SS El Faro

Final Report
On loss of vessel
8/31/17

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APPENDIX

1. Overview

The SS EL Faro was built in 1975 at Sun Shipbuilding and Dry Dock as a Roll on Roll off vessel. In 1992 she was lengthened by adding 90 feet of parallel mid-body and in 2006 the then-named SS Northern Lights was converted to a con/ro vessel, which carried containers on the main deck and Roll on / Roll Off (Ro-Ro) cargo below the main deck.

The 1992 conversion involving the addition of 90 foot of parallel mid-body to the vessel was considered a major conversion, under U.S. law,[1] according to the U.S. Coast Guard. Accordingly, the entire vessel was required to "meet all current standards, as far as is reasonable and practicable, in effect at the contract date of [the] major conversion." *See* U.S. Coast Guard Navigation & Vessel Inspection Circular 10-81, Ch. 1, Enc. 1 at p. 2. The ship, then-named the Northern Lights, was in the Alaska service through 2006.

The U.S. Coast Guard did not consider the 2006 conversion to be a major conversion. Accordingly, as a general matter, the latest statutory rules at the time of the conversion did not apply. The 2006 conversion involved the removal of the partial spar deck forward of the house and above the main deck, adding beams to the main deck for strength to carry containers, the addition of approximately 2000 long tons of permanent ballast, and increasing the load line draft approximately 2 feet to 30'2-5/8". The 2006 conversion allowed the vessel to carry Container Cargo on deck and Ro-Ro cargo below deck. After this (2006) conversion the ship was renamed the SS El Faro.

After the 2006 conversion, the El Faro was used in service between Jacksonville Florida and San Juan Puerto Rico. At the time of the loss, the EL Faro and was due to go into the shipyard in February 2016 for a regular shipyard over hall. The SS El Faro was to be back to the Alaska service. A riding crew of five workers were on board installing equipment necessary for Alaska service (but this equipment was and not needed in its present service).

The SS El Faro set sail from Jacksonville, Florida on September 29, 2015 in route to San Juan, Puerto Rico. On October 1, 2015 at about 0730, local time the SS El Faro was lost in hurricane Joaquin.

This report assesses the condition of the SS El Faro at its departure from Jacksonville on September 29, 2015, and at various stages along the vessel's voyage prior to it is sinking. The opinions expressed herein are based on various sources of vessel documentation that I have reviewed, testimony given at the NTSB/USCG MBI hearings, and my education, training, and experience and are provided to a reasonable degree of engineering certainty.

The stability criteria applicable to the SS El Faro dates back to the 1992 major conversion; namely, the USCG Weather Criteria 46 CFR 170.170, and the SOLAS Probabilistic Damaged Stability requirements that were in force in 1992.

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[1] *See* 46 U.S.C. § 2101.

2. Stability Characteristics on Voyage 185S and Required GM

I evaluated various aspects of the loss of the EL FARO, as set forth below, including an evaluation of the vessel's compliance with applicable stability requirements. As a practicing Naval Architect and Professor of Naval Architecture S.U.N.Y. Maritime College, at Fort Schuyler, N.Y. for more than 41 years, I have performed stability analyses on more than 200 vessels, and have develop Trim & Stability Books, or similar stability guidance for Masters, for over 100 vessels. I also served as instructor for the use of CARGOMAX for Chief Mates and Captains for a new class of nine container vessels for a major US Flag carrier. Such guidance is usually submitted for review and approval to the American Bureau of Shipping (ABS) and/or the U.S. Coast Guard. I have routinely used CARGOMAX/HECSALV[2] for more than 30 years in the course of my work.

i. Departure Condition Comparison: T&S Book and CARGOMAX

The stability of the SS El Faro on voyage 185S departing Jacksonville Florida heading to San Juan, Puerto Rico, was first evaluated by using hydrostatics and calculation procedures from the stability booklet, DWG No. 1252-700-602, Rev E, dated February 14, 2007 with the ABS approval stamp dated May 31, 2007. Results are shown in Table 1.

Separately, I also computed the trim and stability of the SS El Faro for voyage 185S using the CARGO MAX software used by El Faro crew and shore side personnel. In comparing the results of the two sets of calculations, CARGOMAX computes the stability within the accuracy of the T & S book. A comparison of these two sets of calculations is shown in Table 2. As shown below, the calculations using the stability booklet and CARGOMAX are virtually identical and the differences are well within acceptable tolerances. The tolerance is within the classification society standards.

In the stability tables the following symbols are used;

FO = Fuel Oil FW = Fresh Water SWB = Salt Water Ballast
vcg = vertical center of gravity VM = Vertical Moment
lcg = longitudinal center of gravity LM = Longitudinal Moment
tcg = Transverse center of gravity TM = Transverse Moment
FSM = Liquid Free Surface Moment FS = Free Surface correction for KG
KG = height of the vessels center of gravity above the keel
LCG and TCG location of the center of gravity from midships or centerline.

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[2] CARGOMAX AND HECSALVE are software products of Herbert Engineering Corp. CARGOMAX is used by ship operators throughout the world and HECSALV is used by Naval Architects.

Table 1 – T&S Book Stability Results

Voyage 185S - SS El Faro
JAX/SJ T&S BOOK Procedure

item	weight	vcg	VM	lcg	LM(-A+F)	tcg	TM(-P+S)	FSM
Lightship	19943.0	27.820	554814	-45.135	-900127	0.000	0	
Constant	171.9	52.859	9086	-52.932	-9099	0.000	0	
Containers	6864.7	77.011	528657	-45.019	-309042	-0.109	-748	
RO/RO	4183.9	38.434	160804	5.172	21639	0.908	3799	
FO	1272.0	5.927	7539	-87.371	-111136	0.000	0	10922.3
FW	1863.0	11.892	22155	37.700	70235	0.543	1012	2620.9
SWB	238.0	17.510	4167	63.674	15154	9.049	2154	228.4
Misc. Tks	90.7	29.594	2684	61.325	5562	-3.710	-336	109.2
			1289908		-1216813		5880	13881

WEIGHT= 34627.2 **KG= 37.251** **LCG= -35.140** **TCG= 0.170**

FS= 0.401

KG'= 37.652

From T&S Book at even keel

@	**34667**	**Displacement**
T_m=	30.198	Mean draft
LCB=	24.515	Longitudinal Center of Buoyancy
LCF=	59.825	Longitudinal Center of Flotation
MCT1"=	5282	Moment to Change Trim 1"
KM_t=	41.93	Transverse Metacentric Height
TPI=	124.74	Tons per Inch Immersion
Calculated		
GM_t =	4.278	Transverse GM including Free Surface
trim=	-5.805	
Angle Heel=	2.27	DEGREES

Table 2 Comparison of CARGOMAX and T&S BOOK Results

	CARGOMAX	**T&S Book**	
@	**34627.2**	**34667**	Long Tons
T_m=	30.163	30.198	Feet
LCB=	-24.54	-24.515	Feet
LCF=	-59.865	-59.825	Feet
MCT1=	5278	5282	Ft LT
KM_t=	41.934	41.93	@ 5' TRIM,41.5 even keel
	TPI=	124.74	
GM_t =	4.282	4.278	Feet
trim=	-5.795	-5.805	Feet
Angle Heel=	2.27	2.27	DEGREES

CARGOMAX does indicate an angle of list, which is, according to testimony, not typically observed on board the vessel. Based on a review of the inclining experiment results, this can be explained in that the El Faro lightship has an off centerline center of gravity (TCG) not reflected in the T&S book or CARGOMAX. The calculation of TCG was not required by regulation or any U.S. Coast Guard policy. Based on testimony of various witnesses, as a matter of operational procedure, the ship’s tanks and cargo are loaded to remove the list angle compensating for the off center TCG of the lightship. There is no provision for calculating list in the T&S book, nor was there a requirement to do so in the regulations at the time of the approval. When the “corrected “ calculations are preformed below, the calculated angle still remains 1.35 degrees if TCG of the lightship is included, the results are shown in Table 3 below. Note, however, because there was no requirement to actually calculate and use TCG in the performance of the stability test, the TCG listed in the stability test results cannot be relied with absolute certainty. In any event, the stability test results appear accurate. An accurate and examination of TCG during the inclining would have given us certainty, however it was not done and not required.

Table 3 –Calculation with lightship TCG

Voyage 185S - SS El Faro - JAX/SJ With Lightship TCG

item	weight	vcg	VM	lcg	LM(-A+F)	tcg	TM(-P+S)	FSM
Lightship	19943.0	27.820	554814	-45.135	-900127	-0.120	-2393	
Constant	171.9	52.859	9086	-52.932	-9099	0.000	0	
Containers	6864.7	77.011	528657	-45.019	-309042	-0.109	-748	
RO/RO	4183.9	38.434	160804	5.172	21639	0.908	3799	
FO	1272.0	5.927	7539	-87.371	-111136	0.000	0	10922.3
FW	1863.0	11.892	22155	37.700	70235	0.543	1012	2620.9
SWB	238.0	17.510	4167	63.674	15154	9.049	2154	228.4
Misc. Tks.	90.7	29.594	2684	61.325	5562	-3.710	-336	109.2
			1289908		-1216813		3486	13881
WEIGHT=	**34627.2**	**KG=**	**37.251**	**LCG=**	**-35.140**	**TCG=**	**0.101**	
		FS=	**0.401**					
		KG'=	**37.652**					

	CARGO MAX	
@	**34627.2**	**Tons Displacement**
T_m=	30.163	Mean Draft
LCB=	-24.54	Longitudinal Center of Buoyancy
LCF=	-59.865	Longitudinal Center of Flotation
MCT1”=	5278	Moment to Change Trim 1"
KM_t=	41.934	Transverse Metacentric Height
GM_t =	4.282	Transverse GM including Free Surface

trim= -5.795
Angle Heel= 1.35 DEGREES

CARGOMAX load cases for this vessel typically indicates a slight angle of heel where a lower angle of heel is observed. Actual cause as shown in Table 3 is the off centerline (TCG) of the lightship not included in the trim and Stability book or CARGOMAX.

ii Comparison: Table of Offsets 1992-2010

I compared the available offsets from 1992 (GHS), 2006 (GHS), 2007 (CARGOMAX), 2010 (CARGOMAX)[3] and original shipyard offsets. I also calculated the hydrostatic properties for the above offsets using HECSALV, Rhino/Orca and MAXSURF[4] Stability. Results of the calculation show the hydrostatics properties calculated in each program are the same.

Free surface moment is computed as actual moment in each tank group or the largest free surface moment from any two of the largest tanks in each tank group. The free surface used in the calculations is the larger of the two.

Some of the CARGOMAX records I reviewed for the El Faro showed what might be perceived as discrepancies in draft observed vs. draft calculated in CARGOMAX. These perceived discrepancies, however, can be attributed to variable salinity (and specific gravity) at the dock in Jacksonville versus open seawater salinity. The specific gravity of the water at the dock can vary from 1.001 to 1.025 (standard seawater). When corrected for salinity, the drafts observed and the CARGOMAX calculated drafts were generally the same.

The difference in angle of heel is explained in Table 3.

iii. GM Requirements (Intact & Damage)

a. Intact Stability Requirements

CARGOMAX uses the USCG weather criteria to determine the required GM. The weather criteria in CARGOMAX can be selected as a specific number of tiers of containers on deck or a specific profile of containers above three tiers on deck. It also has an “auto wind heel” feature that calculates the weather criteria based on actual container profile. The Trim and Stability Book, by contrast, has required GM curves based on discrete number of containers on deck (e.g. two tier, three tier, etc.). The auto wind heel feature in CARGOMAX is the most

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[3] GHS – General Hydrostatics Program – Creative Systems
CARGOMAX – Herbert Engineering Stability Software

[4] HECSALV – Herbert Engineering NA software
Rhino/Orca Rhinoceros5 graphic software with Orca Stability add in
Bentley engineering Software - MAXSURF Stability

accurate way to calculate required GM since it uses the actual container profile in the calculation. Based on my review, the required GM curves in the Trim and Stability book and CARGOMAX, and the auto wind heel feature in CARGOMAX, are true and accurate and in accordance with the USCG Weather criteria in 46 CFR 170.170. Due to the age of the El Faro and its last major conversion in 1992, it is my opinion that the USCG weather criteria is the correct criteria applicable for the vessel.[5]

b. Damage Stability Requirements

The case documentation I have reviewed also indicates that the SS El Faro was required by the U.S. Coast Guard to satisfy the SOLAS Probabilistic Damage Stability requirements in force in 1992, as a result of the 1992 major conversion. The damage stability (and intact stability) calculations were submitted and approved by ABS in the course of the 1992 conversion.

There is no mention of probabilistic damage stability requirements in CARGOMAX, in the approved Trim and Stability book from 2006, or in any of the supporting calculations. I have not been provided any evidence that calculations were submitted to and approved by ABS at the time of the 2006 conversion and stability approval[6].

c. Required GM Curves

When both intact and damage stability requirements apply, as in the case of the El Faro, the GM requirements for all drafts should be calculated and compared using both criteria. Whichever criteria results in a greater required GM is the governing, minimum GM requirements.

After this is evaluated for all drafts, a “required GM curve” is produced for use by the vessel’s personnel, and incorporated into CARGOMAX. In the case of the El Faro, the required GM curve is on page 16 of the El Faro’s approved Trim & Stability Booklet.

In this case, I first calculated the required GM curve based the U.S. Coast Guard weather criteria for one, two, and three tiers of containers (shown in orange, blue, and maroon curves in Figure 1, respectively). I then calculated the required GM based on the 1992 SOLAS Probabilistic Damaged Stability requirements in force at the time of the major conversion of the SS El Faro. This is also depicted in Figure 1 (in baby blue). Finally, ABS also calculated the

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[6] Because the vessels draft was increased by approximately 2 feet in 2006, a damage stability analysis should have been performed (in my opinion). However, this apparent oversight is of no consequence in this case.

SOLAS Probabilistic Damage Stability for the load line draft, shown below in Figure 1 (in gray/light blue). Figure 1 also shows the actual GM of the SS El Faro on departure from Jacksonville on September 29, 2015

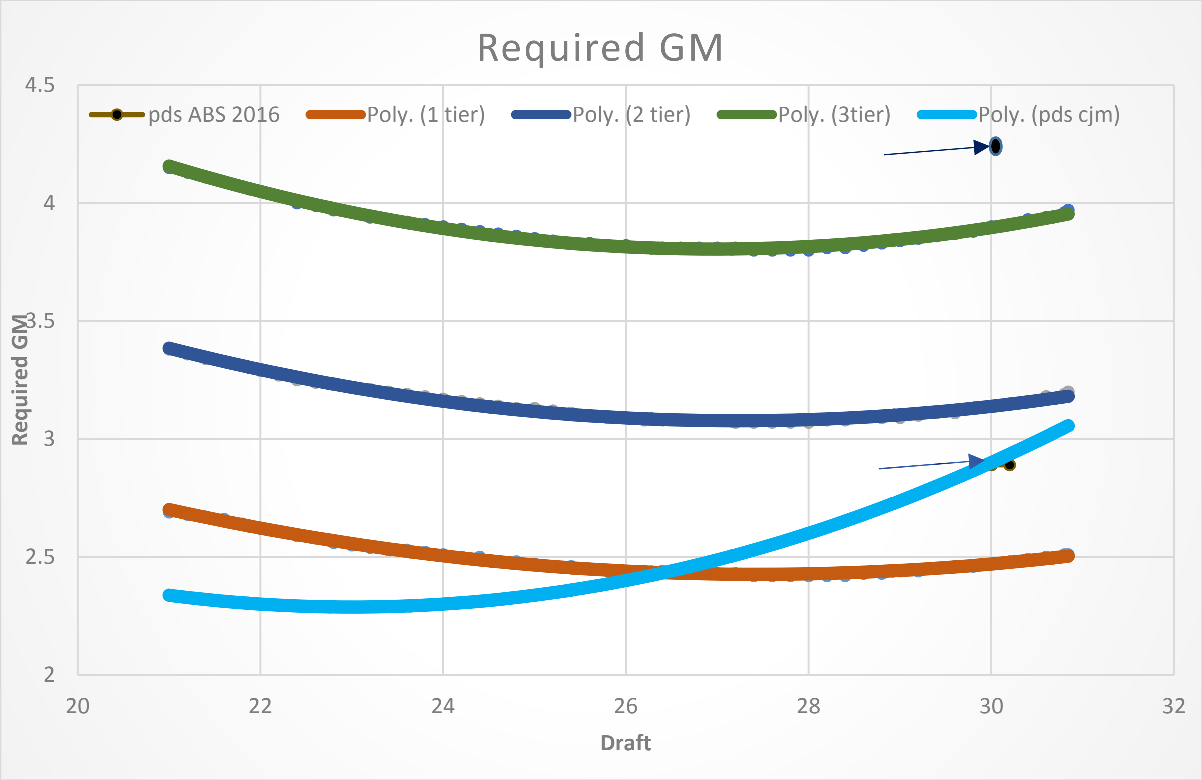

Figure 1 Weather Criteria and Probabilistic Damaged Stability Required GM.

As shown above, the required GM for two and three tiers for the weather criteria are higher than the GM required by the Probabilistic Damaged Stability requirements. Specifics relevant to voyage 185S are noted as follows:

- Actual GM corrected for free surface voyage 185S departure is 4.28 feet.
- GM required by weather criteria three triers is 3.91 feet.
- GM required by weather criteria auto wind heel is 3.63 feet.
- GM required by the SOLAS Probabilistic Damage Stability requirements is 2.90 feet.

Actual GM exceeded required GM in all cases.

For the accident voyage, the U.S. Coast Guard weather criteria resulted in the most restrictive GM requirements. In fact, application of the Probabilistic Damage Stability requirements would only affect the required GM if the SS El Faro were carrying less than two tires of containers on deck.[7]

iv. Tote Practice - "GM Margin"

Tote had a practice of having a GM margin of 0.5 feet upon departing Jacksonville, which allows for the loss in GM due to the burn off of fuel and consumables. The loss in GM was calculated for voyage 185S as well as several prior voyages. When calculating arrival GM in San Juan starting with departure GM in Jacksonville the reduction in GM is always less than 0.5 feet. This validates the goal of having a GM margin of at least 0.5 feet.

Another valid practice would be for the mates to calculate both departure and expected arrival condition before departing Jacksonville, verifying that both arrival and departure conditions meet the applicable GM requirements.

In my opinion, either method described above is valid. Tote used a method for the SS El Faro that is an acceptable method to comply with GM requirements during the voyage from Jacksonville to San Juan.

The Final Trim and Stability condition for the SS El Faro shows a departure ship weight of 34,624.5 Long Tons with an LCF draft of 30.163 feet and a mid-ship draft 29.76 feet with a trim of 5.797 feet by the stern. The displacement at the 30.198 foot even keel load line draft is 34,677 Long Tons. This yields an available deadweight of 52.5 long tons in this loaded condition based on information in the Trim and Stability booklet, with the ship at even keel with no trim.

However, using the midships draft of 29.76, accounting for trim, yields an available deadweight in excess of 600 Long Tons; CARGOMAX correctly and more accurately calculates available deadweight using mid-ships draft.[8] In other words, the EL FARO could have loaded approximately 600 Long Tons of additional weight (cargo, fuel, ballast, etc.) and still be within its maximum draft limitations.

The ballasting options for the SS El Faro were limited to adding ballast to DT No. 1A and Aft Peak tanks port, starboard and center. The total available salt water ballast capacity of 1294.7

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[7] Accordingly, in my opinion, the apparent failure to incorporate the SOLAS Probabilistic Damage Stability requirements into the required GM curve, approved for the vessel by ABS, played no role in the casualty. The main in reason for this conclusion is that the GM of the vessel on the accident voyage is far in excess of the minimum GM requirements established by the SOLAS damage stability requirements. In addition, the required GM curves for one (or two) tiers of containers on deck are not applicable to the EL FARO's final voyage, since the vessel was carrying 3-4 containers on deck.

[8] The difference between the available deadweight calculated using the Trim & Stability Booklet and CARGOMAX is easily explained. When ships are trimmed by the stern, as the El Faro was on its final voyage, the volume of displacement generally increases and therefore the deadweight capacity increases. This increase in displacement due to trim by the stern is not accounted for in the Trim and Stability Book; the method used in the Trim & Stability Book simplifies the manual calculations performed by the mates, but underestimates the available deadweight. The method used in CARGOMAX for calculating available deadweight is more accurate.

long tons. This total exceeds the ships available deadweight and allows for addition ballasting as fuel is burned off.

The available deadweight leaves options to add ballast to increase stability during this voyage. DT No. 1A had 150 LT of ballast, upon departure. If 75.5 LT of ballast are added to this tank the GM_t would be increased by 0.024 feet and the GM_t margin would increase by 0.004 feet, including the effects of free surface.

With 600 long tons of available deadweight, you can add 100 Long Tons of Sea water ballast to DT No. 1A and including the effects of lower weight and free surface you can increase the GM_t by 0.03 feet and increase the GM margin accordingly.

Additional ballast can be added as fuel is burned off during the voyage. An additional 349 LT can be added to DT No. 1A to replace burned off fuel, filling the tank and eliminating the tanks free surface effect.

In addition, if ballast water in the AFT Peak S tanks is removed and then added to the DT No. 1A the ships VCG would be lowered by 0.05 feet and there would be no Free Surface effect from the emptied tank increasing GM_t by an additional 0.055 feet. The total increase in GMt would be 0.085 feet by shifting and adding ballast.

Additional ballast capacity is available in the No.2 INBD P/S DB (and could have been) ballasted while at sea. Theses tanks in CARGOMAX are designated as fresh water tanks, but I am advised by Tote operational personnel that these tanks were fully capable of receiving salt-water ballast at sea. I have reviewed ballast water inventory records, which confirms this.

3. Stability Characteristics & Effects of Operating Environment

i. Effects of water on the Shelter Deck

Some witnesses testified that the Ponce class vessels occasionally experienced green water on deck in instances of heavy weather; therefore, I evaluated the potential impact this might have on the vessel's stability. The presence of water on the deck adversely affects the stability of the vessel in two ways. First, it increases the vessel's VCG and therefore decreases the vessel's GM. Second, the presence of such water will also increase the free surface effect on the vessel. However, at the same time, the water that enters the shelter deck will tend to quickly be shed overboard through drains and freeing ports all along the deck.

To reduce the GM to one-half its original value would require almost 8000 tons of water on deck. With the available drainage of the openings in the shelter deck, this would in my opinion be impossible. 8000 Long tons of water on the second deck would be approximately 4.25 of water (average height) over the entire deck.

To remove the GM margin of 0.640 feet - thereby placing the vessel's stability within the minimum applicable regulatory requirements - would require about 3000 tons of water on the shelter deck. This would be an average of 1.65 feet of water on the entire deck area. Both examples above take into account the weight of the water and its free surface; however, the available drainage would not likely allow these heights of water on deck.

In my opinion, water on deck would alone not be sufficient to cause a loss of stability of the SS El Faro.

ii. Effects of water in Cargo Hold

It was reported that a Scuttle (manhole in shelter deck, bulkhead deck) was open or had popped

Picture from El Faro

Picture from El Yunque

open. The scuttle in question is shown below in a picture board the EL FARO in 2008.

The pictures show the scuttle, drains and other overboard openings in the area of the shelter deck. The level of water on second deck needs to be 1.0 feet above the deck in order for water to enter it (from height of manhole above the deck from photo and ships plans). Any water on the deck would generally tend to slosh port and starboard, and an open cover to the scuttle would allow water to enter the watertight hold below. This flooding alone is not likely the only cause of the loss of the vessel. Water falling into the lower hold would lower the vessels VCG by the addition of the water weight at the bottom of the hold and increase the VCG of the vessel due to free surface effect. The calculations show that the two effects, weight and free surface, would almost cancel each other's effect. The lower hold from the tank top to about half way to the third deck would need to be full of flooding water for this to reduce the GM.

