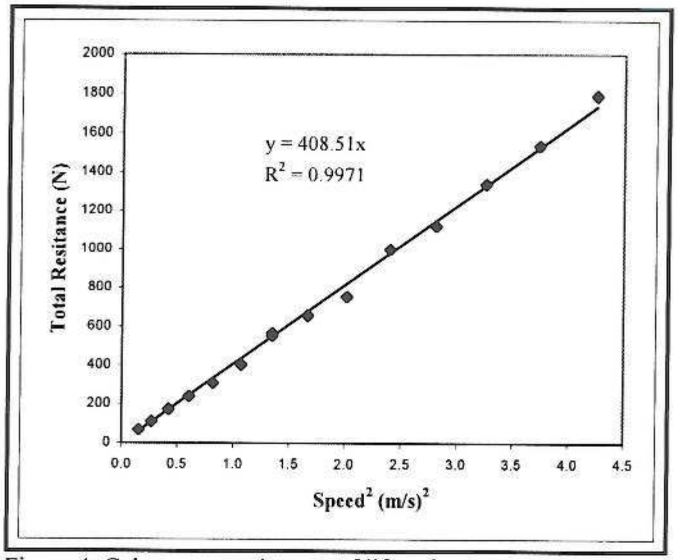

Figure 4. Calm water resistance of life raft at different tow speeds

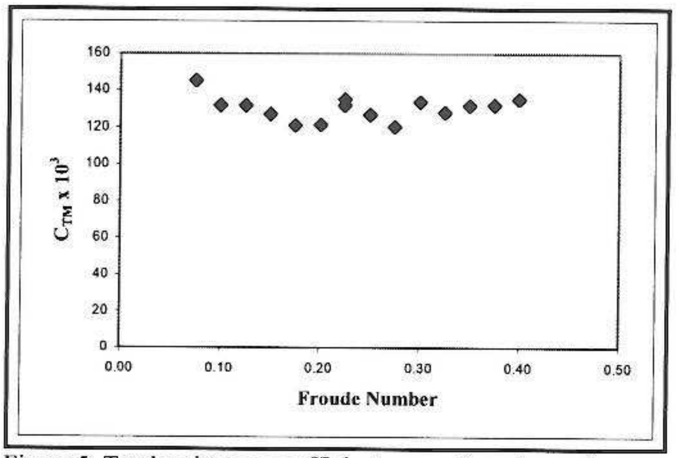

Figure 5. Total resistance coefficient versus Froude number

b. Life raft added resistance

Added resistance tests of a full-scale, 16-person life raft were conducted in regular waves with a constant wave slope of 1:15. The results are described in Mak et al. 2005 and 2006. The response function, R_{AW}/ζ_a^2, is computed from regular wave tow test data in the tank. A typical plot of the measured tow force response function and a fitted smoothing spline is shown in Figure 6.

For the validation of Equation 1, tow force measured in irregular wave tests in the tow tank and tow force measured in sea trials are used. Originally, the scope of the work described in Mak et al. 2005 did not require the use of sea trial data, until an opportunity to apply the results to the present work presented itself. Since the frequencies for wave spectra at sea are lower than those measured in the tank, it is necessary to use a smoothing spline curve through all the data points to help define the response function at low frequencies, where no data was measured. The measured data in the tank helped to define the spline.

It can be seen that the spline fitted well to all the measured tank data and appears quite reasonable throughout the entire frequency range. A possible improvement for further consideration would be to conduct tests at lower wave frequencies in the tow tank, so that the range of frequencies that required data extrapolation is reduced.