This vessel has cargo holds that are symmetric about the centerline and it is therefore unlikely that water in 3 hold, alone, caused the list. A more likely cause of the observed list was a steady beam wind and waves. The steady wind heel would cause the water in the hold to pocket on one side of the hold causing an off center weight and increasing the heel of the vessel; initially heel was to starboard, and after the vessel turned to put the wind on the starboard side, the vessel heeled to port. When subject to heavy beam winds and seas, the vessel will list to one side, and any water in Cargo Hold 3 would tend to settle to the port side; this accumulation of water on one side would have contributed to the list. A combination of factors, wind waves and water in the hold could cause the reported list of approximately 15 degrees.[9]

It is noted that the USCG weather criteria specifies a wind pressure not a wind speed, the specified wind pressure is 17.18 pounds per square foot (0.00767 LT/ft^2). Using the laws of physics (Bernoulli's equation), this wind pressure in the criteria equates to a wind speed of approximately 67 knots. It is further noted that the USCG Weather Criteria limits the angle of list to a maximum of 14 degrees or one-half the freeboard angle. One-half the freeboard angle in the loaded condition is 7.43 degrees. During the MBI hearings, I observed some questions from the panel members about whether these assumed conditions are conveyed to the Master as operational restrictions. One should not misconstrue the assumed wind pressure/wind speed and maximum angle of heel in the stability criteria as an operational limitation or requirement. It is merely a standard that has been established, over many years, to measure the vessel's stability. The U.S. Coast Guard weather criteria does not require such an operational limitation and the criteria has never been applied in that way. In my career over the course of 35 years, I have

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[9] The ABS Rapid Response Damage Assessment (ABS-RRDA) team, employed by Tote in the response effort, produced 4 reports for the SS El Faro in October of 2015 during its assessment and response effort: the initial condition, Hold D (Cargo Hold 3) flooded to 10%; Hold D (Cargo Hold 3) flooded till equilibrium; and Hold D Cargo Hold 3) flooded to 10% plus a 75 knot beam wind. All four reports show the SS El Faro with sufficient stability to survive in still water conditions. The reports were calculated in an attempt to reproduce the potential source of the reported list of approximately 15 degrees. All calculations were done using HECSALV software. I have reviewed these calculations and they appear to be accurate with the assumptions used by ABS-RRDA.

reviewed or developed approximately 200 trim and stability booklets, which have been approved by either the U.S. Coast Guard or ABS. I have never seen a trim and stability booklet contain such an operational restriction from the Weather Criteria, nor have I seen that information included on an informational basis.

Looking down the scuttle to Cargo Hold 3 from Shelter deck on the EL YUNQUE.

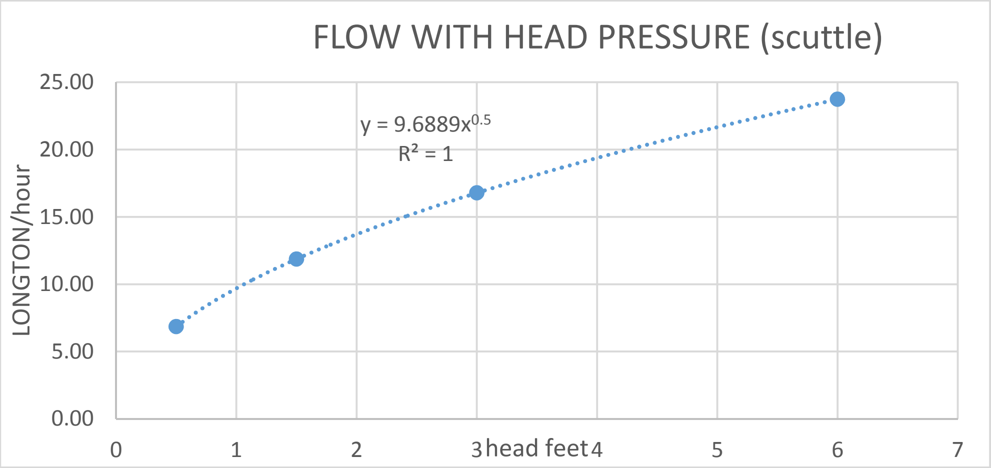

Figure 3 – Potential scuttle Flow vs head pressure. Calculation in Appendix 4.

iii. Probabilistic Damage Stability

Navigation and Vessel Inspection Circular No. 4-93 (NVIC 4-93) sets forth the requirements contained in IMO Resolution A.684 (17) SOLAS Regulations on Subdivision and Damage Stability of Dry cargo Ships of over 100 Meters (328 feet) in length. These requirements are commonly known as the probabilistic damage stability requirements, which accepted the international standard into 46 CFR part 174 Subpart 1. The international standard was published as Resolution A.684 (17), and became effective on February 1, 1992.

The probabilistic approach of the regulations takes into account the probability of various extents of damage occurring anywhere along the ship's length and the resulting flooding. At the same time, it takes into account the probability that the ship will survive the damage given its stability and draft. This provides a rational means of assessing the safety of ships, where flooding is concerned, no matter what their arrangements might be. For instance, a ship may be designed with less subdivision (i.e. watertight compartments) in part of its length, provided it has additional subdivision in areas shown to have a higher probability of damage. In this respect, it frees designers and operators from unnecessarily arbitrary restrictions on arrangements.

I performed a probabilistic damage stability analysis for the SS El Faro and it is summarized in the stability section of this report. *See* figure 1 and associated discussion. The probabilistic damaged stability was performed with the use of the GHS program version 15, using the 1992 criteria. The required GM curve for probabilistic damaged stability was not in the Trim and Stability Book. The required GM for probabilistic damaged stability is less than what is required for a two-tier-on-deck USCG Weather Criteria. As a result, this probabilistic damage stability requirement would have had no effect on the loading of the EL Faro or the trim and stability for the SS El Faro on voyage 185S.

iv. Deterministic Damage Stability

Deterministic damaged stability involves studying the effect of a vessel when a water tight compartment is open to the sea. The ship in the stability condition is then compared to a standard of survival. One standard that is often used is the MARAD design letter #3, one compartment damaged stability requirement. Application of this requirement assumes damage as follows:

- Damage to one watertight compartment within the boundary of the compartment.
- Extent of damage inboard is 20% of the ships beam (B/5).
- Damage keel to main deck.
- Consider all possible unsymmetrical flooding possibilities.
- The vessel must survive (i.e. remain upright assuming still water conditions);

In equilibrium, after the assumed damage is imposed, the ship must have:

- Righting arm curve with a minimum of 20 degrees of positive stability.
- Maximum heel angle of 15 degrees.
- Minimum maximum righting arm of 4 inches.
- No down flooding points within 20 degrees of equilibrium angle.

This calculation would be done for the operational range of drafts considering each damaged compartment, to develop a required GM curve. There is no evidence in the records of the vessel that this calculation was done for the El Faro. This calculation was required for vessels built for foreign trade that received subsidy for their construction and not required of the SS El Faro.

The SS El Faro was evaluated using the departure condition of voyage 185S. Even though these requirements did not apply to the El Faro, I found that the ship exceeded these survivability requirements, for the flooding hold 3.

4. Vessel Modifications

Sun Shipbuilding and Dry Dock in Chester PA as hull number 670, with a Length between Perpendiculars of 700 feet, built the SS El Faro in 1975. Four additional sister ships were built as hulls 662, 664, 666 and 673, with the same LBP.

Also built were hulls 674 and 675 which were longer versions of the first 5 vessels with the addition of 90’-9” of parallel mid-body, giving these two an LBP of 790’-9”. All of these vessels were built as roll on–roll off vessels.

The SS El Faro was in service as the SS Northern Lights servicing the west coast of the United States and Alaska.

In 1992, the SS Northern Lights was lengthened by adding 90’-9” of parallel mid-body to give it the dimensions of hulls 674 and 675. The SS Northern Lights was then returned to service in Alaska delivering trailers from the US west coast. This was considered a major conversion making the Northern Lights subject to the statutory rules and regulations in effect as of 1992. In the Gulf of Alaska, where the Northern Lights operated for many years, weather conditions during the winter months can subject a ship to the most severe wind and wave conditions on earth.

In 2006, the vessel was again modified, including: removing spar deck, strengthening of the main deck to carry containers on deck, and adding permanent ballast for stability (which allows the carrying of containers on deck), and increasing the load line draft by two feet. The modifications were not deemed a major conversion. Thus, stability requirements from 1992 continued to apply to the Vessel. The impact on stability was the requirement to add permanent ballast to the vessel so that the desired number of containers could be carried on deck. Added permanent ballast allowed the vessel to meet required GM criteria. FEU capacity was increased by 232 and the RO/RO capacity was reduced by 40 FEU. Total change is an increase of 192 FEU. Finally the vessel was renamed the SS El Faro and placed in the Florida to Puerto Rico service.

5. Lashing System On Deck and Below Deck

i. Cargo securing manual

The SS El Faro had an approved Cargo Securing Manual (CSM) dated 12 December 2005 and stamped approved by ABS 20 January 2006. The manual provides information on equipment to secure cargo and the proper application of the equipment. The primary purpose of the CSM is to provide guidance to the Master and crew on board the vessel with respect to the proper stowage and securing of cargo units throughout the vessel's voyage. Cargo units on the SS El Faro included ISO standard containers on deck and RO -RO cargo below deck consisting of over the road trailers, containers on trailers, automobiles, and boats on trailers.

Based on my review of the CSM for the El Faro, I found that it complies with the requirements in MSC/Circ.745 dated 13 June 1996 - "Guidelines for the Preparation of the Cargo Securing Manual", and has been prepared in accordance with the International Convention for the Safety of Life at Sea, 1974 (SOLAS) Chapters VI, VII and the Code of Safe Practice for Cargo Stowage and Securing, IMO Resolution A.717 (17) and USCG NVIC 10-97 (Guidelines for Cargo Securing Manual approval). These standards became effective for U.S. flag SOLAS certificated vessels, like the El Faro, on June 8, 2016, with the adoption of the regulations at 33 CFR Part 97, Subpart A (Cargo Securing Manuals). At the time of the El Faro incident, the requirements for Cargo Securing Manuals, set forth above, were not legally required but were instead voluntary guidelines. Page 2 of the Final Rule implementing 33 CFR Part 97.

Over the last 25 years, I have personally prepared or supervised the preparation of Cargo Securing Manuals for the entire fleet of a major shipping companies vessels over 30 US Flag vessels as well as 12 Foreign Flag Vessels.

ii. Stowage and Lashing Lo-Lo Containers on Deck

Originally designed and constructed as a Ro-Ro ship for the transport of wheeled vehicles, the ship was converted in 2006 to permit lashed container stowage in stacks on the Main Deck. Modifications to the deck stowage arrangements were designed around the characteristic dimensions and weights of the containers in the Sea Star service.

The weights of containers that can be stowed in each freestanding stack are influenced by many factors including the following:

- Main Deck strength;
- Container strength and stiffness;
- Lashing components strength and stiffness;
- Stack location;
- Stack configuration; and

- Ship characteristics and loading condition, trim, and stability.

Stowage is generally planned ashore, and ultimately approved and adjusted, as needed, by the mates onboard the vessels. A feature in CARGOMAX can be used to determine maximum stack weights of the containers. If the shore side computer evaluation of stack weights is not available, stow plans developed for previous voyages and the Appendix 13 of the CSM contains typical stack weight diagrams that are used to assess allowable stack weights. In addition, the maximum allowable container stack weights, which may be loaded on the Main Deck, listed in Appendix 9 of the CSM, are not to be exceeded. This ensures the weight and arrangement of the containers on deck do not result in excessive stresses on the main deck and surrounding structure.

The SS El Faro's CARGOMAX program also has a feature, which allows the mates and shore side personnel to check the strength of the container securing arrangement (i.e. lashing).

Even though not approved by ABS, this feature in CARGOMAX can be used by the ship's crew, so long as CARGOMAX calculates the lashing margins in accordance with the CSS Code. I have examined this feature of CARGOMAX for the El Faro, and in my opinion, it calculates lashing margins in accordance with the CSS Code

A standard lashing scheme was used for all voyages of the SS El Faro. This scheme included the twist locking of all containers to the deck and to each other and applying a standard ridged rod cross lash to the two outboard most stacks of containers. Rigid rod cross lashes are attached to the bottom container corner fitting of the second tier container to a deck fitting, this forms a letter "X" across the bottom tier of containers. Additional lashings are applied if CARGOMAX indicates that the strength of the lashing components, the deck, or the container itself are exceeded.

The above procedures for lashing cargo containers is set forth in the "EL Class" simplified lashing guidance, which I understand from testimony was used by the mates and shore side personnel when loading the vessels. I have reviewed these procedures. These procedures are a simplified, conservative manner of lashing Lo-Lo containers that usually results in lashing arrangements well in excess of the minimum requirements. This method of lashing is in full compliance with the Cargo Securing Manual.

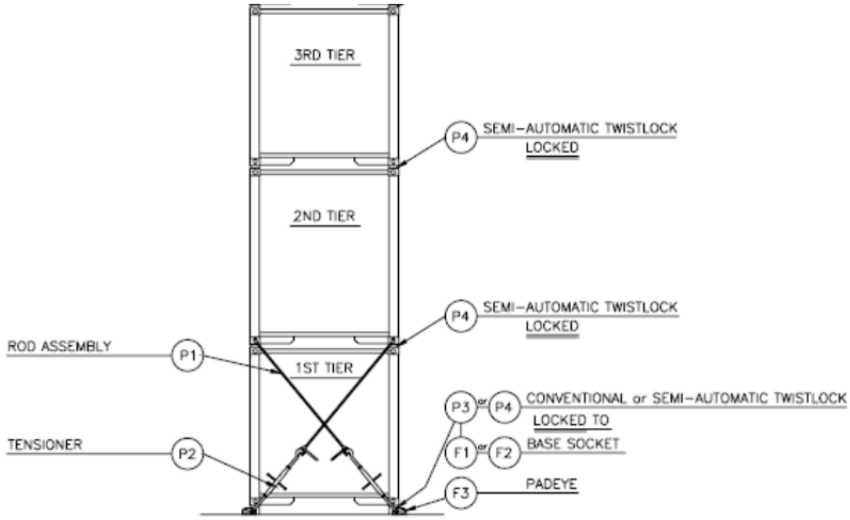

Figure 4 –Typical three high lashing arrangement with single Lash and twist locks[10]

iii. Stowage of Cargo Below Deck - Ro-Ro Cargo

The following general instructions, provided in the CSM are intended to provide guidance in the application of lashings to secure vehicles to the ship[11].

1. Trailers shall be secured to the deck using ROLOC boxes and lashings. Trailers are not to be stowed on their built-in landing legs. Cite to CSM[12].

2. A great deal of personal judgment is required in the placement of lashings on the wide variety of vehicle frameworks encountered in the Ro-Ro trade. Few of these frames have really good lashing points. You will find that some points that appear convenient are not adequately welded or otherwise fastened to the main framework. Usually, the best points are at the juncture of structural members that can support each other against crushing, buckling, or rolling of flanges. Cite to CSM[12].

3. Lashing leads should work against each other. Cite to CSM[12].

4. The athwart ship run or lead of the standard trailer lashing wire shall be a minimum of 4 feet when lashed to the trailer or chassis. When the lashings are led directly to strong securing points on the cargo loaded on a flatbed, the angle between the lashing and the deck in the athwart ship direction shall be 45 degrees or less. Cite to CSM[12].

5. It is usually more effective to wrap the lashing chain bridle around a structural member than to attach the hook to it. Often, the hook point will lever against the structure and distort it. The hook may fall out if the lashing tension is not maintained. Cite to CSM[12].

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[10] See El class lashing guide in Appendix 1 for more lashing examples.

[11] The 11 general instructions and 8 figures below are taken directly from the approved Cargo Securing Manual.

6. Lashings should be placed as high and as wide apart on the trailer as possible, assuming there is a choice of structural members to use as lashing points. Cite to CSM[12].

7. In general, lashings should not be attached to the axles. Standard spring arrangements make such lashing ineffective. Cite to CSM[12].

8. Pad eyes and rugged structural members on cargo are often better securing points than may be found on the trailers. These points are particularly desirable in the case of loads with high centers of gravity. Cite to CSM[12].

9. It is poor practice to lash around brake lines, brake boosters, lubrication lines, or any delicate or flimsy mechanisms. Do not allow lashings to lead around or rest on such equipment. Do not lash to sheet metal structures where such structures are unsupported. Cite to CSM[12].

10. Vehicles that have brakes should always be stowed with the brakes set. A vehicle with a standard transmission should be left in reverse or low gear and one with an automatic transmission should be set in park. Cite to CSM[12].

11. Livestock trailers shall not be stowed in the athwart ship direction. Cite to CSM[12].

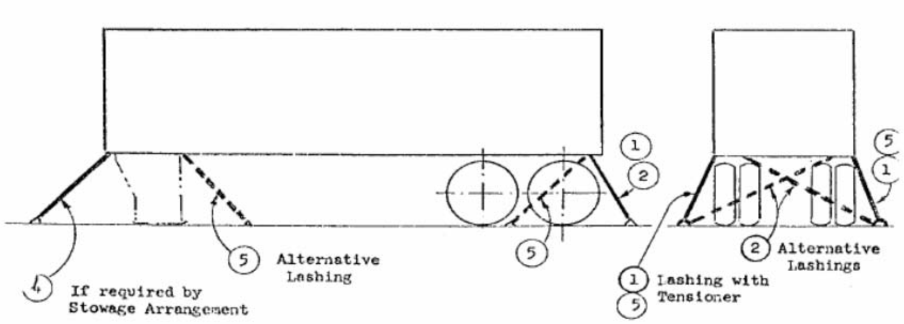

Figure 1. Illustration of Alternative Lashing Arrangements Which Work Against Each Other

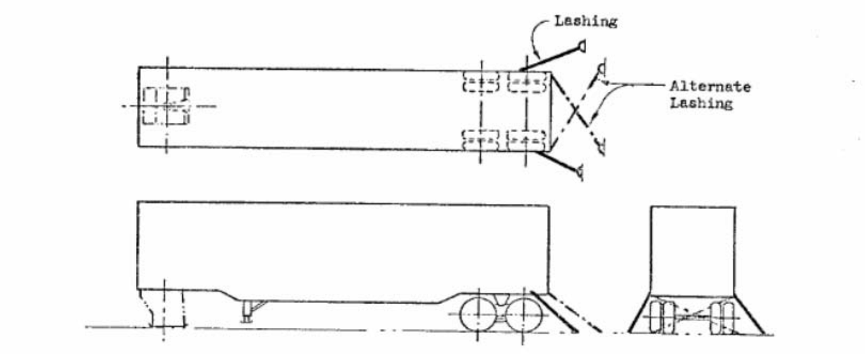

Figure 2. Fore / Aft Stowage with a Roloc Box, Oriented Normally
Two lashings are required at the rear of the trailer with a rearward lead with respect to the trailer.

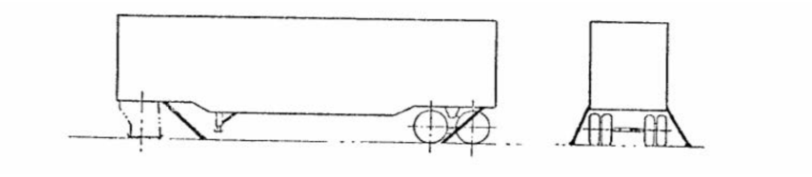

Figure 3. Fore / Aft Stowage with a Roloc Box, Oriented Normally But with D-Rings Located so that a Rear Lead from the Rear Axle is not possible.
Four lashings are required – two opposing sets of lashings.

1

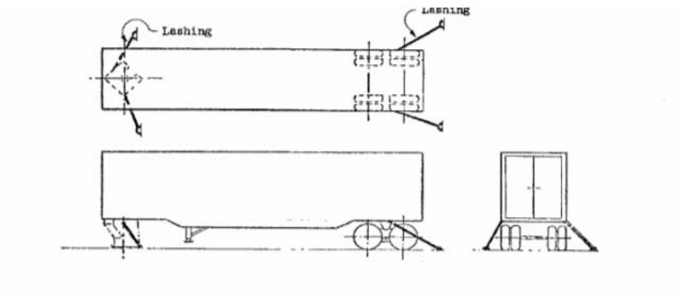

Figure 4. Fore / Aft Stowage with a Roloc Box Oriented at an Angle of 30° or More to the Axis of the Trailer, But with a Rear Lead Possible on the Rear Lashings.
Four lashings are required – two at the rear of the trailer and two from the Roloc box.

2

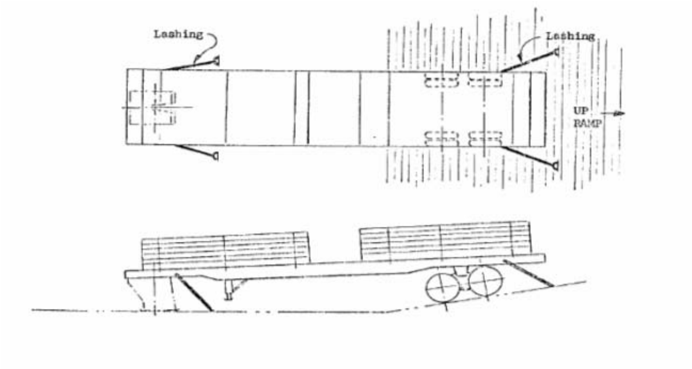

Figure 5. Fore / Aft Stowage on a Ramp with a Roloc Box
Four lashings are required, two at each end. All four lashings are to be led uphill to prevent the trailer from rolling down the ramp.

3

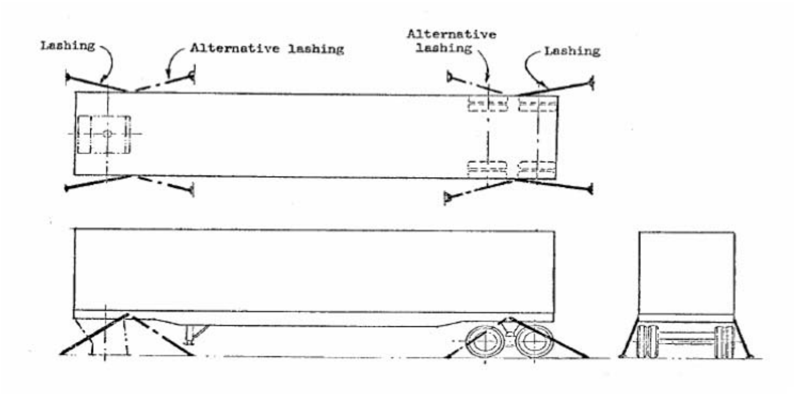

Figure 6. Athwartship Stowage with a Roloc Box, Oriented Normally
All conditions require a minimum of four lashings, two at each end. The set of lashings at either end should lead away from the lashings at the opposite end.

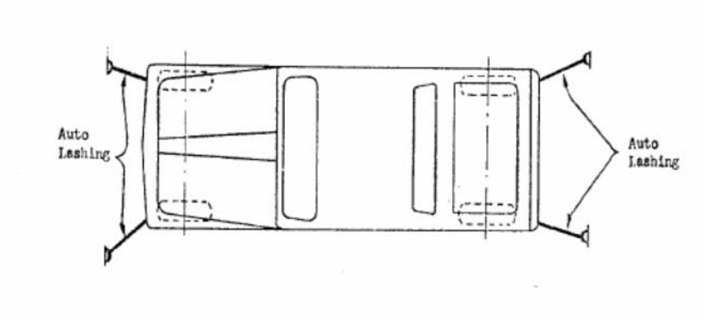

Figure 8. Athwartship Stowage of Automobiles

In assessing the adequacy of the stowage and cargo securing procedures onboard the El Faro generally, and in particular for Voyage 185S, I reviewed the report of the National Cargo Bureau (NCB), dated August 4, 2016.[12] In addition, I performed calculations and provided other assistance to Tote in preparing its response to the NCB's report.[13] I have reviewed Tote's response in its entirety, I fully concur with the content, and all conclusions contained in it.

The report from the NCB concluded that catastrophic lashing failure likely played a role in the loss of the EL FARO. I do not agree. While I very much disagree with the findings NCB's report, in fairness to its authors they appear to have, in many respects, been provided with inaccurate, incomplete, or faulty assumptions to perform their analysis.

I have also reviewed the follow-up reports from the NCB, issued after Tote's response to the initial NCB report.[14] Based on my review of the evidence, and these reports, I make the following additional findings:

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[12] The NCB Report is marked as MBI Exhibit 290.
[13] Tote's response, dated September 16, 2016, is marked as MBI exhibit 290.
[14] These reports, dated November 18, 2016, are marked as MBI exhibits 291, 291, and 293.

- Initial Assumption of NCB was that 60% of the RO/RO cargo was off the button, but the basis for that assumption does not seem to be supported. After further investigation, and review of information provided by a recent Master and Chief Mate of the *El Faro* regarding the stow plan, it appears the best evidence suggests that approximately 4 trailers may have been stowed off button.
- NCB initially assumed that the weight of the trailers was equally on the button and the wheels – weight distribution should be 38.5% ON BUTTON AND 61.5% ON WHEELS. Under the CSS Code and approved Cargo Securing Manual, this weight should be evenly distributed between the button and the wheels.
- Lashing angle was assumed to not be 45 degrees – but angles used for lashing on *El Faro* were 45 degrees.
- Vessel speed was assumed to be 24 Knots – speed actually 19 knots.
- Using the correct assumptions[15] all trailers were determined to have been secured properly, even if you assume all Ro-Ro cargo was stowed off button

In my opinion, based on the available evidence and as reflected in Tote's response to the NCB, the lashing procedures and securing devices employed onboard the EL FARO were in compliance with the CSM and adhered to applicable international guidelines promulgated by the International Maritime Organization (IMO). In my opinion, based on the evidence I have reviewed, including the VDR transcript, the adequacy of the stowage and lashing of cargo played no role in the loss of the vessel.