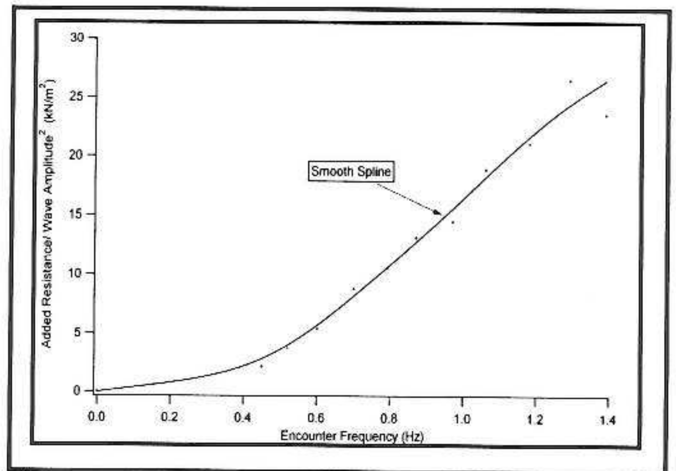

Figure 6. The measured tow force response function, R_{AW}/ζ_a^2, at 2 knots with a smoothing spline

c. Life raft added resistance in wind

Typically, wind velocities are reported at 10 m above mean water level. Small to medium size life raft canopies normally are less than 2 m above mean water level. Therefore, to apply Equation 1, the wind velocity must be adjusted. The wind velocity profile according to API-RP2A (1989) is represented by:

$$\frac{V_h}{V_H} = \left(\frac{h}{H}\right)^{1/n} \qquad (4)$$

Where

V_h	The wind velocity at height h
V_H	The wind velocity at reference height H, typically 10 m above mean water level
1/n	1/13 to 1/7, depending on the sea state, the distance from land and the averaging time interval. It is approximately equal to 1/13 for gusts and 1/8 for sustained winds in the open ocean.

For this study, h = 0.5 m and 1/n = 1/8 were used. When applying Equation 1, the projected area of the raft used was 2.1 m^2 and the drag coefficient used was 0.7 based on that reported by Hodgins and Mak (1995) on various life rafts.

Validation of mean tow force equation with tow tank data

The first step to validate Equation 1 was to tow a full-scale, 16-person, commercially available, SOLAS approved life raft in the NRC-IOT tow tank, in 0.5 m significant height irregular waves. The predicted mean tow forces were compared to measured tow force in irregular wave tests in the tank (Mak et al., 2005).

It should be emphasized that the data used in Equation 1 to predict the mean tow force are derived from tow tests in calm water and regular waves. They are completely independent of the measured irregular waves tow force compared to in the tables. The discussion is focused on tests with water bag ballast which has all the input data required for Equation 1.

Table 2 shows good agreement between the predicted and measured mean tow forces at 2 knots for tests with water bag ballast.

Case	Ballast	Mean Tow Force		Error
		Measured	Predicted	
B	Bags	546.4	497.8	-8.89%
C	Bags	492.8	460.1	-6.65%
D	Bags	537.1	517.5	-3.63%
E	Bags	550.2	520.3	-5.43%
F	Bags	457.0	433.7	-5.09%

Table 2. Comparison of measured and predicted mean tow force in irregular waves in towing tank (2 knots tow speed; significant wave height 0.5 m)

There was also good agreement at 1 and 3 knots (only 2-knots data are presented in this paper). At 3 knots, the prediction errors are all less than 10% with the exception of one case (Case C). At 1 knot, Equation 1 over-predicts in most cases but at higher tow speeds (2 and 3 knots), it under-predicts. The tow force behaves linearly with wave amplitude at low tow speed, as the raft rides up and down the waves. At higher tow speed, the raft plows through the waves as shown in Figure 7. This wave plowing is causing nonlinear phenomena, which are not accounted for in Equation 1. Despite this, the equation still predicts the mean tow force very well.

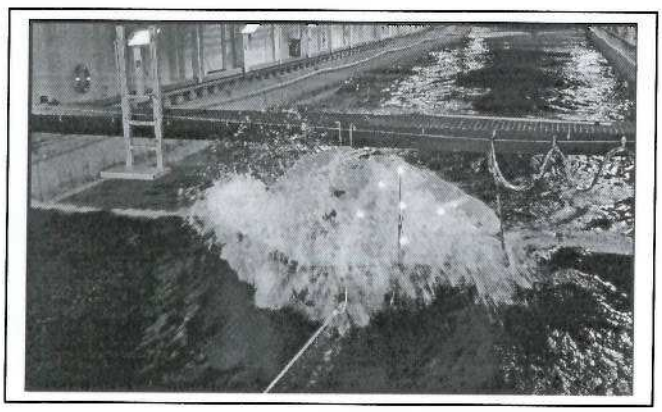

Figure 7. Life raft plowing through waves when towed at high speed

Validation of Significant Tow Force Equation with Tow Tank Data

The initial validation of Equation 2 involves comparing the predicted and measured significant tow forces from towing a full-scale, 16-person life raft in 0.5 m significant height irregular waves in the NRC-IOT tow tank (Mak et al., 2005). In Table 3, the predicted and measured significant tow force variations (i.e. average of one-third highest tow force variation about its mean) are compared at 2 knots.

Case	Ballast	m_0 [N^2]	Predicted Significant Tow Force Variation [N]	Measured Significant Tow Force Variation [N]	Error
B	Bags	43797	837	751	11.5%
C	Bags	31422	709	650	9.0%
D	Bags	46175	860	761	12.9%
E	Manikins	45546	854	760	12.3%
E	Bags	32293	719	670	7.3%
F	Manikins	45084	849	777	9.3%
F	Bags	33560	733	660	10.9%

Table 3. Comparison of measured and predicted significant tow force in irregular waves in towing tank (2 knots tow speed; significant wave height 0.5 m)

In the table, m_0 is equal to $\int S_{raft}(f)df$, and is the area under the $S_{raft}(f)$ curve. The estimated significant tow force variation is computed as $(F_{variation})_{1/3} = 4\times\sqrt{m_0}$, where $S_{raft}(f) = |RAO(f)|^2 \times S_e(f)$. The nomenclatures of all the symbols are explained in Equation 2.

There is good agreement at other tow speeds (only 2-knots data are presented in this paper). The best agreement is at 1-knot tow speed, where the prediction error is less than 5%. At 2-knots and 3-knots, the prediction errors gradually increase. Equation 2 tends to over-predict at higher tow speeds. This is probably because at low tow speeds, the raft rides up and down with the waves, and the tow force behaves linearly with wave amplitude. At high tow speeds, the raft plows through the waves, and the tow force response becomes nonlinear. Wave plowing is believed to limit the raft from surging forward since wave crest height is reduced and it dissipates the raft forward momentum in the wave breaking process.

Validation of the Maximum Tow Force Equation with Tow Tank Data

Using the predicted results of Equations 1 and 2 as input to Equation 3, the maximum tow forces were predicted. Table 4 shows the comparison of predicted and measured maximum tow force at 2 knots tow speed. The number of waves, N, used was 100, and C_{waves} = 1.61. The discussion is focused on tests with water bag ballast which has all the input data required for Equation 3.

The results show that the predicted and measured maximum tow force agreed very well at 1 to 3 knots tow speed. Among all the test cases with ballast bags at various tow speeds, they all had less than 16% error (only 2-knots data is presented in this paper).

Case	Ballast	Predicted Mean Tow Force [N]	Predicted Significant Tow Force [N]	Predicted Maximum Tow Force [N]	Measured Maximum Tow Force [N]	Error
B	Bags	497.8	837.1	1396.3	1430.4	-2.4%
C	Bags	460.1	709.1	1221.2	1386.5	-13.5%
D	Bags	517.5	859.5	1440.1	1505.4	-4.5%
E	Bags	520.3	718.8	1291.8	1460.8	-13.1%
F	Bags	433.7	732.8	1220.2	1241.4	-1.7%

Table 4. Comparison of predicted and measured maximum tow force in irregular waves in towing tank (2 knots tow speed; significant wave height 0.5 m)

Applying the equations to sea trial data

Since the equations were developed using the tank carriage as a towing mechanism, it is believed that the predicted tow force would more closely resemble towing by a large vessel than by a small vessel (e.g. a fast rescue craft). For the purpose of this discussion, a large vessel is one that has considerable mass and power. Unlike a small vessel, its passage through head seas is unlikely hindered by the mass of the raft it is towing.

At the time this paper was written, there was limited sea trial data, so the validation of the proposed equations cannot be as exhaustive as the tank results. However, the sea trials still generate useful information and help to illustrate the value of the equations.