All cargo lashing system are designed to withstand forces generated by vessel motions and the effects of wind, and apply a factor of safety. No cargo lashing system to my knowledge applies a lashing force requirement due to sloshing of water in an enclosed lower hold. Lashings are never designed for sloshing loads due to flooding water.

It is important to note that lashings are designed to be able to withstand a certain amount of force; forces that the regulations assume are likely to be encountered under certain operating settings. Lashings are not designed to withstand unlimited forces under any circumstances. Therefore, when the design limitations are exceeded, lashings can and do fail, but that does not mean that such lashings were not proper or did not comply with the CSS code or other regulations and requirements. As this pertains to the El Faro, the lashings below deck are designed to withstand certain forces but are not designed to withstand additional forces exerted by forces of water in the hold. Such water, especially when moving as the vessel rolls, heaves, and pitches, can exert additional forces on cargo lashings that exceed their design limitations. If it were the case that cars in fact broke lose in Hold 3 (as a comment on the VDR might suggest), given the amount of water likely in hold 3 by 0545, the failure of those lashings was due to the forces exerted by the considerable amount of water in that hold, and not by any failure to follow proper and required lashing requirements. No conceivable lashing profile that

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[15] Appendix 2 has summary of all calculations for trailers on second deck

would normally be used for lashing automobiles could withstand such forces associated rapid movement of that amount of water.

6. Cargo Ventilation System

Because the El Yunque is considered to be a sister vessel to the El Faro, I attended the El Yunque in the course of my participation in this matter. As part of my attendance on the vessel, I inspected, among other things, the cargo ventilation system, including all intake and exhaust ventilation structures on the second deck. I also have reviewed various drawings of the cargo hold ventilation system.

i. Supply Ventilation

Supply vents and vent fans for the El Faro were contained in enclosed structures under the main deck, similar to those shown below on the El Yunque. The structure housing the supply vents is provided with drain holes, similar to those shown in the photograph,[16] and internal baffles. The purpose of the drain holes is to allow any water that enters the structure to escape. The vent inlets, which allow air to enter the system, are shown on the sides of the structure.

The arrangement of the baffles is such that water in the structure would need to be is approximately 13.04 feet above the second deck to enter the fan plenum. Any water which does not go over the baffle and into the fan plenum would be expected to drain out by gravity through the drain holes. In addition, the vent fans are fitted with weather tight closures (fire dampers). The vent system would be considered a possible down flooding point in damage stability cases, but because of the location and arrangement of the intake vents on the El Faro, they have no effect on the probabilistic damaged stability calculations. Intake vents have weather tight fire dampers fitted in them.

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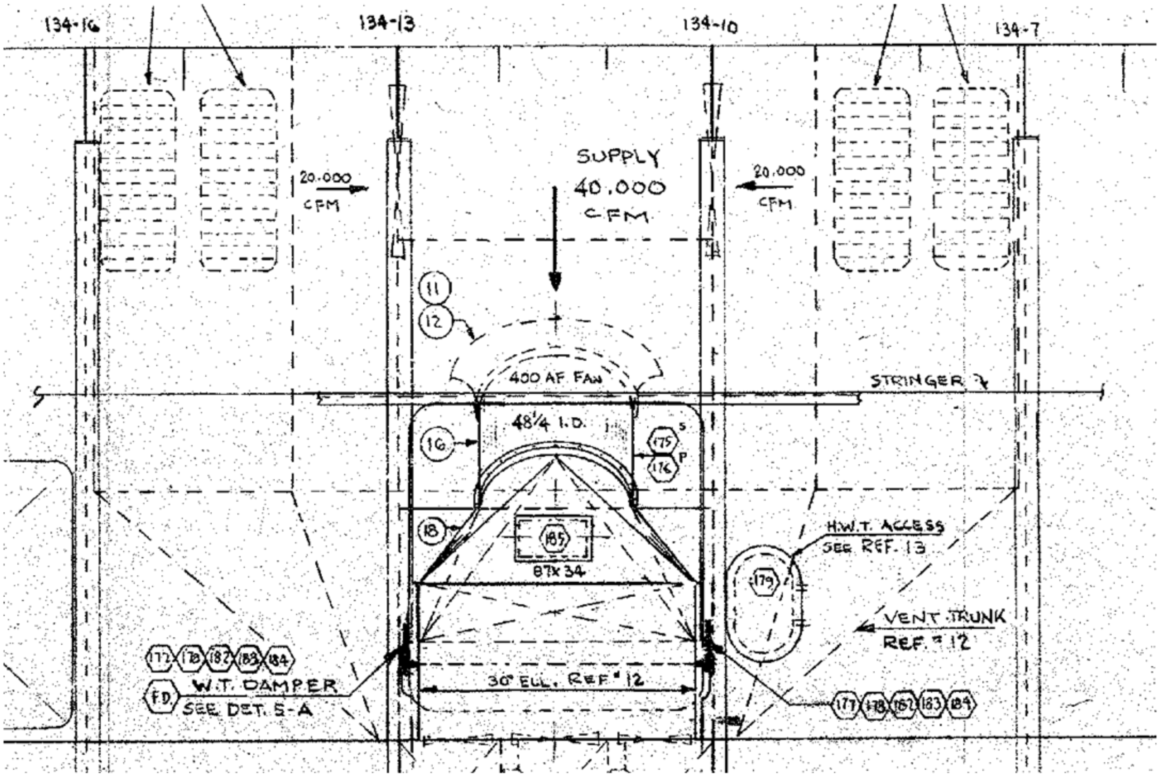
[16] The drain holes observed on the El Yunque, shown in the photograph, were approximately 6 inch semi-circle holes. Underwater photographs taken of the El Faro by the NTSB (and other historical photographs) show that the drain holes on the ventilation intake structure on the El Faro are considerably smaller than the drain holes observed on the El Yunque. The drawings for the El Faro show drain holes of one inch in diameter, which is consistent with the photographic evidence available for the El Faro.



ii. Exhaust Ventilation

Exhaust Vents can be seen on the side of the main hull between the intake vent structures, as shown in the photo of the El Yunque below. The exhaust vents have similar baffling arrangements as the intake vents. The exhaust vents have down flooding points at a greater angle than the intake vents, so the intake vents are used as the most critical down flooding points in performing the deterministic damaged stability analysis. Baffles in the exhaust vents are 13.77 feet above the 2nd deck. Exhaust vents have fire dampers fitted in them.

Mr. Tom Gruber of ABS testified in the USCG MBI that this ventilation system would be approved for a new vessel built today, and I agree. The pictures above are of the SS El Yunque, a sister vessel of the SS El Faro.

7. Effect of Wind Heel angles

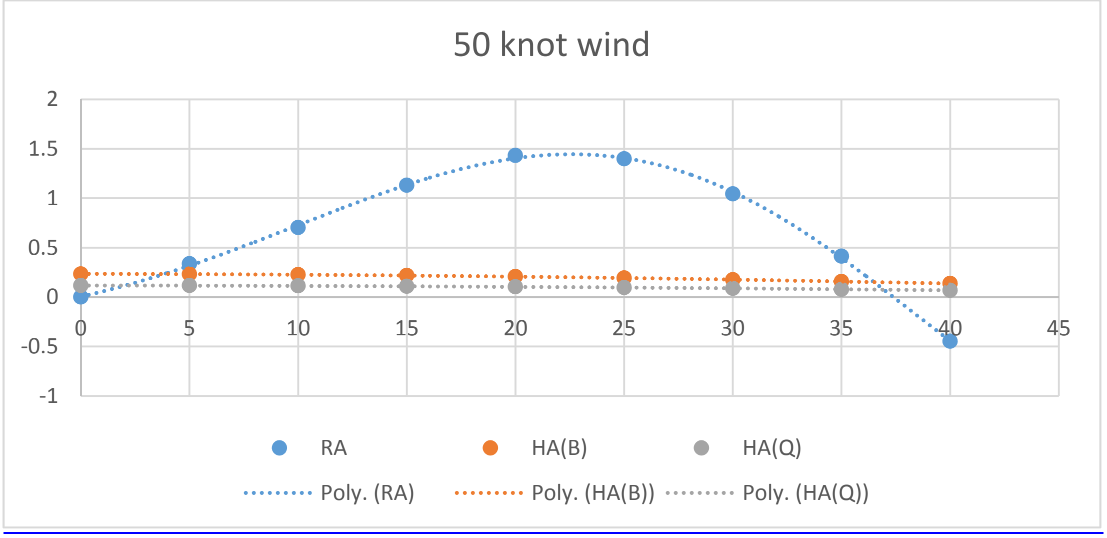
To better understand the effect that the wind had on the El Faro, in the hours leading up to the loss of the vessel, I calculated and plotted the wind heeling moment and the statical stability curve for the vessel for voyage 185S.

The formula below is used to calculate the wind heeling arm that changes with the angle of heel and in a steady wind. The wind heeling curve is plotted on the ships as loaded statical stability curve the point where the curves cross is the steady angle of heel in CALM seas. Wind heel angle is calculated using the formula below[17];

$$\text{WHA} = .0035V_w^{2}AL\cos^{2}\Theta/2240\Delta$$

WHA = wind heeling arm plotted on statical stability curve.
V_W = wind speed in knots.
A = vessel projected profile area above water.
L = distance between the centroid of the above water projected area to below water projected area.
Θ = angle of the wind relative to the vessel beam.
2240 = 2240 pounds in one long ton.
Δ = vessel displacement in long tons.

Sample wind heel calculation for a 50-knot wind.
Blue Curve is the vessels statical stability curve.
The orange curve is for a beam wind. Wind heel angle about 4 degrees.
The gray curve is for a beam on the quarter or 45 degrees off the beam. Wind heel angle about 2 degrees.



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[17] Applied Naval Architecture – Robert B. Zubaly

8. Analysis of Stability Conditions on the El Faro due to the effects of Joaquin

i. Overview of Dynamic Analysis

In order to assess the conditions that the EL FARO likely experienced along the vessel's accident voyage route, due to the effects of Joaquin, I performed a dynamic stability analysis of the vessel using the MAXSURF program. I assessed the vessel's stability at 0000, 0100, 0200, 0300, 0330, 0400, 0430, 0500, 0530, 0600, 0630, 0700 and 0730.

ii. "Maxsurf Motions" (MAXSURF)

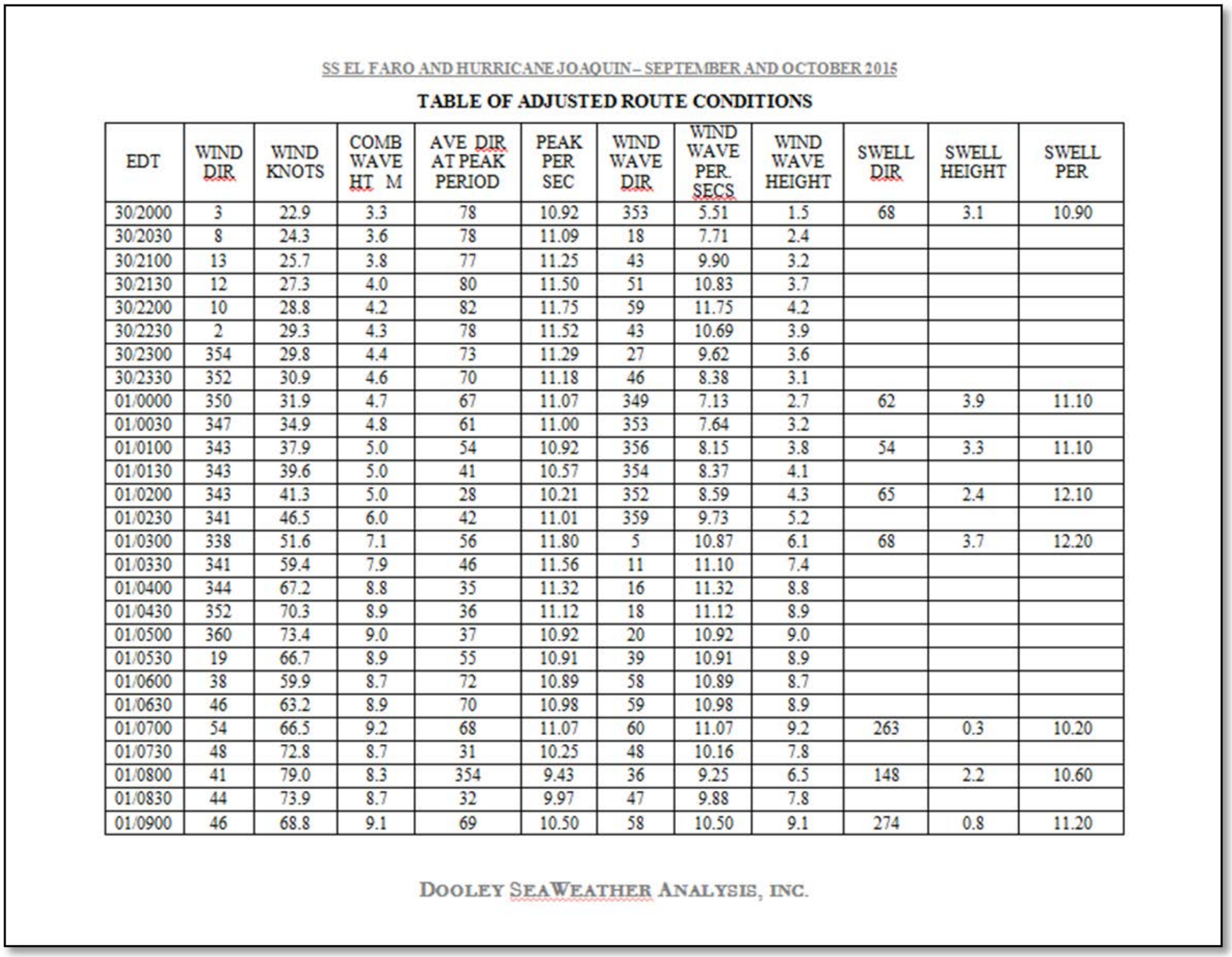
Unlike many other vessel stability software programs which calculate static righting arms and measure a stability of the vessel under calm, still water conditions, MAXSURF can be used to calculate and predict the behaviour of a vessel in dynamic conditions, taking into account wave and other dynamic effects. The MAXSURF program uses the linear strip theory to evaluate ship motions. I have used MAXSURF for 25 years in the course of my work.

A model of the SS El Faro based on the GHS/HECSALV computer models, as well as original lines drawing of the El Faro with appendages, was used in perfomering the analysis. The model shape and properties match the properties of the El Faro within industry acceptable limits. The model was loaded in MAXSURF using the departure condition of voyage 185S. This departure condition was adjusted for consumable items used during the voyage, primairly fuel burned between departure of the vessel and the morning hours of October 1, 21015 (approximately 240 long tons of fuel burned). The condition of the vessel was also adjusted for water on the second deck and water in lower three hold that entered through the popped open scuttle.

Assumed wind and wave data (see further discussion below) is input into MAXSURF. In addition to assumed wind and wave data, vessel speed and heading are are also input into the program.

iii. Source of Input Data

The ship's heading information and ship speed were obtained from the VDR data. Assumed wind speed/direction and signficant wave height/wave period/principle wave direction were provided by Dooley Sea Weather Analysis, Inc. A table of these assumed wind speed, wave heights, and directions, which the El Faro was believed to have been experiencing, is provided here:



SS EL FARO AND HURRICANE JOAQUIN – SEPTEMBER AND OCTOBER 2015

TABLE OF ADJUSTED ROUTE CONDITIONS

EDT	WIND DIR	WIND KNOTS	COMB WAVE HT M	AVE DIR AT PEAK PERIOD	PEAK PER SEC	WIND WAVE DIR	WIND WAVE PER. SECS	WIND WAVE HEIGHT	SWELL DIR	SWELL HEIGHT	SWELL PER
30/2000	3	22.9	3.3	78	10.92	353	5.51	1.5	68	3.1	10.90
30/2030	8	24.3	3.6	78	11.09	18	7.71	2.4			
30/2100	13	25.7	3.8	77	11.25	43	9.90	3.2			
30/2130	12	27.3	4.0	80	11.50	51	10.83	3.7			
30/2200	10	28.8	4.2	82	11.75	59	11.75	4.2			
30/2230	2	29.3	4.3	78	11.52	43	10.69	3.9			
30/2300	354	29.8	4.4	73	11.29	27	9.62	3.6			
30/2330	352	30.9	4.6	70	11.18	46	8.38	3.1			
01/0000	350	31.9	4.7	67	11.07	349	7.13	2.7	62	3.9	11.10
01/0030	347	34.9	4.8	61	11.00	353	7.64	3.2			
01/0100	343	37.9	5.0	54	10.92	356	8.15	3.8	54	3.3	11.10
01/0130	343	39.6	5.0	41	10.57	354	8.37	4.1			
01/0200	343	41.3	5.0	28	10.21	352	8.59	4.3	65	2.4	12.10
01/0230	341	46.5	6.0	42	11.01	359	9.73	5.2			
01/0300	338	51.6	7.1	56	11.80	5	10.87	6.1	68	3.7	12.20
01/0330	341	59.4	7.9	46	11.56	11	11.10	7.4			
01/0400	344	67.2	8.8	35	11.32	16	11.32	8.8			
01/0430	352	70.3	8.9	36	11.12	18	11.12	8.9			
01/0500	360	73.4	9.0	37	10.92	20	10.92	9.0			
01/0530	19	66.7	8.9	55	10.91	39	10.91	8.9			
01/0600	38	59.9	8.7	72	10.89	58	10.89	8.7			
01/0630	46	63.2	8.9	70	10.98	59	10.98	8.9			
01/0700	54	66.5	9.2	68	11.07	60	11.07	9.2	263	0.3	10.20
01/0730	48	72.8	8.7	31	10.25	48	10.16	7.8			
01/0800	41	79.0	8.3	354	9.43	36	9.25	6.5	148	2.2	10.60
01/0830	44	73.9	8.7	32	9.97	47	9.88	7.8			
01/0900	46	68.8	9.1	69	10.50	58	10.50	9.1	274	0.8	11.20

DOOLEY SEAWEATHER ANALYSIS, INC.

Wind heel angle is calculated by applying the wind velocity perpendicular the beam of the ship on the ships profile area. The calculation results are listed on the direction plots referenced below.

iv. Analysis Results;

The following is provided from the MAXSURF Users Manual for Version 21:

MAXSURF Motions, an application which may be used to predict the motion and seakeeping performance of vessels designed using MAXSURF. MAXSURF Motions is the seakeeping analysis program in the MAXSURF software suite. It uses the MAXSURF geometry file to calculate the response of the vessel to user-defined sea conditions. Multiple methods are available to calculate the vessels response: a linear strip theory method is used to analyze the SS EL Faro.

The linear strip theory method is based on the work of Salvesen et al, it is used to calculate the coupled heave and pitch response of the vessel. The roll response is calculated using linear roll damping theory.

When linear strip theory is used to compute the coupled heave and pitch motions of the vessel, the following underlying assumptions are implied:

- Slender ship: Length is much greater than beam or draft and beam is much less than the wavelength).
- Hull is rigid.
- Speed is moderate with no lift from forward speed.
- Motions are small and linear with respect to wave amplitude.
- Hull sections are wall-sided.
- Water depth is much greater than wavelength so that deep-water wave approximations may be applied.
- The hull has no effect on the incident waves (so called Froude-Kriloff hypothesis).

A simplified forced, damped mass-spring system is assumed for the uncoupled roll motions. This assumes the following;

- An added inertia in roll is used which is assumed to be a constant proportion of the roll inertia.
- A constant user-specified linear damping is used.

See Appendix 4 for equations of motion.

What the El Faro was experiencing based on weather data and input into MAXSURF and the resulting calculation including vessel motions, wind heel angle heel angle due to water in hold and heel angle due to shift in cargo in the hold.

RMS (average values of roll pitch and heave) are given in the results. Extreme values of motions can be twice the RMS value.

i. Condition at 0000 EST - October 1, 2015

I first used MAXSURF to calculate and analyze the predicted dynamic motions of the vessel at midnight (0000 EST) on October 1, 2015, based on the assumed environmental conditions noted in figure 8-1 below.

The analysis shows that, during this time frame of the voyage, the main source of water on deck would be due to some water spray entering the 2nd deck, primarily from the stern due to the relative wind direction coming from the port quarter of the vessel. There is ample overboard openings and freeing ports on the second deck to allow this amount of water to freely drain overboard. Additional results of the motion study, including wind heel angle at 0000 EST, are shown below.

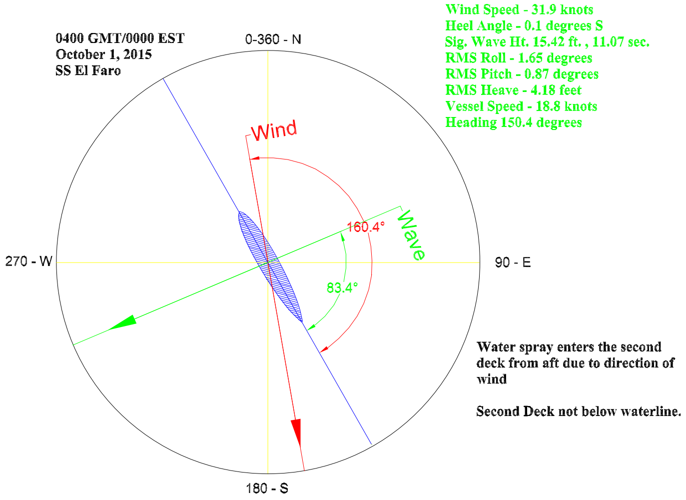
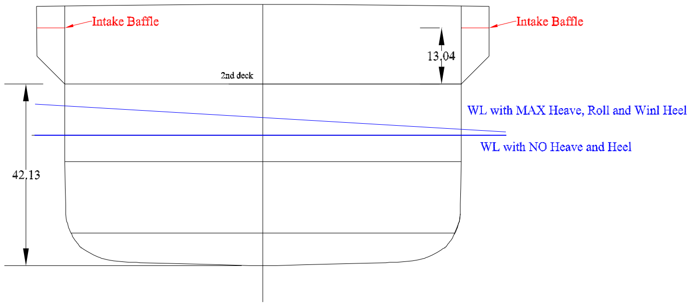


Figure 8-1

The analysis shows that the vessel is slightly heeling due to wind, and rolling and heaving due to wave action. Shown below is the vessel's midships cross section in way of hold number three looking aft. The max heave is shown as well as max roll angle as well as the wind heel angle. Vessel pitch is not depicted. Ship rolls about the wind heel angle. At this point in the voyage, the ship is pitching slightly, but riding out the weather very well.

1 October 2015 - 0000 EST



Midships looking Aft at 3 Hold intake Vent

ii. Condition at 0100 EST - October 1, 2015

I next used MAXSURF to calculate and analyze the predicted dynamic motions of the vessel at 0100 EST on October 1, 2015, based on the assumed environmental conditions noted below in figure 8-2.

The result of the calculations performed using MAXSURF, for 0100 EST are shown below. The prediction of the vessels roll, pitch and heave are displayed on the direction charts. The calculations and analysis indicates that roll has increased, pitch has decreased and heave has decreased slightly during this time period.

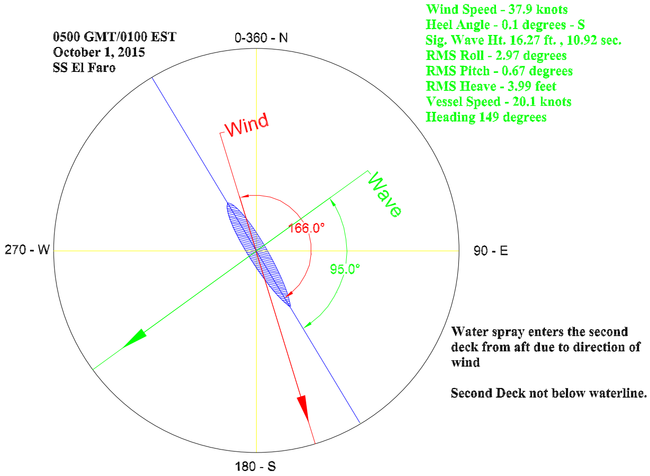
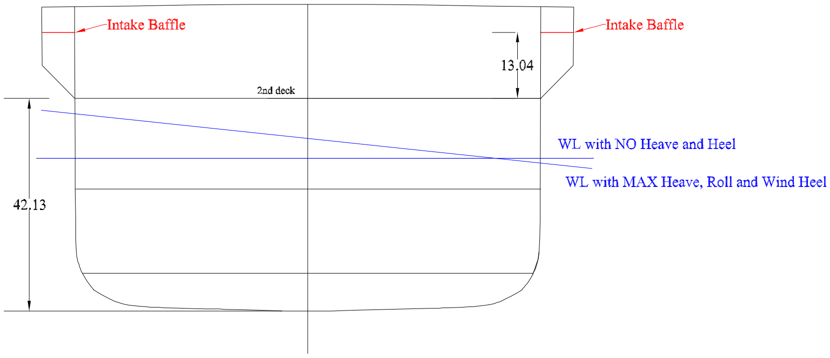


Figure 8-2

The analysis shows that, during this time frame of the voyage, the main source of water on the second deck would have been due to some water spray; again, this spray is primarily due to the relative wind direction from the stern/port quarter of the vessel. There is ample overboard openings and freeing ports on the second deck to allow this amount of water to freely drain overboard.

Additional results of the motion study, includingwind heel angle at 0100 EST, are shown below.

1 October 2015 - 0100 EST



Midships looking Aft at 3 Hold intake Vent

The analysis shows that, during this time frame of the voyage, the vessel is heeling slightly to starboard due to wind, and rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three looking aft. The max heave, roll angle, and wind heel angle are shown. Vessel pitch is not depicted

At this point in the vessel’s voyage, the ship is predicted to have been pitching slightly, but riding out the weather very well.

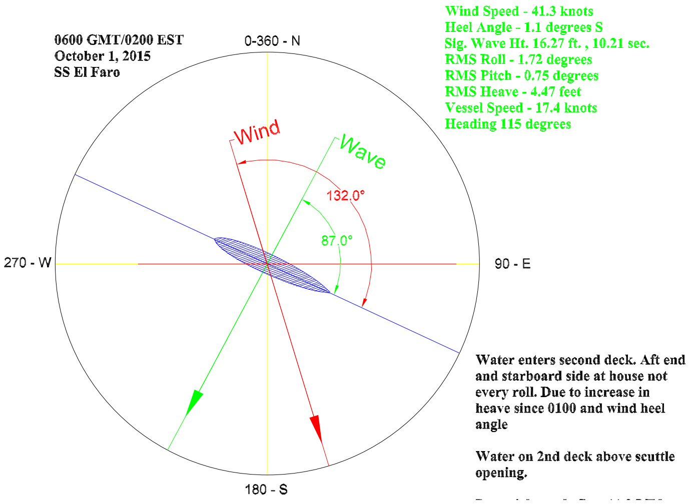
iii. Condition at 0200 EST - October 1, 2015

I next used MAXSURF to calculate and analyze the predicted dynamic motions of the vessel at 0200 EST on October 1, 2015, again based on the assumed environmental conditions noted below in figure 8-3

The result of the calculationsperformed using MAXSURF, for 0200 EST are shown below. The prediction of the vessel’s roll, pitch and heave are displayed on the direction charts. The calculations and analysis indicate that roll has decreased, pitch has increased slightly and heave has increased slightly.

During this period of time, the calculations indicate that there would have likely been a reduction of the water spray entering the 2nd deck. This reduction is due to the change in relative wind direction toward the beam.

The significant wave height was predicted by Dr. Dooley to be less than 17 feet at this point in the vessel’s voyage.



0600 GMT/0200 EST
October 1, 2015
SS El Faro

Wind Speed - 41.3 knots
Heel Angle - 1.1 degrees S
Sig. Wave Ht. 16.27 ft. , 10.21 sec.
RMS Roll - 1.72 degrees
RMS Pitch - 0.75 degrees
RMS Heave - 4.47 feet
Vessel Speed - 17.4 knots
Heading 115 degrees

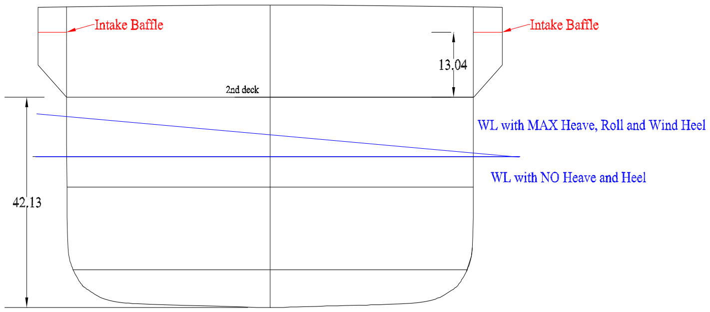
Water enters second deck. Aft end and starboard side at house not every roll. Due to increase in heave since 0100 and wind heel angle

Water on 2nd deck above scuttle opening.

Figure 8-3

Additional results of the motion study, with wind heel angle at 0200 EST, are shown below.

1 October 2015 - 0200 EST



Midships looking Aft at 3 Hold intake Vent

The calculations show that, during this time frame in the voyage, the vessel is heeling slightly more to starboard (1.1 degrees) due to the increasing beam wind, and is rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three looking aft. The max heave is shown as well as max roll angle and wind heel angle. Vessel pitch is not depicted

At this point in the voyage, the calculations indicate the ship is also pitching slightly, but riding out the weather very well.

Water sea spray enters the second deck from the stern quarter. Water enters aft end of second deck ocassionally not on every pitch and roll cycle. Water will pocket to the side of the due to wind heel. Water accumulates near scuttle, and may splash over the scuttle. However, there is ample overboard openings and freeing ports on the second deck to allow this water to freely drain overboard.

vi. Condition at 0300 EST - October 1, 2015

I next examined the dynamic motions of the vessel at 0300 EST on October 1, 2015, again based on the assumed environmental conditions noted below in figure 8-4. The predicted wind speed has increased to 51.6 knots with a relative direction from the stern quarter, yielding a wind heel angle of 1.6 degrees. The significant wave height increased to 23.29 feet.

The result of the calculations perfomed using MAXSURF, for 0300 EST, are shown below. The prediction of the vessel's roll, pitch and heave are displayed on the direction charts. The calculations and analysis indicate that the vessel's roll has decreased and pitch and heave have increased. This change in the vessel's motion is likely a result of the change in relative wave direction, as the vessel's bow heads slightly more into the waves.

The analysis indicates that water begins to enter the second deck aft, on the starboard side, approximately every other time the vessel pitches. Water entering the second deck aft flows forward and aft as the ship pitches. Water that reaches the starboard scuttle leading into the three hold, if open, would allow water to enter the hold. Potential rate of water flow into 3 hold is 13 LT/hour, estimated by pocketed height of water at the scuttle of 2 feet.

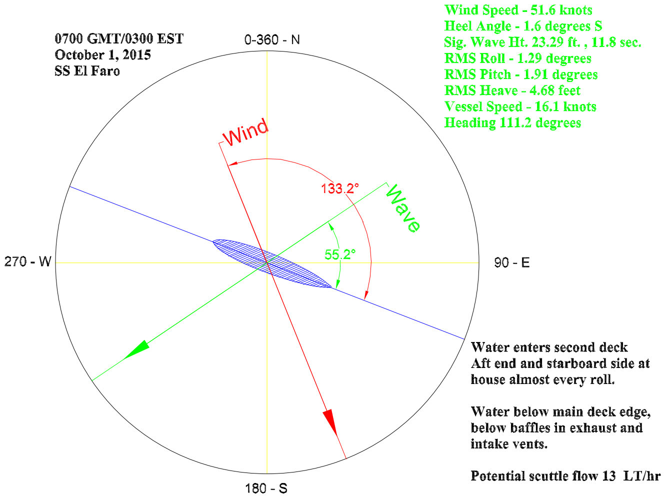
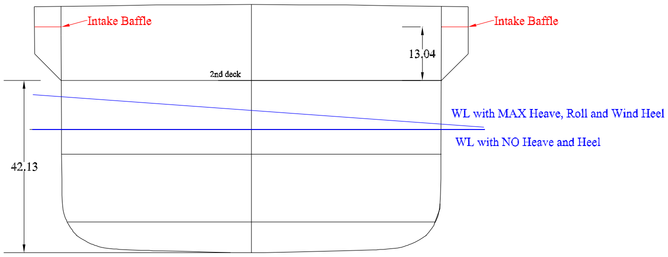


Figure 8-4

Additional results of the motion study, including the wind heel angle at 0300 EST, are shown below.

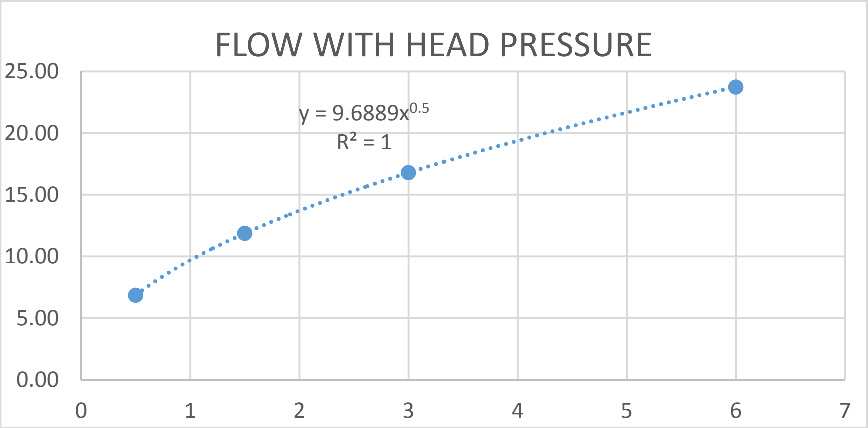
1 October 2015 - 0300 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 1.97 degrees trim would increase by 12 feet.

The calculations show the vessel is heeling more due to higher wind speed, and rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three looking aft. The max heave, roll angle and wind heel angle are shown. Vessel pitch is not depicted. With a pitch angle of 1.97 degrees, the draft aft would increase by 12 feet. This will cause green water to enter the second deck at aft end at every extreme roll, heave and pitch motion. Water enters the second deck from the stern as the vessel pitches.

A small amount of water begins to enter Hold 3 through the starboard scuttle access with an estimated two feet of water pocketed at the scuttle. At nthis time only a small ammout of water has entered 3 hold.

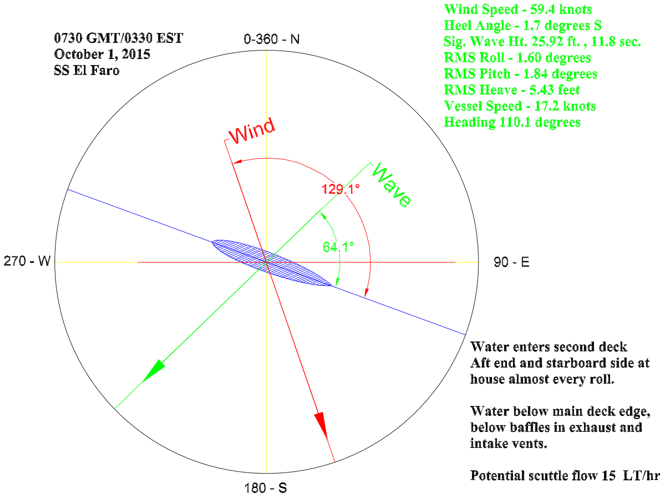


The chart to the left is the potential flow of water though the scuttle on the second deck[18], showing flow rate vs height of water at the scuttle. Rate of flow 'Y' Axes and Height 'X"Axes

v. Condition at 0330 EST - October 1, 2015

I next examined the dynamic motions of the vessel at 0330 EST on October 1, 2015, again based on the assumed environmental conditions noted below in figure 8-5. The predicted wind speed has increased to 59.4 knots with a relative direction from the stern quarter, yielding a wind hell angle of 1.7 degrees. The significant wave height increased to 25.92 feet.

The result of the calculations performed using MAXSURF, for 0330 EST, are shown below. The prediction of the vessel's roll, pitch and heave are displayed on the direction charts. Roll and heave have increased and pitch has decreased slightly.



0730 GMT/0330 EST
October 1, 2015
SS El Faro

Wind Speed - 59.4 knots
Heel Angle - 1.7 degrees S
Sig. Wave Ht. 25.92 ft. , 11.8 sec.
RMS Roll - 1.60 degrees
RMS Pitch - 1.84 degrees
RMS Heave - 5.43 feet
Vessel Speed - 17.2 knots
Heading 110.1 degrees

Water enters second deck
Aft end and starboard side at
house almost every roll.

Water below main deck edge,
below baffles in exhaust and
intake vents.

Potential scuttle flow 15 LT/hr

---

[18] Calculation based on engineering standard practice found in MARKS Mechanical Engineering Handbook.

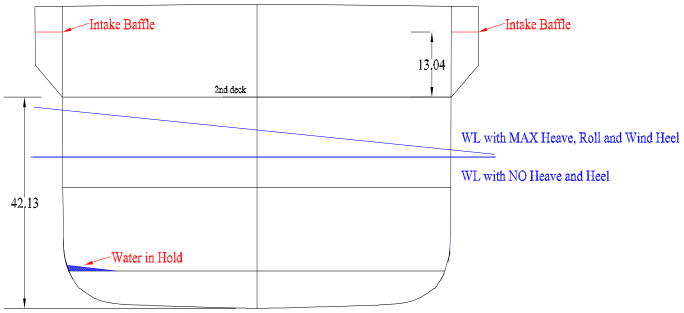
Figure 8-5

The analysis shows that at this point in the voyage, water begins to consitently enter the starboard side of the second deck through the aft openings of the shelter deck, as the vessel pitches (water enters almost every other pitch). Water entering the second deck aft flows forward and aft as the ship pitches. With a pitch angle of 1.84 degrees, the draft aft would increase by 11.25 feet. This will cause green water to enter the second deck at aft end at every extreme roll, heave and pitch motion. Water enters the second deck from the stern as the vessel pitches.

Water in the area of the starboard scuttle would enter directly into the three hold, if the scuttle were open. Potential rate of water flow into three hold is 15 LT/hour.

Additional results of the motion study, including the wind heel angle at 0330 EST, are shown below. The analysis predicts that the vessel is heeling due to wind, and rolling and heaving due to wave action. Shown below is the vessel's midships section in way of hold number three. The mean heave,roll angle, the heel angle due to wind, and the effects of water in the three hold, are shown below.Vessel pitch is not depicted.

1 October 2015 - 0330 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 1.84 degrees trim would increase by 11.25 feet.

At this point in the voyage, the analysis indicates that the vessel is also pitching, but riding out the weather well.

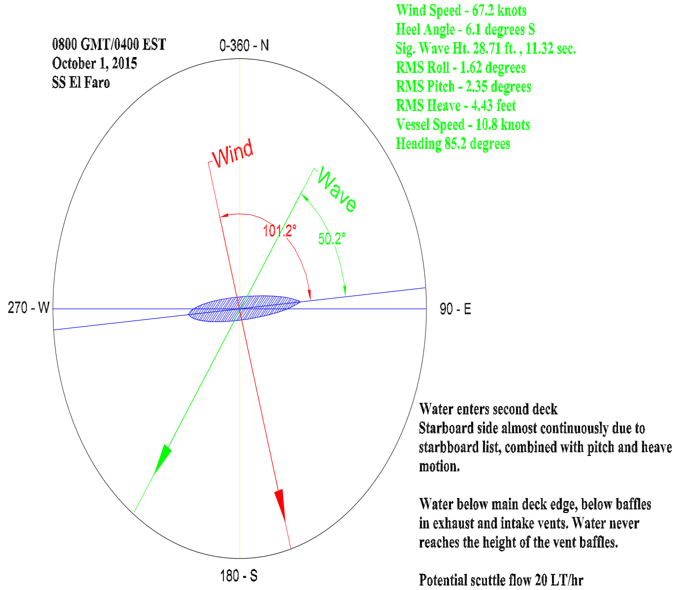
Sea spray and water would likely continue entering the second deck from the stern quarter and additional water enters the second deck from the starboard side aft of the house as the vessel pitches.

By 0330, it is estimated that approximately 7 long tons of water could have enter through the starboard scuttle acccess to hold three The water would tend to accumulate on the starboard side, as shown.

vi. Condition at 0400 EST - October 1, 2015

I next examined the dynamic motions of the vessel at 0400 EST on October 1, 2015. The predicted wind speed has increased to 67.2 knots with a relative direction closer to the beam, yielding a wind heel angle of 6.1 degrees. The significant wave height increased to 28.71 feet.The result of the calculations performed using MAXSURF, for 0400 EST, are shown below. The prediction of the vessel's roll, pitch and heave are displayed on the direction charts Figure 8-6. Roll and pitch have increased slightly, and heave has decreased.

Water continues to enter the second deck aft as the vessel pitches, almost every pitch, on the starboard side. Water entering the second deck aft flows forward and aft as the ship pitches. Water in the area of the starboard scuttle would enter directly into the three hold, if the scuttle were open. Potential rate of water flow into three hold is 20 long tons/hour.



0800 GMT/0400 EST
October 1, 2015
SS El Faro

Wind Speed - 67.2 knots
Heel Angle - 6.1 degrees S
Sig. Wave Ht. 28.71 ft., 11.32 sec.
RMS Roll - 1.62 degrees
RMS Pitch - 2.35 degrees
RMS Heave - 4.43 feet
Vessel Speed - 10.8 knots
Heading 85.2 degrees

Water enters second deck Starboard side almost continuously due to starboard list, combined with pitch and heave motion.

Water below main deck edge, below baffles in exhaust and intake vents. Water never reaches the height of the vent baffles.

Potential scuttle flow 20 LT/hr

Figure 8-6

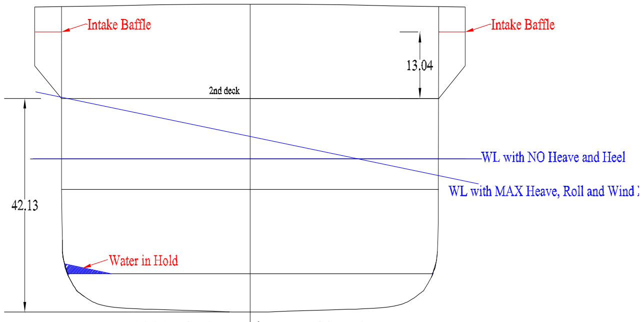
These findings are consistent with the VDR transcript. At 0346-0347, when the Second Mate turns over the watch to the Chief Mate, she indicates in those conversations that the vessel is pitching badly. The pitch estimated by MAXSURF increased from 1.84 degrees at 0300 to 2.53 degrees. Similarly, the Chief Mate observes that the vessel is heeling to starboard at 0348, and the Captain states at 0412 that "the only way to do a counter on this [heel] is to fill the port side ramp tank up." According wind heel calculations, from 0330 to 0400 the predicted heel increased from 1.7 degrees to 6.1 degrees.

From VDR
"2nd Mate 0347 – Pitching"
"Chief Mate 0348 heeling badly assumed from wind"

Additional results of the motion study, including the wind heel angle at 0400 EST, are shown below.

The analysis indicates the vessel is heeling due to wind, and water accumulating on the starboard side ofthe hold; the vessel is also rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three. The mean heave,roll angle, heel angle due to wind, and the effects of water in the three hold are shown below. Vessel pitch is not depicted. With a pitch angle of 2.35 degrees, the draft aft would increase by 14.4 feet.

1 October 2015 - 0400 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 2.35 degrees trim would increase by 14.4 feet.

At this point in the voyage, the ship is predicted to be pitching and heeling to starboard at a mean heel angle of 6.1 degrees due to wind heel plus 0.25 degrees from water in hold.

Water enters the second deck from the starboard side continuously as the vessel heels over, rolls, pitches, and heaves.

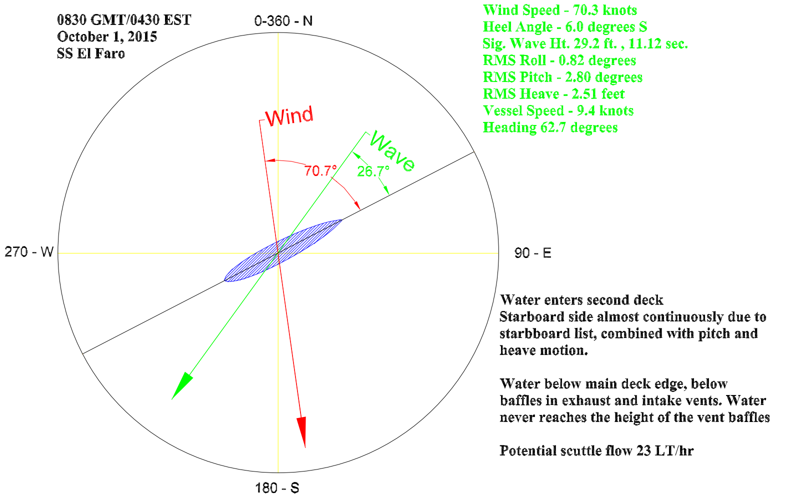
By 0400, it is estimated that approximately 15 long tons of water could have entered into hold three through the starboard scuttle access..

vii. Condition at 0430 EST - October 1, 2015

I next examined the dynamic motions of the vessel at 0430 EST on October 1, 2015. The predicted wind speed has increased to 70.3 knots with a relative direction closer to the beam, yielding a wind heel angle of 6.0 degrees. The significant wave height increased to 29.2 feet.

The result of the calculationsperformed using MAXSURF, for 0430 EST, are shown below. The prediction of the vessels roll, pitch and heave are displayed on the direction charts. Roll has decreased, pitch increased, and heave has decreased.

Water continues to enter the second deck aft, on the starboard side, each time the vessel pitches. Water entering the second deck aft flows forward and aft as the ship pitches. Water at the starboard scuttle into three hold allowing water to enter 3 hold. Potential rate of water flow into 3 hold is 23 LT/hour.



Wind Speed - 70.3 knots
Heel Angle - 6.0 degrees S
Sig. Wave Ht. 29.2 ft. , 11.12 sec.
RMS Roll - 0.82 degrees
RMS Pitch - 2.80 degrees
RMS Heave - 2.51 feet
Vessel Speed - 9.4 knots
Heading 62.7 degrees

Water enters second deck Starboard side almost continuously due to starbboard list, combined with pitch and heave motion.

Water below main deck edge, below baffles in exhaust and intake vents. Water never reaches the height of the vent baffles

Potential scuttle flow 23 LT/hr

Figure 8-7

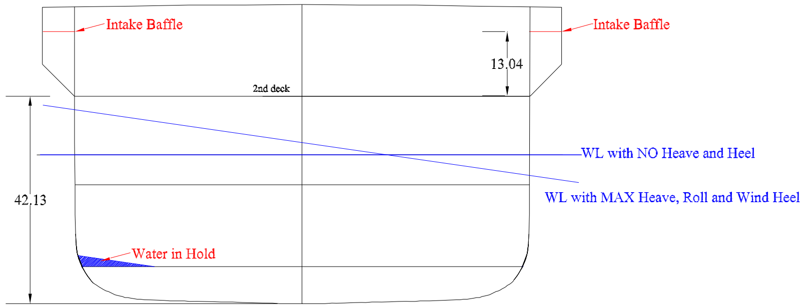
VDR note transcript:
“Capt. 0428 pounding now”

Calculated show pitch is 2.8 degrees bow out of water very few pitches.

Additional results of the motion study, including the wind heel angle at 0430 EST, are shown below.

The analysis indicates the vessel is heeling due to wind and water accumulating on the starboard side of the three hold; the vessel is also rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three. The mean heave, roll angle, heel angle due to wind heel, and the effects of water in hold three are shown below. Vessel pitch is not depicted. With a pitch angle of 2.8 degrees, the draft aft would increase by 17.1 feet.

1 October 2015 - 0430 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 2.8 degrees trim would increase by 17.1 feet.

At this point in the voyage the ship is predicted to be pitching and heeling to starboard with a mean heel angle of about 6.65 degrees.

Water continues to enter the second deck from the starboard side continuously as the vessel heels over rolls pitches and heaves.

By 0430, it is estimated that approximately 35 long tons of water could have entered hold three through the starboard scuttle access if it was open. Adding about 0.65 degrees of list.

The bilge alarm in hold 3 does not go off at this time. With water pocketing in the hold on the starboard side, water is does not lift the float long enough for the bilge alarm to ring. The float is above the tank top.[19]

viii. Condition at 0500 EST - October 1, 2015

I next examined the dynamic motions of the vessel at 0500 EST on October 1, 2015. The predicted wind speed has increased to 73.4 knots with a relative direction closer to the beam, yielding a wind heel angle of 4.4 degrees. The significant wave height increased to 29.53 feet.