In the following sections, the results from two sea trials will be presented and compared with predicted tow force from the equations. During the months of June and July 2005, Simões Ré et al. (2006) performed two tow tests on 16- and 42-person life rafts at sea. Water bags were used for ballast in both sea trials. The first sea trial involves towing a full-scale 16-person life raft by a fast rescue craft. The raft and ballast condition were the same as they were in the tank study. The second sea trial involves towing a full-scale 42-person life raft by a large vessel and by a fast rescue craft. A full set of instrumentation similar to that used in the tow tank tests was employed. Additionally a wave buoy was deployed at the test site approximately one week prior to the sea trials. The buoy logged the incident wave power spectral density function at ½ hour intervals. It provides test site-specific detailed wave information.

Towing a 16-person life raft by a fast rescue craft

a. Comparison of predicted and measured mean tow force

The predicted mean tow force, its contributing components and the measured mean tow force at sea, for Case B at 2 knots tow speed with ballast bags, are shown in Table 5. The significant wave height is 1.3 m. It shows that the measured and predicted mean tow force agree well.

Measured Mean Tow Force [N]	Calm Water Resistance [N]	Predicted Added Wave Resistance [N]	Predicted Added Wind Resistance [N]	Predicted Mean Tow Force [N]	Error
687.1	403.7	258.3	13.9	675.9	-1.6%

Table 5. Comparison of measured and predicted mean tow force in sea trial (16-person raft towed at 2 knots by Fast Rescue Craft; significant wave height 1.3 m)

b. Comparison of predicted and measured significant tow force

Table 6 shows the predicted and measured significant tow force variation in sea trial, at 2-knot tow speed with ballast bags. The verification of Equation 2 is limited to computing $(F_{variation})_{1/3} = 4 \times \sqrt{m_0}$. $S_{raft}(f)$ was obtained by computing the power spectrum from the measured tow force rather than obtained from $S_{raft}(f) = |RAO(f)|^2 \times S_e(f)$. This is because the wave spectrum measured at sea has a much lower frequency range than those tested in the tank. So, $|RAO(f)|^2$ was not available for the frequency range of the wave spectrum at sea. A model scale raft tow test is required to provide $|RAO(f)|^2$ in the frequency range of interest, and this points to the necessity of model tests.

Equation 2 over-predicts the significant tow force variation, similar to its prediction in the tow tank. The over-prediction error is slightly higher than for the comparable tow speed in the tow tank. It is believed that increased significant wave height and wave plowing at high tow speed combined to create more wave breaking and nonlinear phenomena not accounted for by Equation 2. Energy is lost in the wave breaking process and this may reduce life raft tow force variation. Also, towing the life raft by a fast rescue craft may also contribute to the difference, since the predictions should resemble more closely a raft towed by a large vessel.

m_0 [N^2]	Predicted Significant Tow Force Variation [N]	Measured Significant Tow Force Variation [N]	Error
208563	1826.75	1538.16	18.8%

Table 6. Comparison of measured and predicted significant tow force in sea trial (16-person raft towed at 2 knots by Fast Rescue Craft; significant wave height 1.3 m)

c. Comparison of predicted and measured maximum tow force

Table 7 shows good agreement between the predicted and measured maximum tow force, at 2-knot tow speed with ballast bags. While in this particular case, the predicted maximum tow force from Equation 3 agreed well with the measured maximum tow force, readers should be cautioned that more data from sea trials is required to fully validate the equations and to assess the difference between towing by a large vessel and a small vessel.

Predicted Mean Tow Force [N]	Predicted Significant Tow Force [N]	Predicted Maximum Tow Force [N]	Measured Maximum Tow Force [N]	Error
675.9	1826.7	2758.4	3018.9	-9.4%

Table 7. Comparison of measured and predicted maximum tow force in sea trial (16-person raft towed at 2 knots by Fast Rescue Craft; significant wave height 1.3 m)

Towing a 42-person life raft by a fast rescue craft and by a large vessel

At the time this paper was written, no tow tests had been conducted in the tank on the 42-person life raft. Therefore, the necessary input information for Equations 1 and 2 are unavailable. However, the formulation of Equation 3 can still be validated with the measured tow force, using the measured F_{mean} and $(F_{variation})_{1/3}$. To perform this validation, F_{mean} is computed as the arithmetic mean of the time series. $(F_{variation})_{1/3}$ is computed as (4 x Standard Deviation), recognizing that it is approximately equal to $4 \times \sqrt{m_0}$.