The result of the calculations performed using MAXSURF, for 0500 EST, are shown below. the prediction of the vessels roll, pitch and heave are displayed on the direction charts. Roll has decreased and pitch and heave have increased.

Water continues to enter the second deck aft, on the starboard side, each time thethe vessel pitches. Water entering the second deck aft flows forward and aft as the ship pitches. Water accumulating in the area of the starboard scuttle into three hold would continue to enter three hold. Potential rate of water flow into 3 hold is 23 LT/hour.

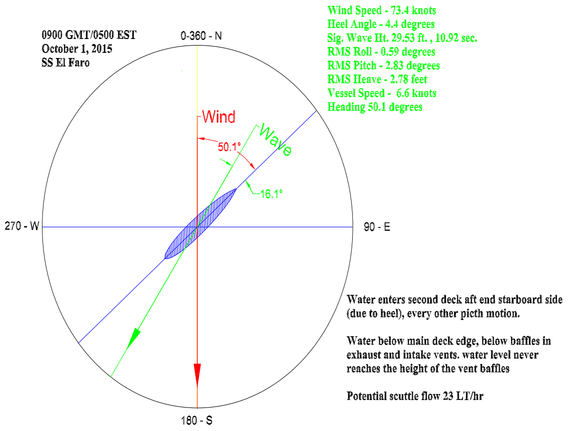


Figure 8-8

Additional results of the motion study, including wind heel angle at 0500 EST are shown below.

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[19] Bilge alarm does not actuate immediately there is a delay built into the alarm. Float is assumed about 6 inches above the tank top. SOLAS convention does not require a bilge alarm for this vessel. Tote installed the alarm and it was tested weekly.

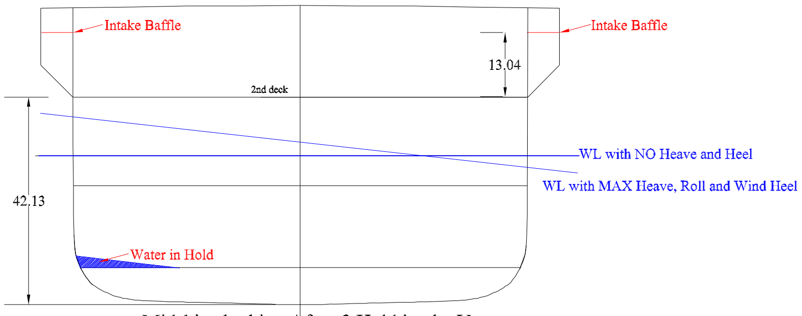
The analysis indicates the vessel is heeling due to windand water accumulating on the starboard side of hold three; the vessel is also rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three. The mean heave,roll angle, heel angle due to wind, and the effects of water inin hold three are shown below.d. Vessel pitch is not depicted. With a pitch angle of 2.83 degrees, the draft aft would increase by 17.3 feet.

At this point in the voyage, the the ship is also pitching and heeling to starboard and a mean value of about 5.2 degrees.

Water enters the second deck from the starboard side continuously as the vessel heels over rolls pitches and heaves.

By 0500, it is estimated that 46 long tons of water could have entered hold three through the starboard scuttle access if open adding 0.75 degrees to vessels list.

1 October 2015 - 0500 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 2.83 degrees trim would increase by 17.3 feet.

At this point in the voyage the ship is predicted to be pitching and heeling to starboard with a mean heel angle of about 6.33 degrees.

ix. Condition at 0530 EST - October 1, 2015

I next examined the dynamic motions of the vessel at 0530 EST on October 1, 2015. The predicted wind speed has decreased to 66.7 knots with a relative direction close to the bow, yielding a wind heel angle of 1.1 degrees. The heel angle has decreased, primarily due to a change in wind profile, as the vessel heads more directly into the wind. The significant wave height decreased to 29.20 feet.

The result of the calculations performed using MAXSURF, for 0530 EST, are shown below. The prediction of the vessels roll, pitch and heave are displayed on the direction charts. Roll has decreased and pitch decreasd slightly and heave has decreased.

Water continues to enter the second deck aft, on the starboard side, each time the vessel pitches. Water entering the second deck aft flows forward and aft as the ship pitches. Water accumulating in the area of the starboard scuttle would continue to enter the three hold. Potential rate of water flow into three hold is 22 LT/hour.

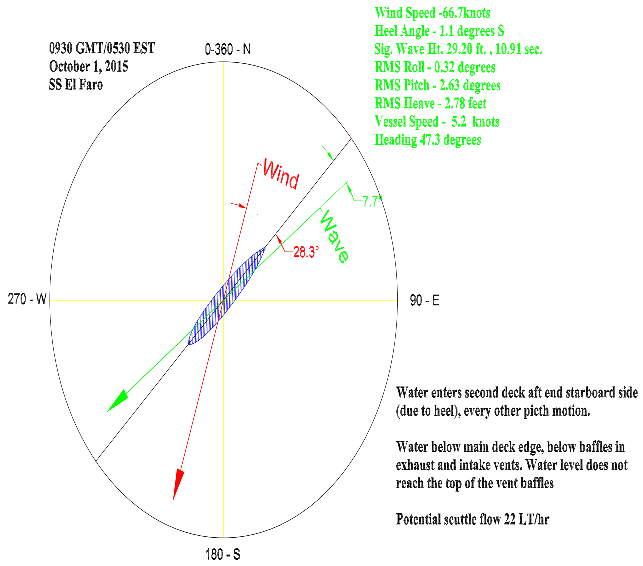


Figure 8-9

Quotes from VDR;

5:43	CAPT-ET	WATER IN 3 HOLD START PUMPING NOW
5:44	CM	FIRST MENTION OF THE SCUTTLE
		GOING TO TRUN THE SHIPGET WIND ON NORTH SIDE
5:52	CAPT-ET	GO FROM S TO P LIST - WATER SOURCE THE SCUTTLE
5:55	CM-UHF	WATER KNEE DEEP AT SCUTTLE POURING INTO HOLD

Additional results of the motion study, including wind heel angle at 0530 EST are shown below.

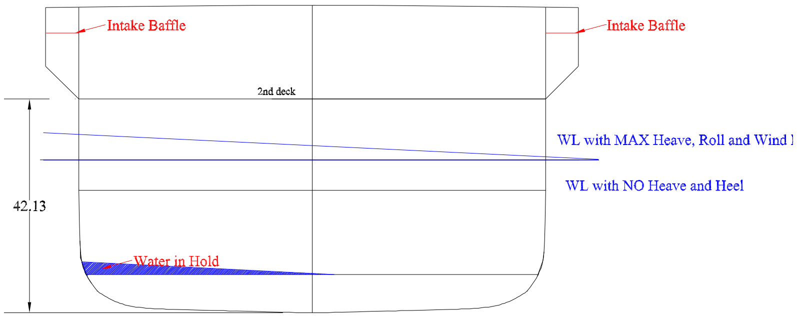
The analysis indicates the vessel is heeling due to wind and water accumulating on the starboard side of hold three; the vessel is also rolling and heaving due to wave action. Shown below is the vessel midships section in way of hold number three. The mean heave, roll angle, heel angle due to wind and the effects of water in hold three are shown. Vessel pitch is not depicted. With a pitch angle of 2.63 degrees, the draft aft would increase by 16.1 feet.

At this point in the voyage, the ship is also pitching and heeling to starboard and a mean value of about 2.1 degrees. The vessel is now heading almost directly into the wind and waves, which minimizes the ships rolling and wind heeling.

Water in hold is at or close to triggering the bilge alarm.Heel angle relatively small so at this time water can go under the bilge alarm float.

By 0530, it is estimated that approximately 59 tons of water could have entered the three hold through the starboard scuttle. This adds about 0.97 degrees to the ships list.

1 October 2015 - 0530 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 2.63 degrees trim would increase by 16.1 feet.

The bilge alarm float above the bilge well in 3 hold is 26 feet off the centerline and above the bilgewell with a requierment of 6 seconds of float time to activate. At this hour and with the amount of water in 3 hold the alarm will activate.

x. Condition at 0600 EST - October 1, 2015

The result of the calculations performed using MAXSURF, for 0600 EST, are shown below. the prediction of the vessels roll, pitch and heave are displayed on the direction charts. Roll has increased and pitch decreasd slightly and heave has increased dramatically.

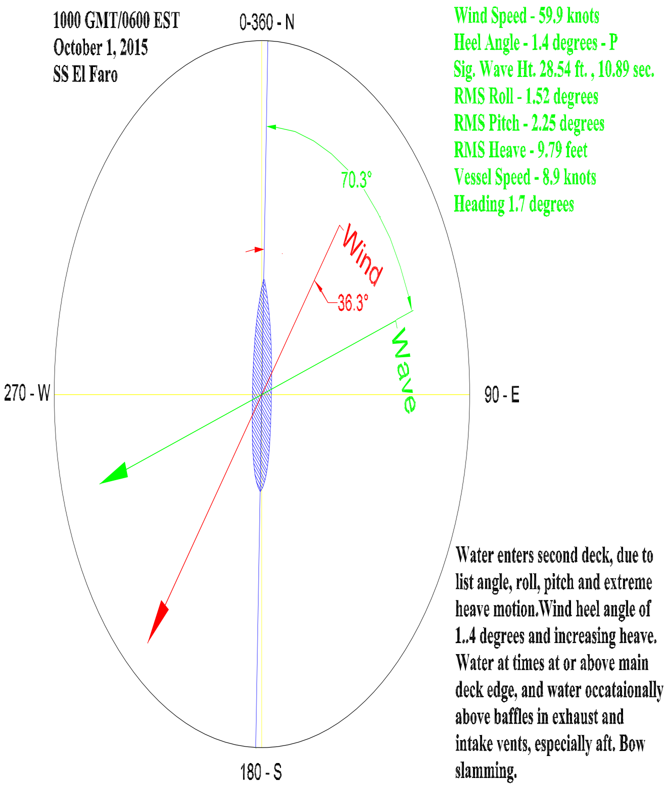
Wind and wave direction are such that the vessel now is heeling to port as opposed to starboard. The change in course was ordered in order to reverse the vessel's list so that the open scuttle could be closed as per VDR transcript.

Water enters the second deck aft as the vessel pitches, every pitch, on port side. Water entering the second deck aft flows forward and aft as the ship pitches. No additional water enters through the scuttle as it has now been closed. An estimated total of 65 LT has entered the 3 hold through the scuttle.

Due to pitch and extreme heave water enters the Engine Room Vents as as reported at 6:00 with a conversation between thw Captain and the Chief Engineer.

The wind speed has decreased to 59.9 knots with a relative direction on the bow quarter, yielding a wind heel angle of 1.4 degrees. Water in the cargo hold causes an additional heel angle of 1.1 degrees

The significant wave height decreased to 28.54 feet.



Water enters second deck, due to list angle, roll, pitch and extreme heave motion.Wind heel angle of 1..4 degrees and increasing heave. Water at times at or above main deck edge, and water occataionally above baffles in exhaust and intake vents, especially aft. Bow slamming.

5:59	CAPT	SCUTTLE POPPED OPEN AND A LITTLE BIT OF WATER IN 3 HOLD-PUMPING IT OUT CM AND SUP-1 AND CLOSING THE SCUTTLE
6:00	CAPT-ET	(ALL THROUGH) the ventilation on phone with chief
6:01	cm-uhf	SCUTTLE CLOSED

Figure 8-10

The results of the motion study, wind heel angle at 0600 EST are shown below.

The vessel is heeling due to wind, rolling, water in hold and heaving due to wave action. The turning of the vessel causes cargo in lower 3 hold to break loose as stated in the VDR transcript that “there were cars floating in the hold.” Shown below is the vessel midships section in way of hold number three. The max heave is shown as well as roll angle, wind heel angle and angle due to water in hold. Vessel pitch is not depicted. With a pitch angle of 2.25 degrees, the draft aft would increase by 13.75 feet.

At this time this ship is also pitching and heeling to port and a mean value of about 2.5 degrees. The vessel has wind and waves on the port side.

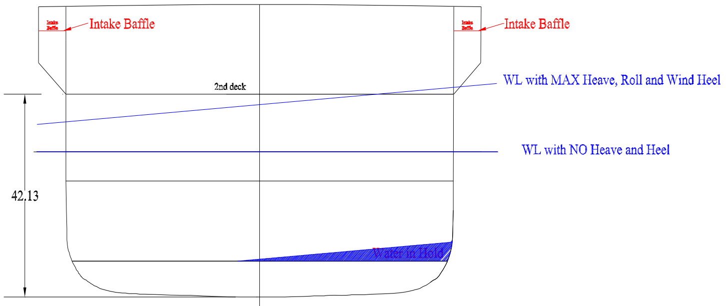
Water enters the second deck from the port side continuously as the vessel pitches, heaves and rolls.

Water in hold has triggered the bilge alarm and bilges are being pumped.

The change in course has resulted in a shift of cargo causing the hold exhaust and intake baffles to briefely be submerged causing water to enter three hold through the vents. Flow rate through the exhaust and intake vents is more than 10 times the flow through the open scuttle. Effect of the water entering the hold through the vents is not shown at this time as the turn has just been made and several roll cycles would be required for the cargo to break loose.

A water starts to enter Hold 3 through the port side vents at a potential flow rate of 240 LT pre hour. An estimated 65 tons of water is in three hold, all from the scuttle.Water entering the holds from the vent has started at this hour very little water from the vents is in the holds, flow is not constant.

1 October 2015 - 0600 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 2.63 degrees trim would increase by 16.1 feet.

xi. Condition at 0630 EST - October 1, 2015

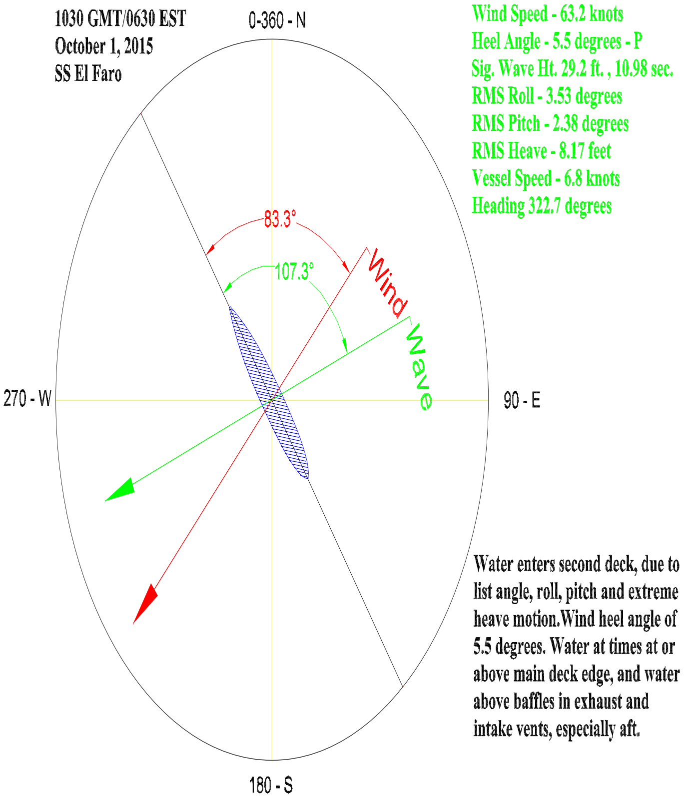
The result of the calculations performed using MAXSURF, for 0630 EST, are shown below. The prediction of the vessel's roll, pitch and heave are displayed on the direction charts. Roll has increased and pitch decreasd slightly and heave has slightly decreased.

Wind and wave direction are such that the vessel now is heeling to port as opposed to starboard. The change in course was ordered in order to reverse the vessel's list so that the open scuttle could be closed as per VDR transcript. The vessel at this point has lost propulsion power, and the vessel goes beam to the wind and waves.

Water enters the second deck aft as the vessel pitches, every pitch, on port side. Water entering the second deck aft flows forward and aft as the ship pitches. No water through the scuttle as it has now been closed. Water reported in 2 hold.

The wind speed has increased to 63.3 knots with a relative direction close to the beam, yielding a wind hell angle of 5.4 degrees.

The significant wave height increaed to 29.2 feet.



1030 GMT/0630 EST
October 1, 2015
SS El Faro

Wind Speed - 63.2 knots
Heel Angle - 5.5 degrees - P
Sig. Wave Ht. 29.2 ft., 10.98 sec.
RMS Roll - 3.53 degrees
RMS Pitch - 2.38 degrees
RMS Heave - 8.17 feet
Vessel Speed - 6.8 knots
Heading 322.7 degrees

Water enters second deck, due to list angle, roll, pitch and extreme heave motion.Wind heel angle of 5.5 degrees. Water at times at or above main deck edge, and water above baffles in exhaust and intake vents, especially aft.

Figure 8-11

6:13	CAPT	I THINK WE JUST LOST THE PLANT
6:18	CAPT	WATER COMING IN THROUGH TH VENTILATION IN ER
6:20	CAPT-ET	PUMP PORT TO STARBOARD RAMPTANKS
6:25	CAPT-ET	PUMPING HOLD 2

The results of the motion study, wind heel angle at 0630 EST are shown below.

The vessel is heeling due to wind, rolling, water in hold and heaving due to wave action. The turning of the vessel causes cargo in lower 3 hold to break loose as stated in the VDR transcript that “there were cars floating in the hold.” Diagram shown is the vessel midships section in way of hold number three. The mean heave is shown as well as roll angle ,wind heel angle and angle due to water in hold and cargo shifted in the hold. Vessel pitch is not depicted

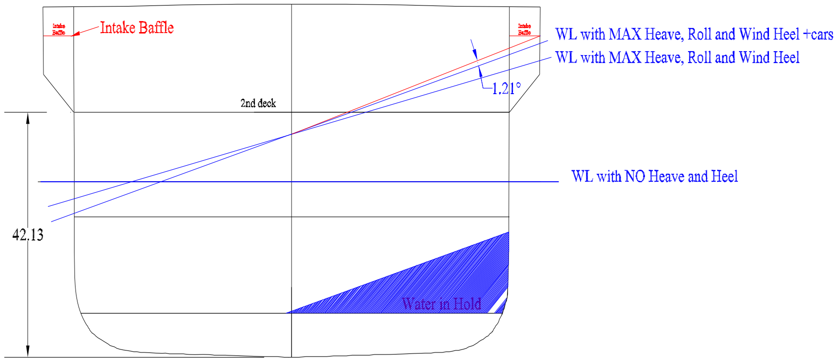
It this hour this ship is also pitching and heeling to port and a mean value of about 6.8 degrees. The vessel has wind and waves on the port side.

Water enters the second deck from the port side continuously as the vessel pitches, heaves and rolls. The water on the second deck raises the vessels KG and lowers the vessels GM.

Water in hold has triggered the bilge alarm and bilges are being pumped. Baffles are submerged causing water to enter three hold through the vents. Flow rate through the exhaust and intake vents is more than 10 times the flow through the open scuttle.

A water enters Hold 3 through the port side vents at a potential flow rate of 240 LT pre hour. An estimated 185 tons of water is in three hold. At extreme roll water is above the third deck in three hold. Only 1.21 additional degrees of list are required to submerge the intake vent baffles. Water from waves passing the vents are of sufficient height to allof water to enter the hold through the vents.

1 October 2015 - 0630 EST



Midships looking Aft at 3 Hold intake Vent
The draft aft including 2.63 degrees trim would increase by 16.1 feet.

At about 0613 on the VDR, the captain states I think we lost the plant. With a loss of propulsion, the vessel is transitioning to a condition with no propulsion forces and is being moved by water currents and wind. The 0630 and 0700 condition shows the vessel with almost beam wind and seas. Sometime after 0613, the vessel is at the mercy of the sea and is experiencing the most severe response to the effects of the hurricane.

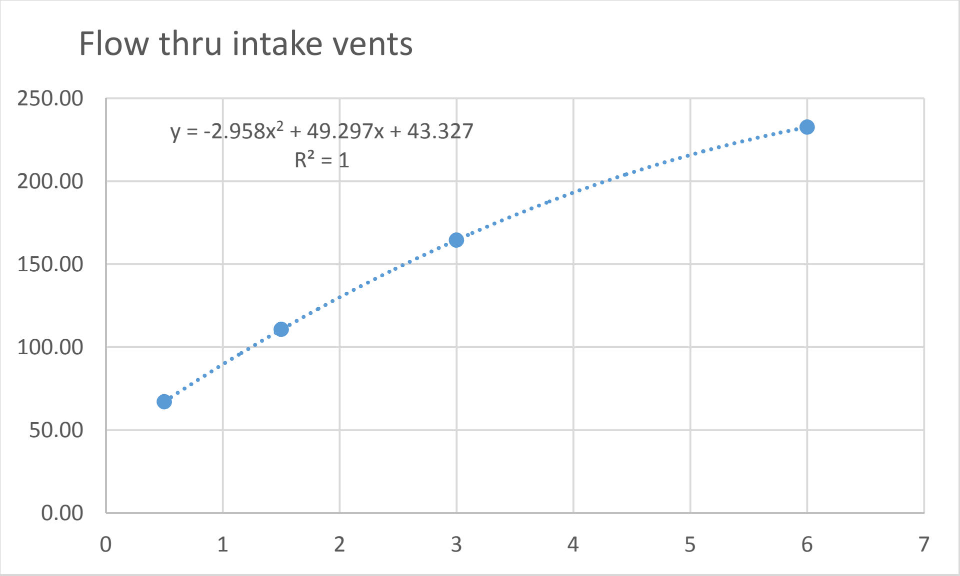


Figure 8-12 Flow through Intake vent, Calculation in Appendix

The additional 120 LT of water through the vents will cause an additional angle of heel of 2 degrees. At this stage, the vents are fully submerged.

xii. Condition at 0700 EST - October 1, 2015

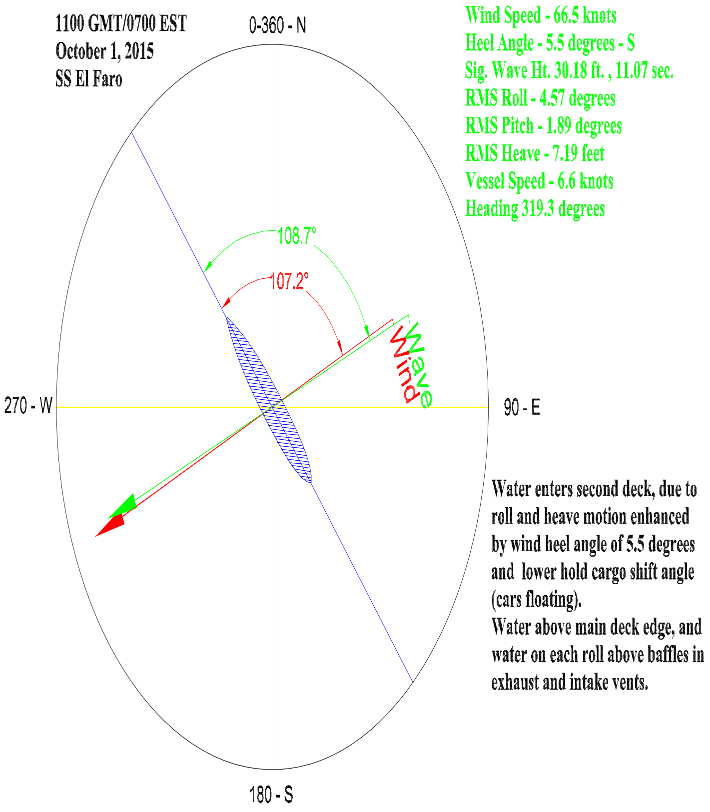
The result of the calculations performed using MAXSURF, for 0700 EST, are shown below. the prediction of the vessels roll, pitch and heave are displayed on the direction charts. Roll has increased and pitch decreasd slightly and heave has slightly decreased.

Wind and wave direction are such that the vessel now is heeling to port as opposed to starboard. The change in course was ordered inorder to reverse the vessels list so that the open scuttle could be closed as per VDR transcript. The vessel at this point has lost propulsion power, and the vessel goes beam to the wind and waves.

Water enters the second deck aft as the vessel pitches, every pitch, on port side. Water entering the second deck aft flows forward and aft as the ship pitches. No water through the scuttle as it has now been closed. Water on 2nd deck raises KG and lowers vessel GM.

The wind speed has increased to 66.5 knots with a relative direction close to the beam, yielding a wind hell angle of 5.5 degrees. Between 0630 and 0700 at some point the vessel is subject to a beam wind which would increase the wind heel angle.

The significant wave height increaed to 30.18 (peak ht.) feet.



1100 GMT/0700 EST
October 1, 2015
SS El Faro

Wind Speed - 66.5 knots
Heel Angle - 5.5 degrees - S
Sig. Wave Ht. 30.18 ft. , 11.07 sec.
RMS Roll - 4.57 degrees
RMS Pitch - 1.89 degrees
RMS Heave - 7.19 feet
Vessel Speed - 6.6 knots
Heading 319.3 degrees

Water enters second deck, due to roll and heave motion enhanced by wind heel angle of 5.5 degrees and lower hold cargo shift angle (cars floating).
Water above main deck edge, and water on each roll above baffles in exhaust and intake vents.

Figure 8-13

6:45	CAPT	A LOT OF WATER IN THE CARGO HOLD AREA (2nd deck?)
6:55	CAPT-ET	RECAP OF FLOODING NOT ABANDON SHIP PLANT OFF
7:15	CM	WATER RISING IN HOLD

The results of the motion study, wind heel angle at 0700 EST are shown below. The vessel is heeling due to wind, rolling, water in hold and heaving due to wave action. The turning of the vessel causes cargo in lower 3 hold to break loose as stated in the VDR transcript that “there were cars floating in the hold”. Shown below is the vessel midships section in way of hold number three. The mean heave is shown as well as roll angle ,wind heel angle and angle due to water in hold and cargo shifted in the hold. Vessel pitch is not depicted. The VDR vepotrs a ship speed of 6.6 knots however for MAXSURF analysis purposes from this time foward the input ship speed is 0 knots as all propulsion forces are lost.

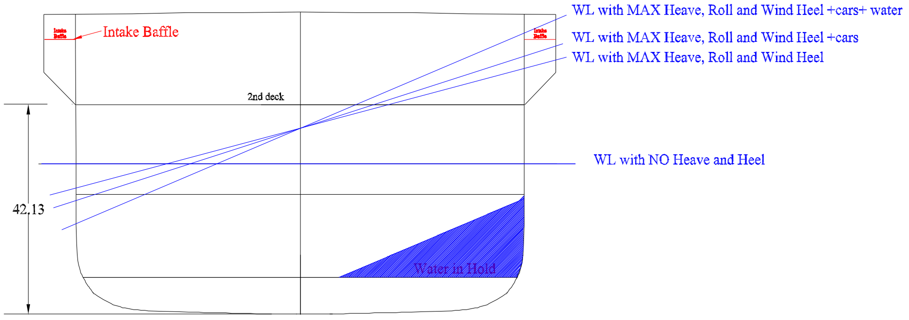
It this hour this ship is also pitching and heeling to port and a mean value of about 6.9 degrees. The vessel has wind and waves on the port side. Additional heel of 3 degrees is caused by shifted cars on the tank top and additional heel from water in hold, now 305 long tonsof water is in three holdan additional 4.98 degrees.

Water enters the second deck from the port side continuously as the vessel pitches, heaves, and rolls, water held on second deck due to large list. The water on the second deck raises the vessels KG and lowers the vessels GM.

Water in hold has triggered the bilge alarm and bilges are being pumped. Baffles are submerged causing water to enter three hold through the vents both intake and exhaust .

A water enters Hold 3 through the port side intake vents at a potential flow rate of 240 LT per hour. An estimated 305 tons of water is in three hold.

1 October 2015 - 0700 EST



Midships looking Aft at 3 Hold intake Vent

xiii. Condition at 0730 EST - October 1, 2015

The result of the calculations performed using MAXSURF, for 0730 EST, are shown below. the prediction of the vessels roll, pitch and heave are displayed on the direction charts. Roll has decreased and pitch decreasd slightly and heave has slightly decreased.

Water is now intering the hold thruogh the intake and exhaust vents as bothe baffeleing arrangements are under water, for an additional 240 tons of water. Cars moving in the hold cause an additional 3.5 dergrees of heel. A total of 545 long tons of water in now esirmated to be in hold 3 with and undetermined amount of water in hold 2.

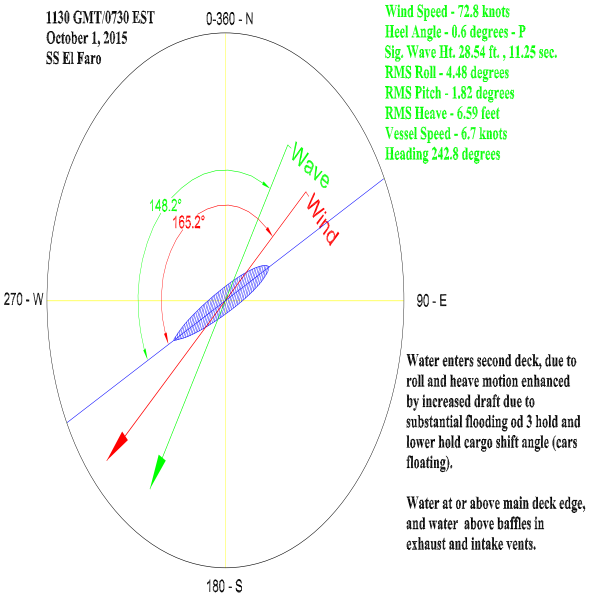
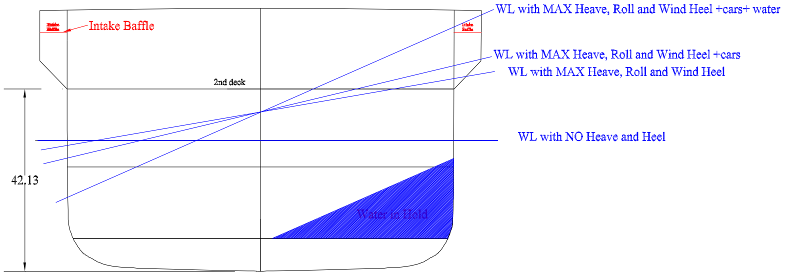


Figure 8-14

At extreme angle of heel, the water in the hold is above the third deck. Water is pouring into holds 3 and possibly 2 at this hour approximately 9 minutes later the El Faro is lost

1 October 2015 - 0730 EST



Midships looking Aft at 3 Hold intake Vent

Summary of ship condition at all times in the MAXSURF Motions analysis is given below;

Time	winds (knots)	waves height feet	heel (due to wind) degrees	heel (water) degrees **	heel (cars) degrees	MAX heel total (degrees) NO roll		Roll RMS (Mean)	Roll Extreme	Extreme Roll (wind+water+cars)	RMS heave feet*	Distance from water to baffle RMS	Distance from water to baffle EXTREME	Pitch RMS (mean)/ Extreme	Vessel Speed	Water In Hold (LT)
0200	41.3	16.37 ft	1.1	0	0	1.10	S	1.72	3.44	4.54	4.47	16.36	11.89	0.75/1.5		
0300	51.6	23.29	1.6	0	0.00	1.60	S	1.91	3.82	5.42	4.68	15.34	10.66	1.91/3.84		
0330	59.4	25.92	1.7	.11	0.00	1.81	S	1.6	3.2	5.01	5.43	14.97	9.54	1.84/3.68	17.2	7.5
0400	67.2	28.71	6.1	0.25	0.00	6.35	S	1.62	3.24	9.59	4.43	11.70	7.27	2.35/4.70	10.8	15
0430	70.3	29.2	6.0	0.65	0.00	6.65	S	0.82	1.64	8.29	2.53	14.82	12.29	2.8/5.6	9.4	35
0500	73.4	29.53	4.4	.75	0.00	5.15	S	0.59	1.58	6.73	2.78	16.03	13.25	2.83/5.66	6.6	46
0530	66.7	29.2	1.1	0.97	0.00	2.07	S	0.32	0.68	2.75	2.78	19.70	16.92	2.63/5.26	5.2	59
0600	59.9	28.54	1.4	1.01	0.00	2.41	P	1.52	3.54	5.95	9.79	9.74	0.05	2.25/4.5	8.9	65
0630	63.3	29.2	5.5	1.1	2.5	9.10	P	3.53	7.06	16.16	8.17	1.62	6.55	2.38/4.76		185
0700	66.5	30.18	5.5	4.98	3.20	13.68	P	4.47	8.94	22.62	7.19	4.06	11.25	1.89/3.78		305
0730	72.8	28.54	.6	8.35	3.5	12.45	P	4.48	8.96	21.41	6.59	2.17	8.76	1.82/3.64		545
												red above baffle				
		*	Heave at mean value extreme is higher													
		**	does not include water in ER or 2 hold													

1

9. Conclusions

- In my opinion, at the time of departure, the SS El Faro was in compliance with all applicable statutory rules, regulations and guidelines, with respect to stability, load line, and cargo securing requirements, and she was operated within these requirements during Voyage 185S.
- At the time of the El Faro's departure, the vessel had a GM_t 0.64 feet more than required by the applicable regulations.
- The stability of the vessel was calculated using the CARGOMAX software provided by Herbert Engineering Corporation and approved by the American Bureau of Shipping, on behalf of the United States Coast Guard.
- The results of the CARGOMAX calculation of ship stability and the results following the Trim and Stability Book calculation method were found to give the same results.
- The company guidelines of having an excess 0.5 feet of GM_t (i.e. GM margin) on departure ensured that GM_t requirements would be met throughout the voyage and at arrival in San Juan PR. Probabilistic damage stability required GM_t curve was not incorporated into the required GM curve found in the Trim and Stability book. This required GM_t was less restrictive than the USCG Weather Criteria that was in the trim and stability book in the overwhelming majority of operating conditions. The probabilistic damaged stability calculation and GM requirements would only affect the SS EL Faro if there were less than two tiers of containers on deck, which was not the case on this voyage.
- The vessel was reported to be taking on water through an open scuttle on the 2nd deck (also known as the bulkhead deck). This is the deck below the main deck. The flooding water was reported to be under control by phone message/conversation. The flooding water reported in Cargo Hold #3 would not alone, cause the loss of the SS El Faro.
- The vessel was built in 1975 and lengthened in 1993 by 90'-9" and remained a Ro-Ro vessel after this lengthening. This conversion was considered a major conversion, as provided for under U.S. law, thereby subjecting the vessel to the vessel rules and regulations that were in effect at the time of conversion (1992).
- In 2006, the vessel was converted to carry containers on deck and Ro-Ro below deck. The Coast Guard, so rules and regulations from 1992 continued to apply to the vessel did not consider this. The vessel's cargo was stowed and secured with proper securing arrangements in accordance with its approved CSM and applicable international cargo securing guidelines.
- The cargo hold ventilation system exhaust and intake were in accordance with load line regulations. The ventilation system on the SS El Faro, if installed on a new ship, would be approved today, according to the ABS; I agree.

- The owners of the SS El Faro operated the vessel in accordance with all rules, regulations and guidelines. The SS El Faro was deemed fit for duty and seaworthy by the U.S. Coast Guard and ABS. Based on all the evidence, I agree with this conclusion.
- The ship motion study shows that the start of the loss of the SS EL Faro began with water entering 3 hold through to open scuttle. Through the night water in the hold pocketed on the starboard side of the ship causing additional through the scuttle. The bilge alarm in 3 hold sounded alerting the crew to water in 3 hold. The vessel was turned to get the wind on the starboard side allowing the crew to close the open scuttle. Severe pitching motion allowed water to enter the ship and place water on the second deck, which went through the scuttle to the hold below. At the time of the scuttle was closed, it is estimated that 65 long tons of water had entered 3 hold. The changing of the list from starboard to port shifted the water in the hold from starboard to port causing cars in the lower hold to break loose, which in turn caused all the cars in 3 hold to become loose. The loose floating cars in 3 hold caused an additional angle of list of 3 degrees. At this time, the ship lost propulsion and experienced beam winds and the highest wind velocity and most extreme sea conditions. The combination of large wind heel ship rolling due to waves, additional heel due to cars shifting and water in the hold, caused the intake vents and the exhaust vents to go below the water allowing a total of over 600 tons of water to enter 3 hold and probably some water in 2 hold. The bilge alarm sounded in 2 hold, in my opinion due to water entering through the 2 hold vents, sometime in the 0630 to 0739 time period.
- A significant contributing cause in the chain of events of this loss is the unsecured scuttle; in my opinion, if the scuttle was secured, it is likely the SS El Faro would have survived this storm.

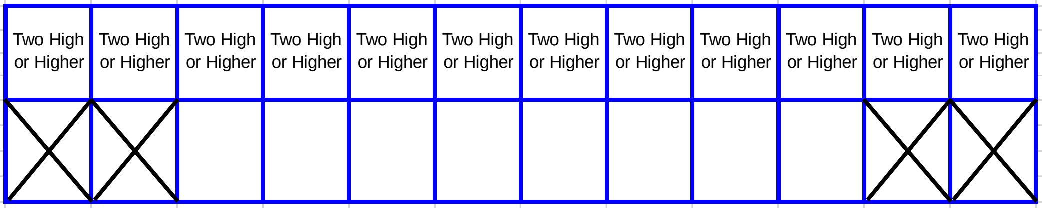
/s/ Prof. Charles J. Munsch

APPENDIX 1 EL Class Minimum Lashing Guide

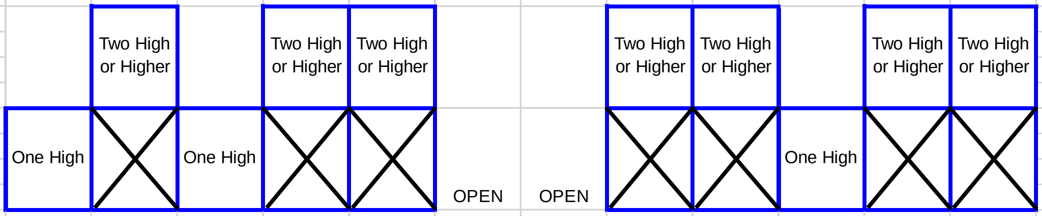
SSL EL Class Minimum Lashing Requirements - LoLo

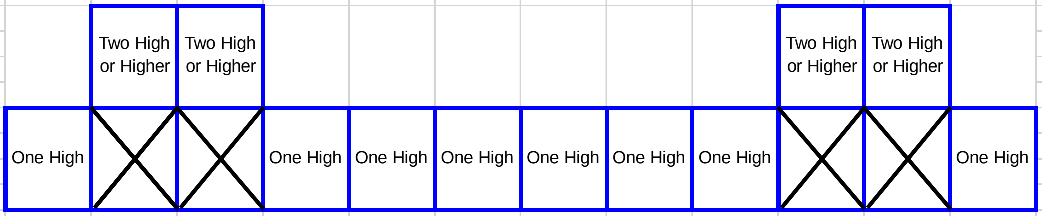
Additional lashing may be required for individual stacks as determined by Marine Operations.

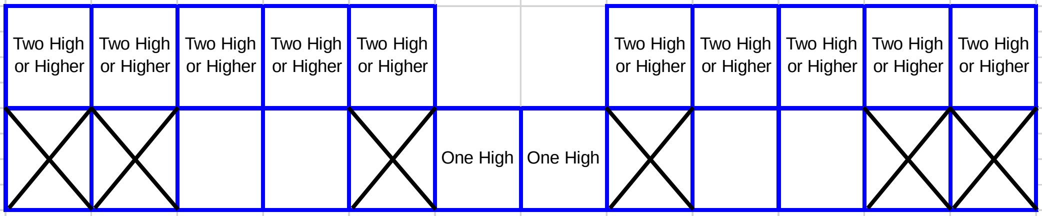
All bays will have the outer two high container stacks lashed regardless of where the outside box is located.



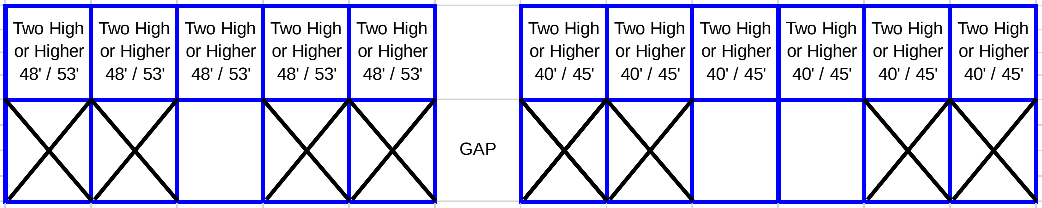
If there are two high containers next to an open cell located in the interior of the bay they will be treated as outer stacks.

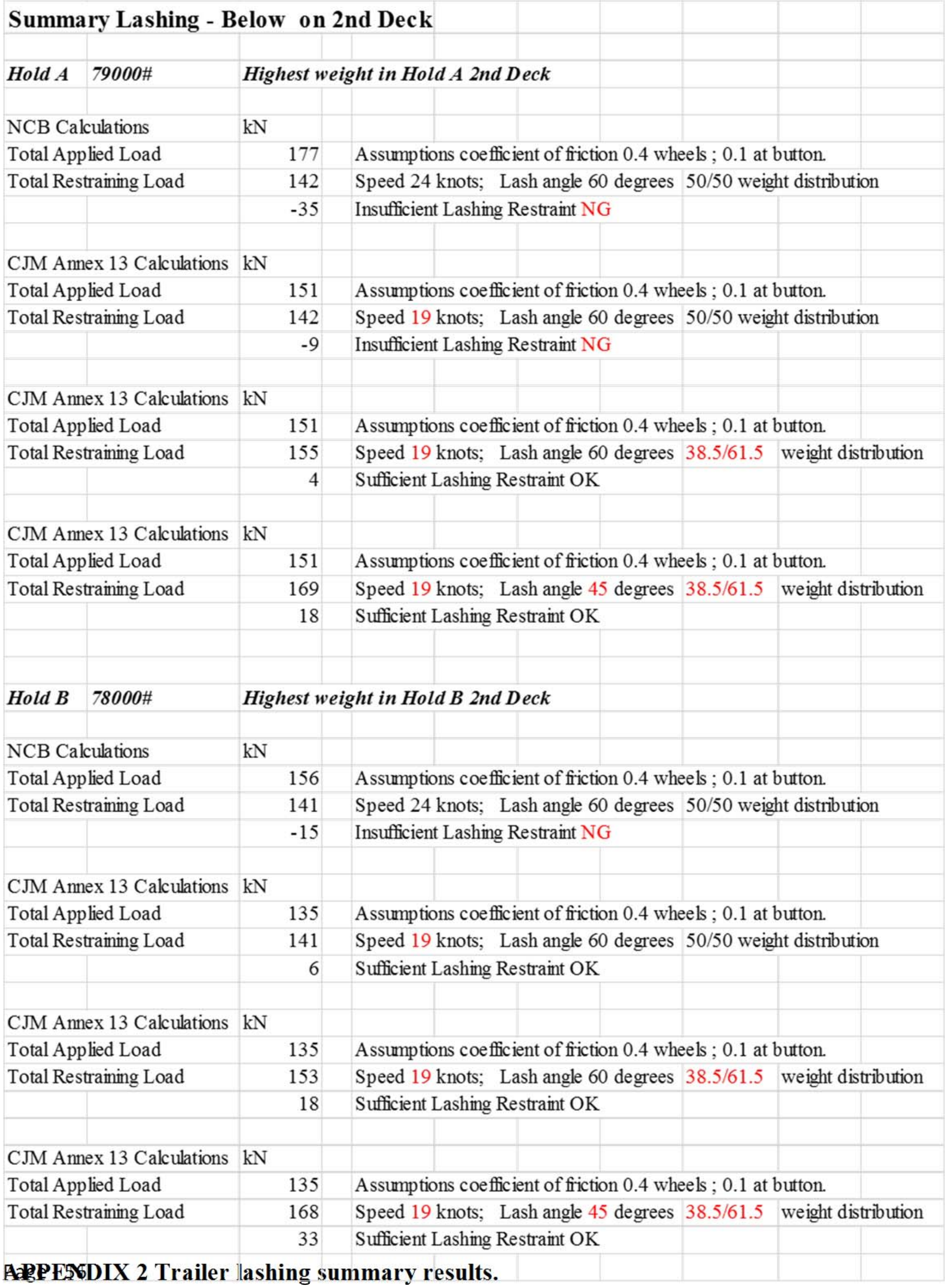






If there are two high 48' / 53' containers next to a stack of 40' / 45' containers in the interior of a bay - a gap is created. Both the 2 high 48' / 53' stacks and 40' / 45' stacks of the bay they will be treated as outer stacks and lashed.





Summary Lashing - Below on 2nd Deck			
Hold A	***79000#***	***Highest weight in Hold A 2nd Deck***	
NCB Calculations		kN	
Total Applied Load		177	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		142	Speed 24 knots; Lash angle 60 degrees 50/50 weight distribution
		-35	Insufficient Lashing Restraint NG
CJM Annex 13 Calculations		kN	
Total Applied Load		151	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		142	Speed 19 knots; Lash angle 60 degrees 50/50 weight distribution
		-9	Insufficient Lashing Restraint NG
CJM Annex 13 Calculations		kN	
Total Applied Load		151	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		155	Speed 19 knots; Lash angle 60 degrees 38.5/61.5 weight distribution
		4	Sufficient Lashing Restraint OK
CJM Annex 13 Calculations		kN	
Total Applied Load		151	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		169	Speed 19 knots; Lash angle 45 degrees 38.5/61.5 weight distribution
		18	Sufficient Lashing Restraint OK
Hold B	***78000#***	***Highest weight in Hold B 2nd Deck***	
NCB Calculations		kN	
Total Applied Load		156	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		141	Speed 24 knots; Lash angle 60 degrees 50/50 weight distribution
		-15	Insufficient Lashing Restraint NG
CJM Annex 13 Calculations		kN	
Total Applied Load		135	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		141	Speed 19 knots; Lash angle 60 degrees 50/50 weight distribution
		6	Sufficient Lashing Restraint OK
CJM Annex 13 Calculations		kN	
Total Applied Load		135	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		153	Speed 19 knots; Lash angle 60 degrees 38.5/61.5 weight distribution
		18	Sufficient Lashing Restraint OK
CJM Annex 13 Calculations		kN	
Total Applied Load		135	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.
Total Restraining Load		168	Speed 19 knots; Lash angle 45 degrees 38.5/61.5 weight distribution
		33	Sufficient Lashing Restraint OK

1 **APPENDIX 2 Trailer lashing summary results.**

Hold C	***76000#***	***Highest weight in Hold C 2nd Deck***			
NCB Calculations		kN			
Total Applied Load		148	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		139	Speed 24 knots; Lash angle 60 degrees	50/50 weight distribution	
		-9	Insufficient Lashing Restraint NG		
CJM Annex 13 Calculations		kN			
Total Applied Load		127	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		139	Speed 19 knots; Lash angle 60 degrees	50/50 weight distribution	
		12	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations		kN			
Total Applied Load		127	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		151	Speed 19 knots; Lash angle 60 degrees	38.5/61.5	weight distribution
		24	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations		kN			
Total Applied Load		127	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		165	Speed 19 knots; Lash angle 45 degrees	38.5/61.5	weight distribution
		38	Sufficient Lashing Restraint OK		
Hold D	***80000#***	***Highest weight in Hold D 2nd Deck***			
NCB Calculations		kN			
Total Applied Load		159	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		144	Speed 24 knots; Lash angle 60 degrees	50/50 weight distribution	
		-15	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations		kN			
Total Applied Load		136	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		144	Speed 19 knots; Lash angle 60 degrees	50/50 weight distribution	
		8	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations		kN			
Total Applied Load		136	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		156	Speed 19 knots; Lash angle 60 degrees	38.5/61.5	weight distribution
		20	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations		kN			
Total Applied Load		136	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load		170	Speed 19 knots; Lash angle 45 degrees	38.5/61.5	weight distribution
		34	Sufficient Lashing Restraint OK		

Hold E & F	***75000#***	***Highest weight in Hold E & F 2nd Deck***		
NCB Calculations	kN			
Total Applied Load	160	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load	138	Speed 24 knots; Lash angle 60 degrees	50/50 weight distribution	
	-22	Insufficient Lashing Restraint NG		
CJM Annex 13 Calculations	kN			
Total Applied Load	137	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load	138	Speed 19 knots; Lash angle 60 degrees	50/50 weight distribution	
	1	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations	kN			
Total Applied Load	137	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load	150	Speed 19 knots; Lash angle 60 degrees	38.5/61.5	weight distribution
	13	Sufficient Lashing Restraint OK		
CJM Annex 13 Calculations	kN			
Total Applied Load	137	Assumptions coefficient of friction 0.4 wheels ; 0.1 at button.		
Total Restraining Load	164	Speed 19 knots; Lash angle 45 degrees	38.5/61.5	weight distribution
	27	Sufficient Lashing Restraint OK		