Table 8 shows the comparison of predicted maximum tow force using this method and the measured maximum tow force. The number of waves, N, is estimated to be around 200 and C_{waves} of 1.71 was used.

It is observed that the maximum tow force predicted using Equation 3 agreed well with the measured maximum tow force in all but one case - the case when the life raft was towed by a fast rescue craft at 2 knots. If one examines the measured tow forces of this case closely, it is obvious that the tow force dropped to zero frequently. The other cases do not exhibit the same behavior. This indicates that the towline became slack frequently and remained slacked for a long duration, up to 10 seconds sometimes. When the towline became taut again, the tow force increased sharply.

Figure 8 presents a close-up plot of the tow force time series from 800 to 1000 seconds to show the phenomenon. The appearance of shock load may indicate that the FRC is traveling too slowly, allowing the raft to catch up as it slides down the wave crest, at which point the towline became slack. A trained crew on the towing craft would attempt to minimize shock load by changing speed, course and towline length. However, during the test, the fast rescue craft was set to use fixed rpm. Shock loads bear no relationship to wave height and are not accounted for by the equations developed.

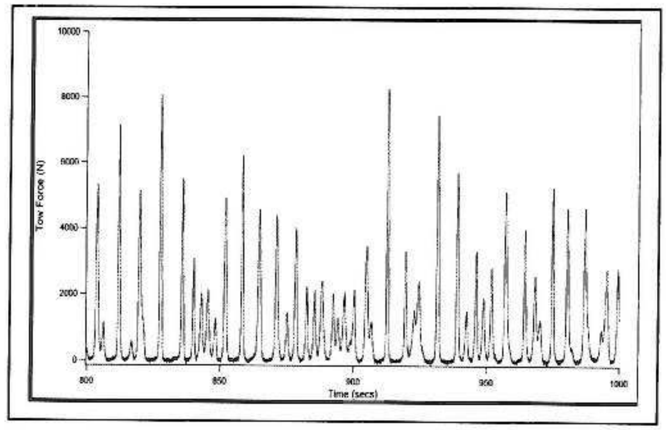

Figure 8. Measured tow force with the 42-person life raft towed by a Fast Rescue Craft (2 knots)

Predicting Mean Tow Force in Moderate Seas

Having validated Equation 1 with a comprehensive set of measured data in the tank and a limited set of measured data in sea trials, the focus now is to predict the tow force in moderate seas (up to 4 m significant wave height). The rationale for this is to determine the relative importance of calm water resistance, added wave resistance and added wind resistance, in order to assess if tow force estimates based on calm water resistance only is conservative for moderate seas.

A study conducted by LeBlond et al. (1982), showed that the best fit to the observed spectra in Canadian waters is usually provided by the JONSWAP spectrum. Using the typical JONSWAP spectrum peak enhancement factor, γ, provided by LeBlond et al. (1982), for Lake Ontario, Pacific Coast and the Grand Banks, encounter spectra were computed based on tow speed.

Towing Vessel	Nominal Tow Speed	Sig. Wave Height [m]	Measured Mean Tow Force [N]	Measured Sig. Tow Force [N]	Predicted Max Tow Force [N]	Measured Max Tow Force [N]	Error
FRC	2 knots	1.37	810	4328	5744	8283	-44.2% Note 1
Large Vessel	2 knots	1.32	3045	4064	7407	7376	0.4%
FRC	3 knots	1.07	1832	3086	5351	5654	-5.7%
Large Vessel	3 knots	1.23	4057	5605	10073	9565	5.0%

Table 8. Comparison of measured and predicted maximum tow force in sea trial (42-person raft towed at 2 knots by Fast Rescue Craft and by large vessel)

[1] Shock loads resulting from repeated occurrence of slack towline becoming taut is unrelated to wave height and are not accounted for by equations developed based on linear relationship between tow force and wave height.

These encounter spectra were then substituted into Equation 1 to predict the raft tow force in head seas. Other inputs required for Equation 1 were obtained from the tow tank results. Wind speed was estimated based on the Beaufort Scale necessary to create the significant wave height and corrected to a height 0.5 m above the mean water level using Equation 4.