Appendix 3 Flow Calculations

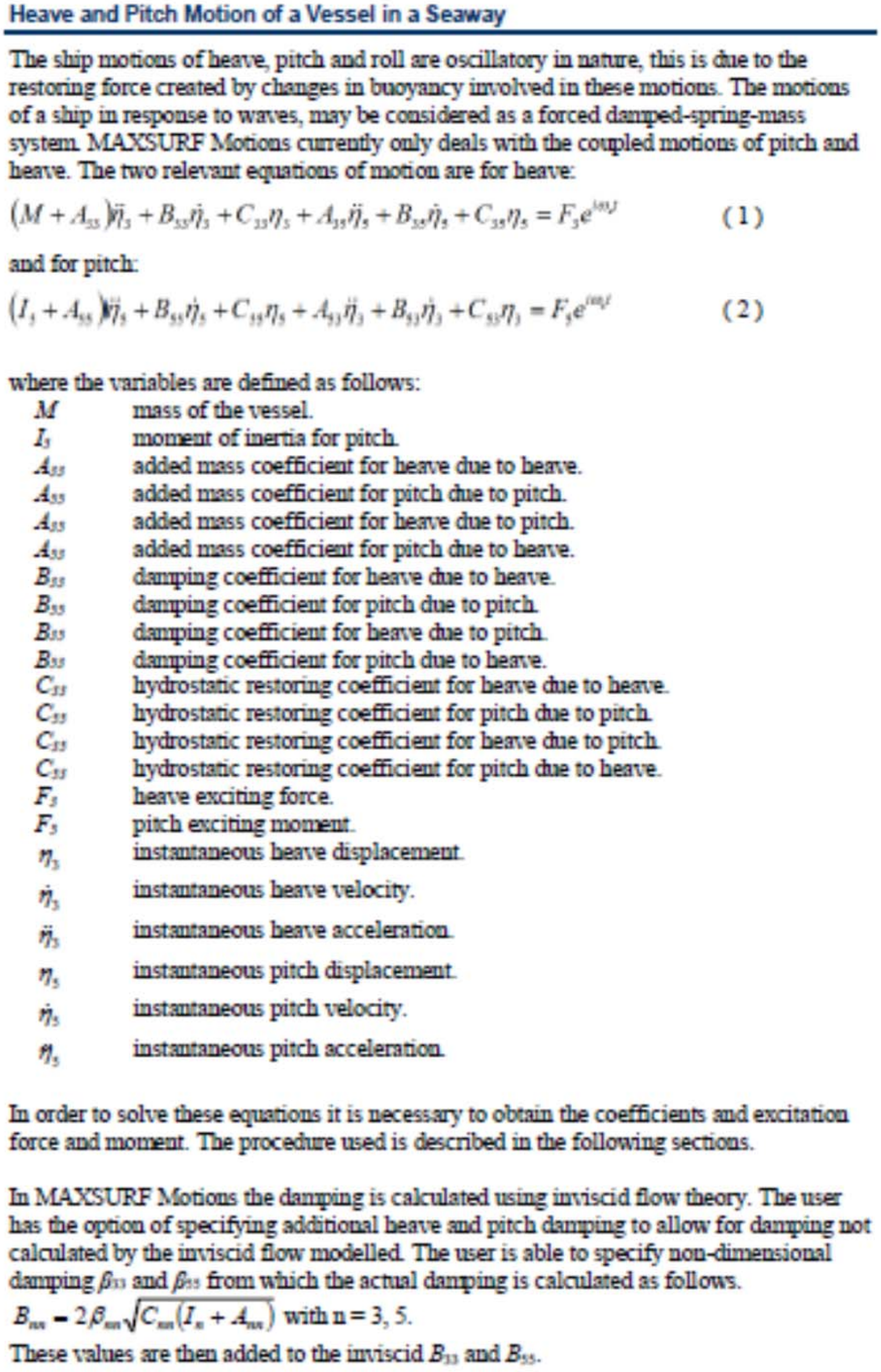
Sample EXCEL SS water flow calculations (Marks Engineering Handbook 11th edition p6-30) for scuttle.

ideal	Vi=(2*ρ*g)^.5				h=	0.5	g=	32.17	ρ=	1.988
	Vi=		5.6548							
actual	V=	Cv*Vi			Cv=	0.98				
	V=		5.5417				r=	0.5		
	Q=	Cc*V*A			Cc=	0.6	A=	1.2854		
	Q=		4.2740	ft^3/sec		0.588				
			31.97	gal/sec						
			1918.30	gal/min						
	7.5		255.77	#/min						
			15346.43	#/hr						
			6.85	LT/hr						

Sample EXCEL SS water flow calculations (Marks Engineering Handbook 11th edition p6-30) for intake vent.

ideal	Vi=(2*ρ*g)^.5				h=	0.5	g=	32.17	ρ=	1.988
	Vi=		5.6548							
actual	V=	Cv*Vi			Cv=	0.98				
	V=		5.5417				r=	0.5		
	Q=	Cc*V*A			Cc=	0.6	A=	12.6		
	Q=		41.8954	ft^3/sec		0.588		pi r2 .75 r=2		
			313.40	gal/sec						
			18803.97	gal/min						
	7.5		2507.20	#/min						
			150431.78	#/hr						
			67.16	LT/hr						

Appendix 4 Maxsurf linear strip theory equations; (From Appendix A of Maxsurf User's Manual)



Heave and Pitch Motion of a Vessel in a Seaway

The ship motions of heave, pitch and roll are oscillatory in nature, this is due to the restoring force created by changes in buoyancy involved in these motions. The motions of a ship in response to waves, may be considered as a forced damped-spring-mass system. MAXSURF Motions currently only deals with the coupled motions of pitch and heave. The two relevant equations of motion are for heave:

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{35}\ddot{\eta}_5 + B_{35}\dot{\eta}_5 + C_{35}\eta_5 = F_3 e^{i\omega t} \qquad (1)$$

and for pitch:

$$(I_5 + A_{55})\ddot{\eta}_5 + B_{55}\dot{\eta}_5 + C_{55}\eta_5 + A_{53}\ddot{\eta}_3 + B_{53}\dot{\eta}_3 + C_{53}\eta_3 = F_5 e^{i\omega t} \qquad (2)$$

where the variables are defined as follows:

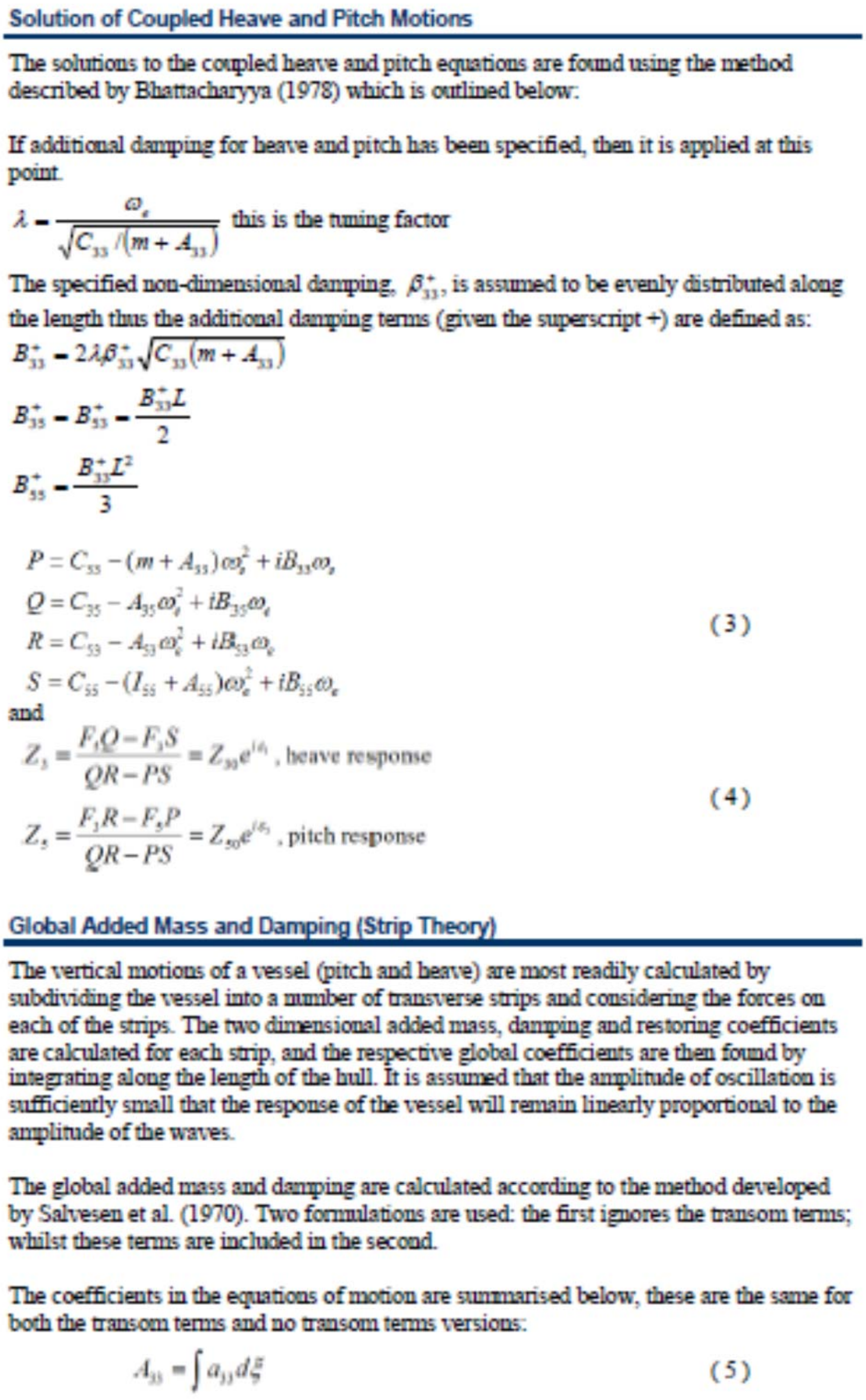
M	mass of the vessel.
I_5	moment of inertia for pitch.
A_{33}	added mass coefficient for heave due to heave.
A_{55}	added mass coefficient for pitch due to pitch.
A_{35}	added mass coefficient for heave due to pitch.
A_{53}	added mass coefficient for pitch due to heave.
B_{33}	damping coefficient for heave due to heave.
B_{55}	damping coefficient for pitch due to pitch.
B_{35}	damping coefficient for heave due to pitch.
B_{53}	damping coefficient for pitch due to heave.
C_{33}	hydrostatic restoring coefficient for heave due to heave.
C_{55}	hydrostatic restoring coefficient for pitch due to pitch.
C_{35}	hydrostatic restoring coefficient for heave due to pitch.
C_{53}	hydrostatic restoring coefficient for pitch due to heave.
F_3	heave exciting force.
F_5	pitch exciting moment.
η_3	instantaneous heave displacement.
$\dot{\eta}_3$	instantaneous heave velocity.
$\ddot{\eta}_3$	instantaneous heave acceleration.
η_5	instantaneous pitch displacement.
$\dot{\eta}_5$	instantaneous pitch velocity.
$\ddot{\eta}_5$	instantaneous pitch acceleration.

In order to solve these equations it is necessary to obtain the coefficients and excitation force and moment. The procedure used is described in the following sections.

In MAXSURF Motions the damping is calculated using inviscid flow theory. The user has the option of specifying additional heave and pitch damping to allow for damping not calculated by the inviscid flow modelled. The user is able to specify non-dimensional damping β_{33} and β_{55} from which the actual damping is calculated as follows.

$B_{nn} = 2\beta_{nn}\sqrt{C_{nn}(I_n + A_{nn})}$ with n = 3, 5.

These values are then added to the inviscid B_{33} and B_{55}.



Solution of Coupled Heave and Pitch Motions

The solutions to the coupled heave and pitch equations are found using the method described by Bhattacharyya (1978) which is outlined below:

If additional damping for heave and pitch has been specified, then it is applied at this point.

$\lambda = \frac{\omega_e}{\sqrt{C_{33}/(m + A_{33})}}$ this is the tuning factor

The specified non-dimensional damping, β_{33}^{+}, is assumed to be evenly distributed along the length thus the additional damping terms (given the superscript +) are defined as:

$$B_{33}^{+} = 2\lambda\beta_{33}^{+}\sqrt{C_{33}(m + A_{33})}$$

$$B_{35}^{+} = B_{53}^{+} = \frac{B_{33}^{+}L}{2}$$

$$B_{55}^{+} = \frac{B_{33}^{+}L^2}{3}$$

$$\begin{aligned} P &= C_{33} - (m + A_{33})\omega_e^2 + iB_{33}\omega_e \\ Q &= C_{35} - A_{35}\omega_e^2 + iB_{35}\omega_e \\ R &= C_{53} - A_{53}\omega_e^2 + iB_{53}\omega_e \\ S &= C_{55} - (I_{55} + A_{55})\omega_e^2 + iB_{55}\omega_e \end{aligned} \qquad (3)$$

and

$$\begin{aligned} Z_3 &= \frac{F_5 Q - F_3 S}{QR - PS} = Z_{30}e^{i\delta_3}\text{, heave response} \\ Z_5 &= \frac{F_3 R - F_5 P}{QR - PS} = Z_{50}e^{i\delta_5}\text{, pitch response} \end{aligned} \qquad (4)$$

Global Added Mass and Damping (Strip Theory)

The vertical motions of a vessel (pitch and heave) are most readily calculated by subdividing the vessel into a number of transverse strips and considering the forces on each of the strips. The two dimensional added mass, damping and restoring coefficients are calculated for each strip, and the respective global coefficients are then found by integrating along the length of the hull. It is assumed that the amplitude of oscillation is sufficiently small that the response of the vessel will remain linearly proportional to the amplitude of the waves.

The global added mass and damping are calculated according to the method developed by Salvesen et al. (1970). Two formulations are used: the first ignores the transom terms; whilst these terms are included in the second.

The coefficients in the equations of motion are summarised below, these are the same for both the transom terms and no transom terms versions:

$$A_{33} = \int a_{33}d\xi \qquad (5)$$

$$B_{33} = \int b_{33} d\xi \qquad (6)$$

$$C_{33} = \rho g \int b d\xi \qquad (7)$$

$$A_{35} = -\int \xi a_{33} d\xi - \frac{U}{\omega_e^2} B_{33} \qquad (8)$$

$$B_{35} = -\int \xi b_{33} d\xi + U A_{33} \qquad (9)$$

$$C_{35} = C_{53} = -\rho g \int \xi b d\xi \qquad (10)$$

$$A_{53} = -\int \xi a_{33} d\xi + \frac{U}{\omega_e^2} B_{33} \qquad (11)$$

$$B_{53} = -\int \xi b_{33} d\xi - U \; A_{33} \qquad (12)$$

$$A_{55} = \int \xi^2 a_{33} d\xi + \frac{U^2}{\omega_e^2} A_{33} \qquad (13)$$

$$B_{55} = \int \xi^2 b_{33} d\xi + \frac{U^2}{\omega_e^2} B_{33} \qquad (14)$$

$$C_{55} = \rho g \int \xi^2 b d\xi \qquad (15)$$

For the transom terms version, the following terms are added to the coefficients given above:

$$A_{33\,\mathrm{Trans}} = -\frac{U}{\omega_e^2} b_{33}^A \qquad (16)$$

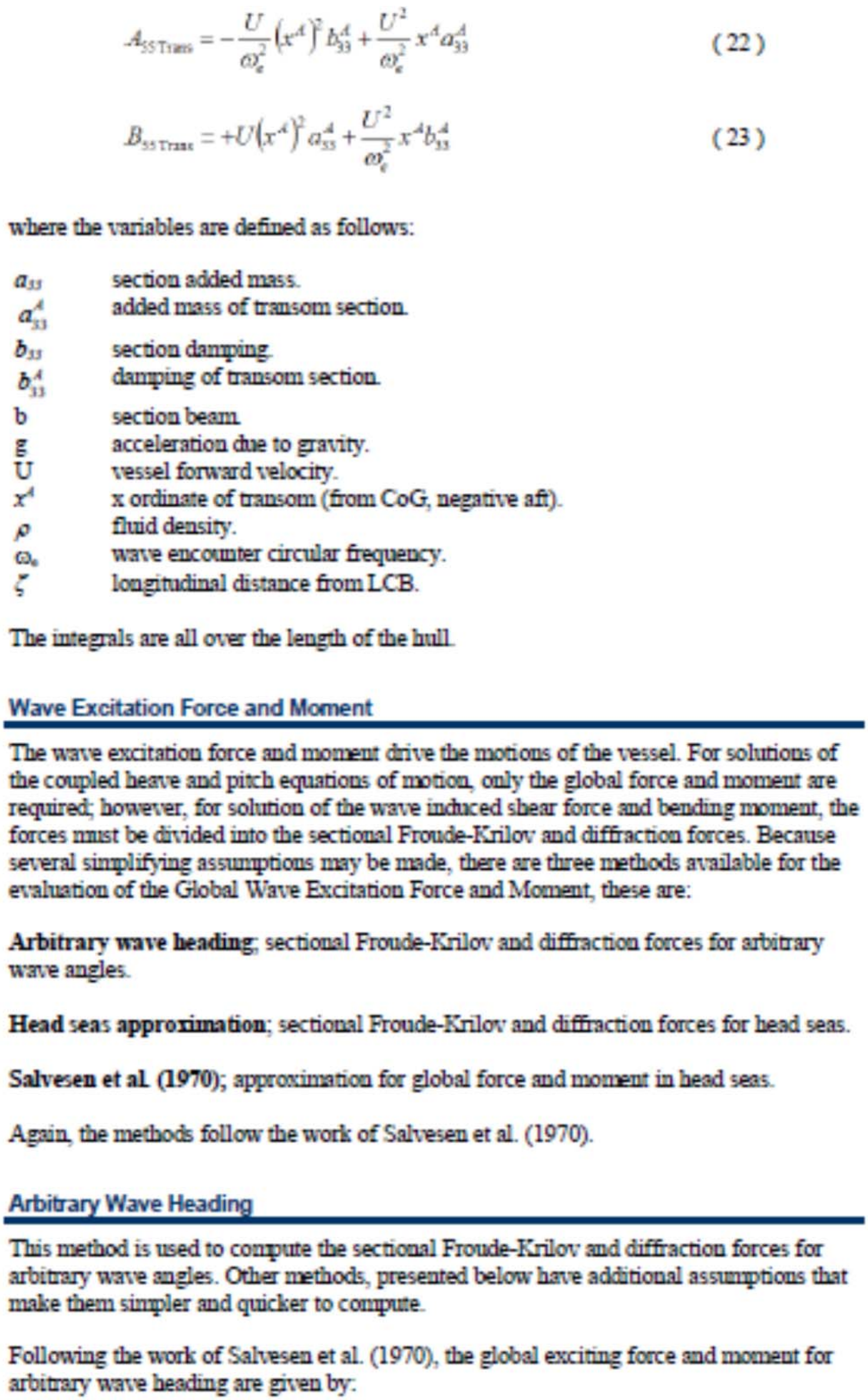
$$B_{33\,\mathrm{Trans}} = +U a_{33}^A \qquad (17)$$

$$A_{35\,\mathrm{Trans}} = +\frac{U}{\omega_e^2} x^A b_{33}^A - \frac{U^2}{\omega_e^2} a_{33}^A \qquad (18)$$

$$B_{35\,\mathrm{Trans}} = -U x^A a_{33}^A - \frac{U^2}{\omega_e^2} b_{33}^A \qquad (19)$$

$$A_{53\,\mathrm{Trans}} = +\frac{U}{\omega_e^2} x^A b_{33}^A \qquad (20)$$

$$B_{53\,\mathrm{Trans}} = -U x^A a_{33}^A \qquad (21)$$



$$A_{55\,\mathrm{Trans}} = -\frac{U}{\omega_e^2}\left(x^A\right)^2 b_{33}^A + \frac{U^2}{\omega_e^2} x^A a_{33}^A \qquad (22)$$

$$B_{55\,\mathrm{Trans}} = +U\left(x^A\right)^2 a_{55}^A + \frac{U^2}{\omega_e^2} x^A b_{33}^A \qquad (23)$$

where the variables are defined as follows:

a_{33}	section added mass.
a_{33}^A	added mass of transom section.
b_{33}	section damping.
b_{33}^A	damping of transom section.
b	section beam.
g	acceleration due to gravity.
U	vessel forward velocity.
x^A	x ordinate of transom (from CoG, negative aft).
ρ	fluid density.
ω_e	wave encounter circular frequency.
ζ	longitudinal distance from LCB.

The integrals are all over the length of the hull.

Wave Excitation Force and Moment

The wave excitation force and moment drive the motions of the vessel. For solutions of the coupled heave and pitch equations of motion, only the global force and moment are required; however, for solution of the wave induced shear force and bending moment, the forces must be divided into the sectional Froude-Krilov and diffraction forces. Because several simplifying assumptions may be made, there are three methods available for the evaluation of the Global Wave Excitation Force and Moment, these are:

Arbitrary wave heading; sectional Froude-Krilov and diffraction forces for arbitrary wave angles.

Head seas approximation; sectional Froude-Krilov and diffraction forces for head seas.

Salvesen et al. (1970); approximation for global force and moment in head seas.

Again, the methods follow the work of Salvesen et al. (1970).

Arbitrary Wave Heading

This method is used to compute the sectional Froude-Krilov and diffraction forces for arbitrary wave angles. Other methods, presented below have additional assumptions that make them simpler and quicker to compute.

Following the work of Salvesen et al. (1970), the global exciting force and moment for arbitrary wave heading are given by:

$$z \qquad (24)$$

$$F_5 = -\rho\varsigma_0 \int \left[\xi\left(f_5 + h_5\right) + \tfrac{U}{i\omega} h_5\right] d\xi - \rho\varsigma_0 \tfrac{U}{i\omega} x_A h_5^{\,A} \qquad (25)$$

where:

f_5	is the sectional Froude-Krilov force.
h_5	is the sectional Diffraction force.

Diffraction Force

The sectional diffraction wave force is given in Equation (26), note that this equation includes the water density, ρ, and the wave amplitude, ζ. The depth attenuation exponent in the e^{kx} term has the opposite sign since MAXSURF Motions sign convention has z $+^{ve}$ down:

$$h_3 = \rho\zeta\omega_0 e^{-ikx\cos\mu} \int_{C_i} (i\hat{z} - \hat{y}\sin\mu) e^{iky\sin\mu} e^{-kz} \phi_{30} dl \qquad (26)$$

Expanding the sine and cosine terms, this may be rewritten as follows:

$$\begin{aligned} h_3 = {} & \rho\zeta\omega_0 \{\cos(kx\cos\mu) - i\sin(kx\cos\mu)\} \times \\ & \int_{C_i} (i\hat{z} - \hat{y}\sin\mu) \{\cos(kx\sin\mu) + i\sin(kx\sin\mu)\} e^{-kz} \phi_{30} dl \end{aligned} \qquad (27)$$

where:

ω_0	is the wave frequency.
ω_e	is the frequency of the oscillation of the section (encounter frequency).
x,y,z	are the longitudinal position of the section, and transverse and vertical points on the section contour respectively.
$\hat{y}, \hat{z}$	are the outward normal unit vector of the section.
C_S, dl	are the section contour and element of arc along the section.
μ	is the wave heading angle.
ϕ_{30}	is the amplitude of the two dimensional velocity potential of the section in heave.