Figure 9 shows the contributing tow resistance components of the life raft in various sea states, for the Grand Banks at 1 and 2 knots tow speed respectively. In each graph, the calm water resistance, the added resistance due to waves, added resistance due to wind and total mean resistance are plotted to show their relative significance. The added resistance due to wind for 1 and 2 knots is virtually identical for this particular life raft and is denoted as $R_{Added\ wind}$ in the graphs.

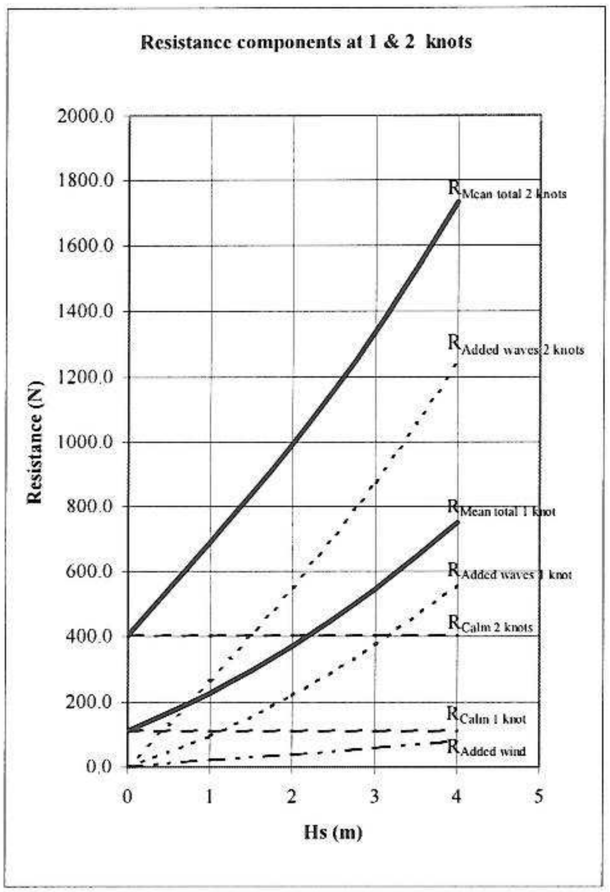

Figure 9. Contributing mean tow resistance components, Grand Banks, 1 and 2 knots

It can be seen that added resistance due to wind is relatively small for this life raft. Added resistance due to waves increases significantly with increased significant wave height. Added wave resistance surpasses calm water resistance at 1.3 m significant wave height for 1-knot tow. It surpasses calm water resistance at 1.7 m significant wave height for 2-knot tow. At these significant wave heights, the total mean tow resistance is already roughly twice the calm water tow resistance. Above 2 m significant wave height, the total mean tow resistance can be several times higher than calm water tow resistance. Tow force variation about its mean, for example, from riding the crest of a wave propagating opposite to the tow direction, will further increase the maximum tow resistance.

This implies that tow force estimate based on calm water tow resistance is not conservative for low to moderate seas. It shows that added resistance due to waves should be given due consideration. For the 16-person life raft being studied in this report, it appears that added resistance due to wind is relatively small and its contribution can be accounted for in applying a conservative safety factor. However, this may not be true for all life rafts because they have different shapes, projected area and drag coefficient.

CONCLUSIONS

1. The life raft tow force was demonstrated to be mostly inertial using the Keulegan-Carpenter number. It was also shown to follow a Rayleigh distribution. These show that tow force response can be treated as a linear system with wave amplitude (or height), and the extreme-value statistics used for waves can be applied to tow force. This is the basis in the formulation of the equations.

2. A method is proposed to predict life raft tow force at different tow speeds and in various sea states, with waves and wind. The method involved using tank experiments to obtain tow force response for one sea state, which can then be used to predict life raft tow force in wind and waves for different sea states.

   Three formulae are proposed to empirically predict the mean tow force, tow force variation and maximum tow force. These formulae were developed for upwind, head seas, which is believed to be potentially the worst-case scenario. As the formulae were developed using a tank carriage as the towing device, they would resemble towing by large vessel more closely than by a small vessel, such as a fast rescue craft.

3. The three equations were extensively validated using tow force measured by towing a full-scale 16-person, commercially available, SOLAS approved life raft in the tank, in head seas with significant wave height of 0.5 m. They were also partially validated with limited sea trial data, by towing the same 16-person life raft and a 42-person life raft in head seas with significant wave height of 1.3 m. The formulae were able to predict maximum tow forces to within 15% of the measured.

4. Results from the 42-person raft, 3-knot tow sea trial appear to indicate that towing by a large vessel will likely generate a larger maximum tow force than towing by a fast rescue craft (a small vessel). Also, towing by both the large vessel and the fast rescue craft (small vessel) resulted in the same order of magnitude of maximum tow force (9,565 N and 5,654 N when towed by the large vessel versus towed by the small vessel respectively.) This may justify the use of a carriage in a towing tank for

life raft tow experiments because it closely simulates towing by a large vessel and would result in more conservative tow load estimation.

5. Shock loads caused by slack towline suddenly becoming taut could result in very high maximum loads. This type of shock load occurs when the towing vessel travels too slowly, allowing the raft to catch up as it slides down the wave crest. This type of shock load bears no relationship to wave height and is not accounted for by the equations developed in this report.

6. Using the equations, it can be shown numerically that added resistance due to waves increases significantly with increased significant wave height. Added wave resistance surpasses calm water resistance at 1.3 m significant wave height for 1-knot tow. It surpasses calm water resistance at 1.7 m significant wave height for 2-knot tow. At these significant wave heights, the total mean tow resistance is already roughly twice the calm water tow resistance. Above 2 m significant wave height, the total mean tow resistance can be several times higher than calm water tow resistance. Tow force variation about its mean, for example, from riding the crest of a wave propagating opposite to the tow direction, will further increase the maximum tow resistance. This implies that tow force values based on calm water tow resistance are very optimistic for low to moderate seas and are not good representations of real world situations.

REFERENCES

1. API-RP2A (1989), "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms", American Petroleum Institute, Washington, D.C., 18th ed.

2. Bhattacharyya, R. (1978), "Dynamics of Marine Vehicles", Wiley-Interscience Publication.

3. Chakrabarti, S.K. (1987), "Hydrodynamics of Offshore Structures", Computational Mechanics Publications, Southampton, Boston.

4. Goda, Y. (2000), "Random Seas and Design of Maritime Structures", World Scientific Publishing Co. Pte. Ltd., Singapore.

5. Hodgins, D.O. And Mak, R.Y. (1995), "Leeway Dynamic Study Phase I - Development And Verification Of A Mathematical Drift Model For Four-Person Liferafts", Prepared For Transportation Development Centre, Transport Canada Report #TP 12309E.

6. LeBlond, P.H., Calisal, S.M. and Isaacson, M, (1982), "Wave Spectra in Canadian Waters", Canadian Contractor Report of Hydrography and Ocean Sciences, No. 6.

7. Lloyd, A.R.J.M. (1989), "Seakeeping – Ship Behaviour in Rough Weather", Ellis Horwood Series in Marine Technology.

8. Mak, L.M., Simões Ré, A. and Kuczora, A. (2005), "Motion Response of a Full-Scale Life Raft in Laboratory Tow Experiments", National Research Council Canada, Insitute for Ocean Technology, Technical Report # TR-2005-11.

9. Mak, L.M., Simões Ré, A. and Kuczora, A. (2006), "Motion Response of a Full-Scale Life Raft in Laboratory Tow Experiments", Proceedings of 25th International Conference on Offshore Mechanics and Arctic Engineering, Paper # OMAE2006-92040.

10. Sarpkaya T. and Isaacson M. (1981), "Mechanics of Wave Forces on Offshore Structures", Van Nostrand Reinhold Company, New York.

11. Simões Ré, A., Kuczora, A., Kennedy, E. and Power, J. (2006), "Open Ocean Towing and Drifting Full-Scale Trials with 16 and 42-person Inflatable Liferafts", National Research Council Canada, Institute for Ocean Technology, Technical Report # TR-2006-14.

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