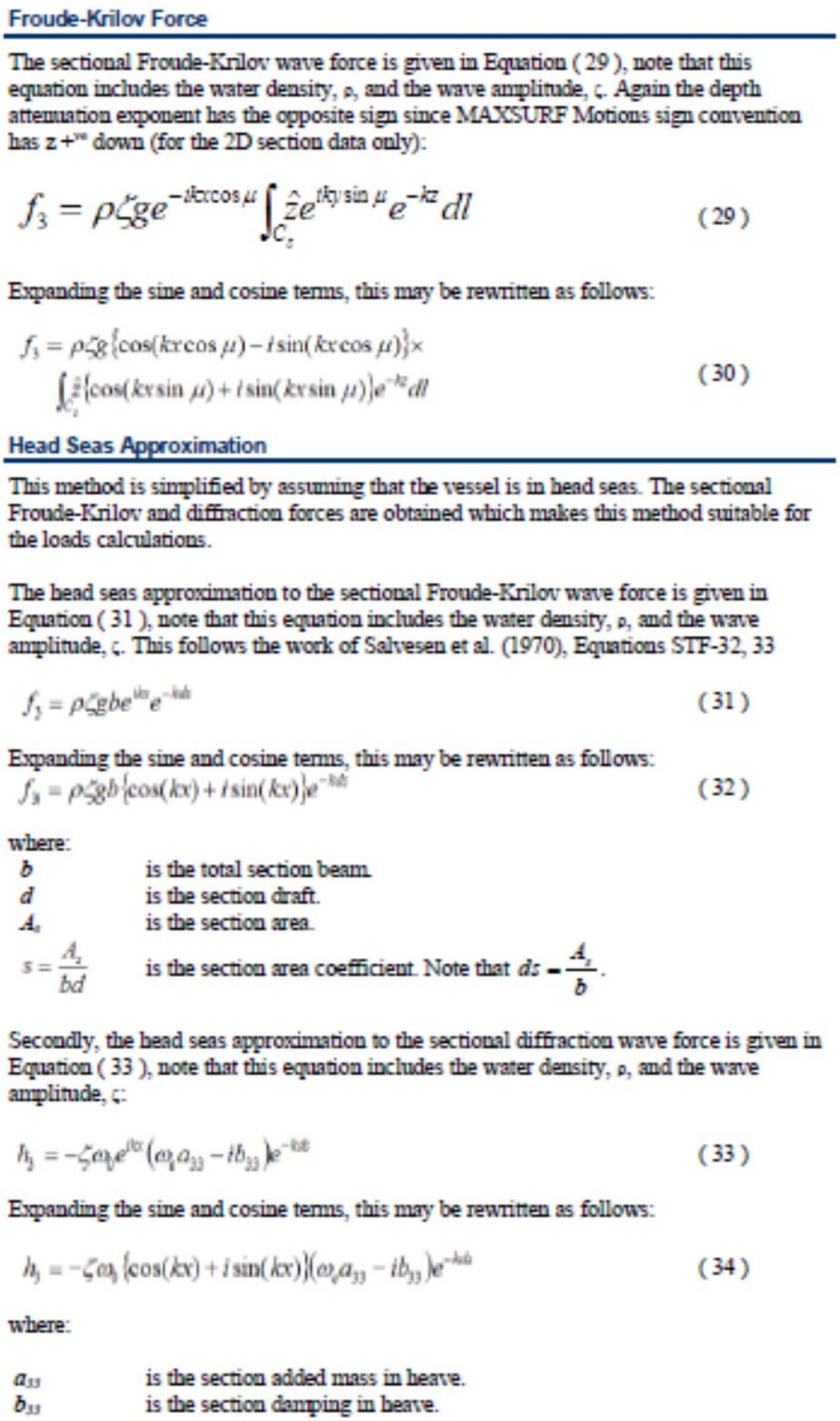
Further, the time varying velocity potential is given by:

$$\phi_3 = \phi_{30} e^{i\omega_e t} = \frac{g\bar{A}}{\pi\omega_e} \left\{ \cos(\omega_e t)\left[\Phi_c + \sum_{m=1}^{\infty} p_{2m}\phi_{2m}\right] + i\sin(\omega_e t)\left[\Phi_s + \sum_{m=1}^{\infty} q_{2m}\phi_{2m}\right]\right\} \qquad (28)$$

The segment length for the integration is calculated assuming a straight line between integration points. The unit normal vector components are calculated from the slope of the mapped section.

The velocity potential on the surface of the section at p=(y, z), is calculated by combining all the individual terms in the velocity potential as per Equation(28), note that it is the amplitude of the velocity potential that is required.

1



Froude-Krilov Force

The sectional Froude-Krilov wave force is given in Equation (29), note that this equation includes the water density, ρ, and the wave amplitude, ζ. Again the depth attenuation exponent has the opposite sign since MAXSURF Motions sign convention has z +^{ve} down (for the 2D section data only):

$$f_3 = \rho\zeta g e^{-ikx\cos\mu} \int_{C_x} \hat{z} e^{iky\sin\mu} e^{-kz} dl \qquad (29)$$

Expanding the sine and cosine terms, this may be rewritten as follows:

$$\begin{aligned} f_3 = \rho\zeta g \{\cos(kx\cos\mu) - i\sin(kx\cos\mu)\} \times \\ \int_{C_x} \hat{z} \{\cos(ky\sin\mu) + i\sin(ky\sin\mu)\} e^{-kz} dl \end{aligned} \qquad (30)$$

Head Seas Approximation

This method is simplified by assuming that the vessel is in head seas. The sectional Froude-Krilov and diffraction forces are obtained which makes this method suitable for the loads calculations.

The head seas approximation to the sectional Froude-Krilov wave force is given in Equation (31), note that this equation includes the water density, ρ, and the wave amplitude, ζ. This follows the work of Salvesen et al. (1970), Equations STF-32, 33

$$f_3 = \rho\zeta g b e^{ikx} e^{-ksd} \qquad (31)$$

Expanding the sine and cosine terms, this may be rewritten as follows:

$$f_3 = \rho\zeta g b \{\cos(kx) + i\sin(kx)\} e^{-ksd} \qquad (32)$$

where:

b is the total section beam.
d is the section draft.
A_s is the section area.
$s = \frac{A_s}{bd}$ is the section area coefficient. Note that $ds = \frac{A_s}{b}$.

Secondly, the head seas approximation to the sectional diffraction wave force is given in Equation (33), note that this equation includes the water density, ρ, and the wave amplitude, ζ:

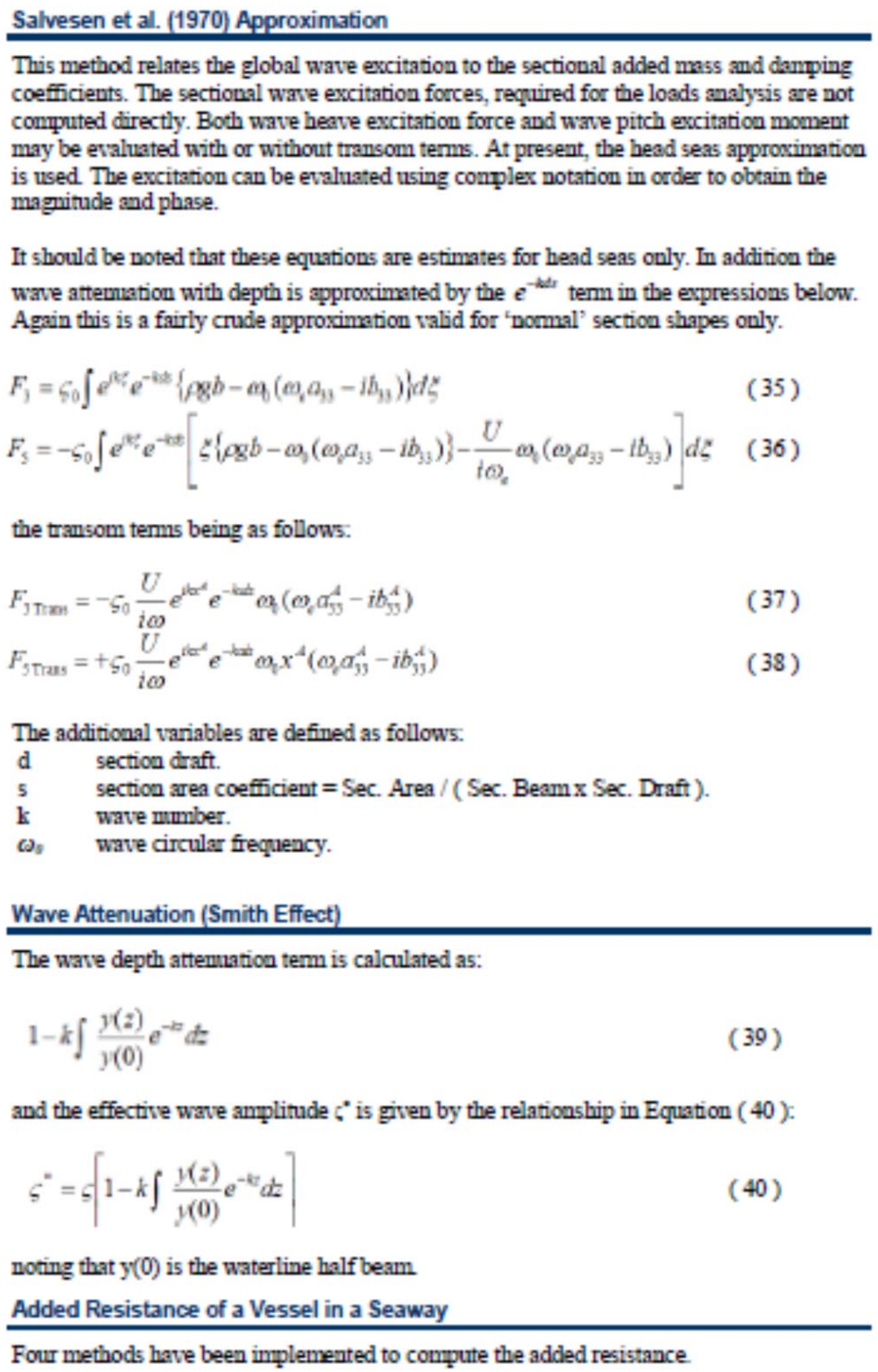
$$h_3 = -\zeta\omega_0 e^{ikx} (\omega_e a_{33} - i b_{33}) e^{-ksd} \qquad (33)$$

Expanding the sine and cosine terms, this may be rewritten as follows:

$$h_3 = -\zeta\omega_0 \{\cos(kx) + i\sin(kx)\} (\omega_e a_{33} - i b_{33}) e^{-ksd} \qquad (34)$$

where:

a_{33} is the section added mass in heave.
b_{33} is the section damping in heave.



Salvesen et al. (1970) Approximation

This method relates the global wave excitation to the sectional added mass and damping coefficients. The sectional wave excitation forces, required for the loads analysis are not computed directly. Both wave heave excitation force and wave pitch excitation moment may be evaluated with or without transom terms. At present, the head seas approximation is used. The excitation can be evaluated using complex notation in order to obtain the magnitude and phase.

It should be noted that these equations are estimates for head seas only. In addition the wave attenuation with depth is approximated by the e^{-kds} term in the expressions below. Again this is a fairly crude approximation valid for 'normal' section shapes only.

$$F_3 = \varsigma_0 \int e^{ik\xi} e^{-kds} \{\rho g b - \omega_0 (\omega_e a_{33} - i b_{33})\} d\xi \qquad (35)$$

$$F_5 = -\varsigma_0 \int e^{ik\xi} e^{-kds} \left[\xi \{\rho g b - \omega_0 (\omega_e a_{33} - i b_{33})\} - \frac{U}{i\omega_e} \omega_0 (\omega_e a_{33} - i b_{33}) \right] d\xi \qquad (36)$$

the transom terms being as follows:

$$F_{3\,\mathrm{Trans}} = -\varsigma_0 \frac{U}{i\omega} e^{ikx^A} e^{-kds} \omega_0 (\omega_e a_{33}^A - i b_{33}^A) \qquad (37)$$

$$F_{5\,\mathrm{Trans}} = +\varsigma_0 \frac{U}{i\omega} e^{ikx^A} e^{-kds} \omega_0 x^A (\omega_e a_{33}^A - i b_{33}^A) \qquad (38)$$

The additional variables are defined as follows:

d	section draft.
s	section area coefficient = Sec. Area / (Sec. Beam x Sec. Draft).
k	wave number.
ω_0	wave circular frequency.

Wave Attenuation (Smith Effect)

The wave depth attenuation term is calculated as:

$$1 - k \int \frac{y(z)}{y(0)} e^{-kz} dz \qquad (39)$$

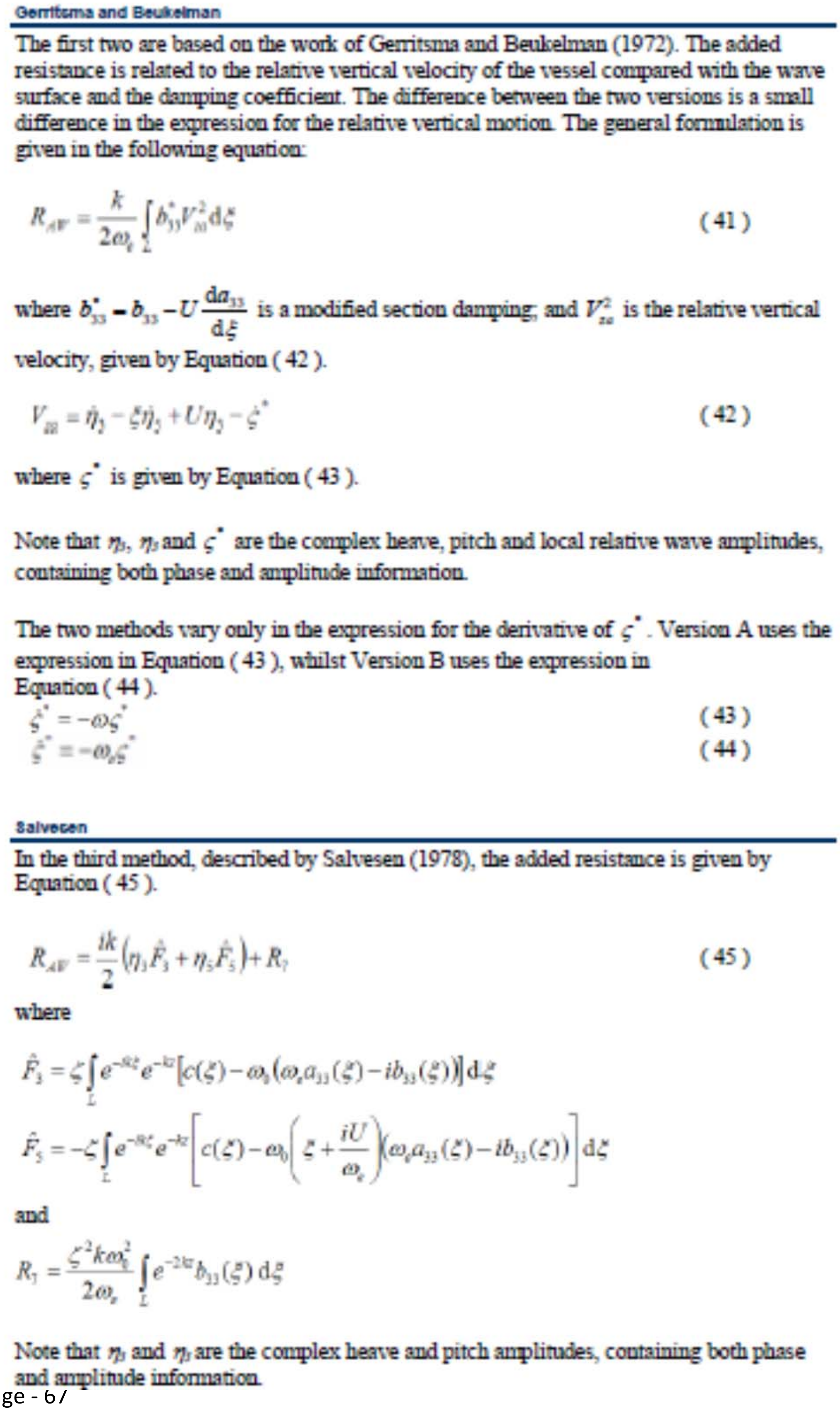
and the effective wave amplitude ς^* is given by the relationship in Equation (40):

$$\varsigma^* = \varsigma \left[1 - k \int \frac{y(z)}{y(0)} e^{-kz} dz \right] \qquad (40)$$

noting that y(0) is the waterline half beam.

Added Resistance of a Vessel in a Seaway

Four methods have been implemented to compute the added resistance.



Gerritsma and Beukelman

The first two are based on the work of Gerritsma and Beukelman (1972). The added resistance is related to the relative vertical velocity of the vessel compared with the wave surface and the damping coefficient. The difference between the two versions is a small difference in the expression for the relative vertical motion. The general formulation is given in the following equation:

$$R_{AW} = \frac{k}{2\omega_e} \int_L b_{33}^* V_{za}^2 \, \mathrm{d}\xi \qquad (41)$$

where $b_{33}^* = b_{33} - U \frac{\mathrm{d}a_{33}}{\mathrm{d}\xi}$ is a modified section damping; and V_{za}^2 is the relative vertical velocity, given by Equation (42).

$$V_{za} = \dot{\eta}_3 - \xi\dot{\eta}_5 + U\eta_5 - \dot{\varsigma}^* \qquad (42)$$

where ς^* is given by Equation (43).

Note that η_3, η_5 and ς^* are the complex heave, pitch and local relative wave amplitudes, containing both phase and amplitude information.

The two methods vary only in the expression for the derivative of ς^*. Version A uses the expression in Equation (43), whilst Version B uses the expression in Equation (44).

$$\dot{\varsigma}^* = -\omega\varsigma^* \qquad (43)$$

$$\dot{\varsigma}^* = -\omega_e\varsigma^* \qquad (44)$$

Salvesen

In the third method, described by Salvesen (1978), the added resistance is given by Equation (45).

$$R_{AW} = \frac{ik}{2}\left(\eta_3\hat{F}_3 + \eta_5\hat{F}_5\right) + R_7 \qquad (45)$$

where

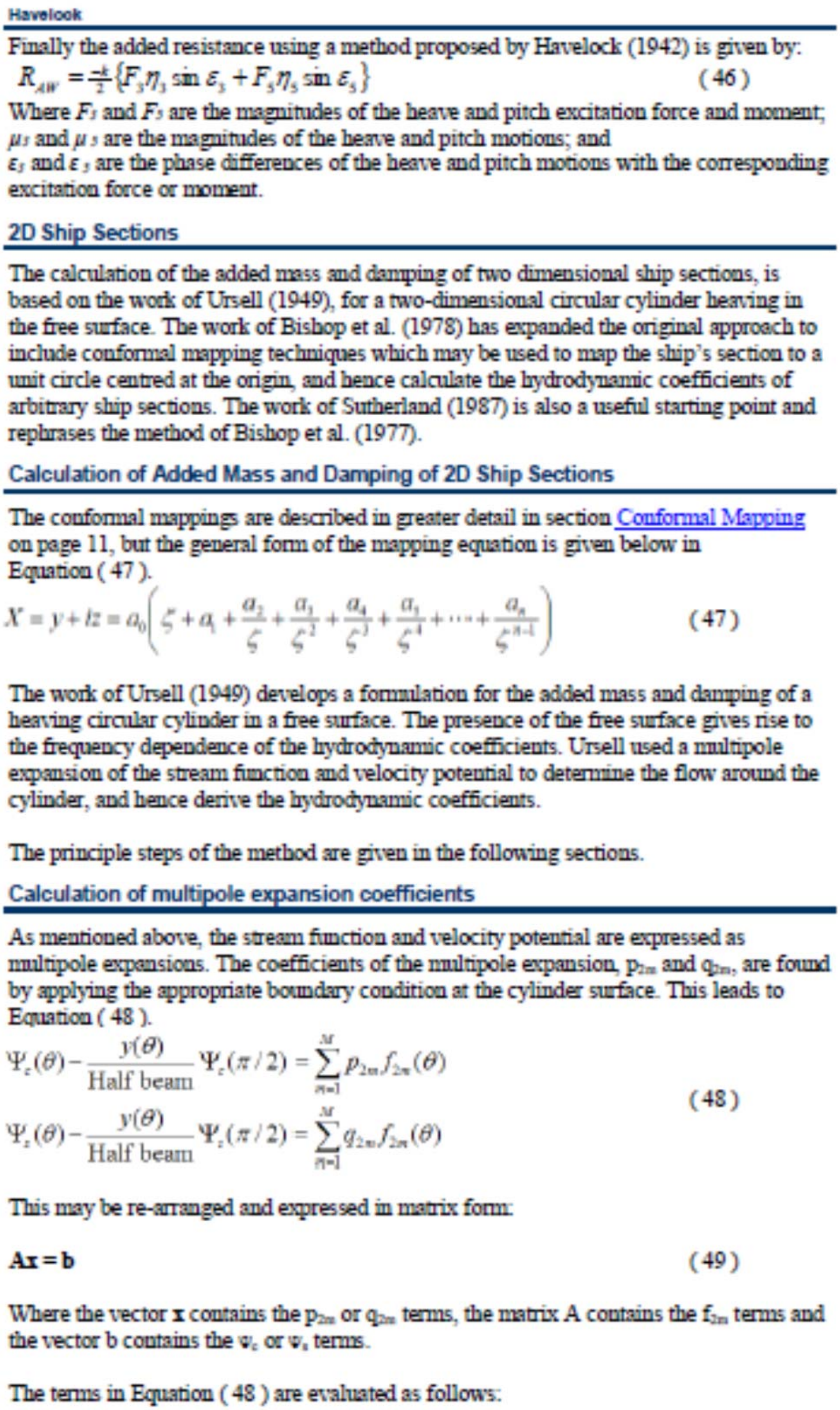
$$\hat{F}_3 = \zeta \int_L e^{-ik\xi} e^{-kz} \left[c(\xi) - \omega_0\left(\omega_e a_{33}(\xi) - ib_{33}(\xi)\right)\right] \mathrm{d}\xi$$

$$\hat{F}_5 = -\zeta \int_L e^{-ik\xi} e^{-kz} \left[c(\xi) - \omega_0\left(\xi + \frac{iU}{\omega_e}\right)\left(\omega_e a_{33}(\xi) - ib_{33}(\xi)\right)\right] \mathrm{d}\xi$$

and

$$R_7 = \frac{\zeta^2 k \omega_0^2}{2\omega_e} \int_L e^{-2kz} b_{33}(\xi) \, \mathrm{d}\xi$$

Note that η_3 and η_5 are the complex heave and pitch amplitudes, containing both phase and amplitude information.



Havelock

Finally the added resistance using a method proposed by Havelock (1942) is given by:

$$R_{AW} = \frac{-k}{2}\left\{F_3\eta_3 \sin\varepsilon_3 + F_5\eta_5 \sin\varepsilon_5\right\} \qquad (46)$$

Where F_3 and F_5 are the magnitudes of the heave and pitch excitation force and moment;
μ_3 and μ_5 are the magnitudes of the heave and pitch motions; and
ε_3 and ε_5 are the phase differences of the heave and pitch motions with the corresponding excitation force or moment.

2D Ship Sections

The calculation of the added mass and damping of two dimensional ship sections, is based on the work of Ursell (1949), for a two-dimensional circular cylinder heaving in the free surface. The work of Bishop et al. (1978) has expanded the original approach to include conformal mapping techniques which may be used to map the ship's section to a unit circle centred at the origin, and hence calculate the hydrodynamic coefficients of arbitrary ship sections. The work of Sutherland (1987) is also a useful starting point and rephrases the method of Bishop et al. (1977).

Calculation of Added Mass and Damping of 2D Ship Sections

The conformal mappings are described in greater detail in section Conformal Mapping on page 11, but the general form of the mapping equation is given below in Equation (47).

$$X = y + iz = a_0\left(\zeta + a_1 + \frac{a_2}{\zeta} + \frac{a_3}{\zeta^2} + \frac{a_4}{\zeta^3} + \frac{a_5}{\zeta^4} + \cdots + \frac{a_n}{\zeta^{n-1}}\right) \qquad (47)$$

The work of Ursell (1949) develops a formulation for the added mass and damping of a heaving circular cylinder in a free surface. The presence of the free surface gives rise to the frequency dependence of the hydrodynamic coefficients. Ursell used a multipole expansion of the stream function and velocity potential to determine the flow around the cylinder, and hence derive the hydrodynamic coefficients.

The principle steps of the method are given in the following sections.

Calculation of multipole expansion coefficients

As mentioned above, the stream function and velocity potential are expressed as multipole expansions. The coefficients of the multipole expansion, p_{2m} and q_{2m}, are found by applying the appropriate boundary condition at the cylinder surface. This leads to Equation (48).

$$\begin{aligned}\Psi_c(\theta) - \frac{y(\theta)}{\text{Half beam}}\Psi_c(\pi/2) &= \sum_{n=1}^{M} p_{2m} f_{2m}(\theta) \\ \Psi_s(\theta) - \frac{y(\theta)}{\text{Half beam}}\Psi_s(\pi/2) &= \sum_{n=1}^{M} q_{2m} f_{2m}(\theta)\end{aligned} \qquad (48)$$

This may be re-arranged and expressed in matrix form:

$$\mathbf{Ax} = \mathbf{b} \qquad (49)$$

Where the vector **x** contains the p_{2m} or q_{2m} terms, the matrix A contains the f_{2m} terms and the vector b contains the ψ_c or ψ_s terms.

The terms in Equation (48) are evaluated as follows:

$$\begin{aligned} y(\theta) &= a_0\left[\sin\theta + a_1\sin\theta - a_2\sin 3\theta + a_3\sin 5\theta + \cdots - (-1)^n a_n \sin(2n-1)\theta\right] \\ z(\theta) &= a_0\left[\cos\theta - a_1\cos\theta + a_2\cos 3\theta - a_3\cos 5\theta + \cdots + (-1)^n a_n \cos(2n-1)\theta\right] \end{aligned} \qquad (50)$$

$$\Psi_c(\theta) = \pi e^{-kz}\sin ky \qquad (51)$$

$$\Psi_s(\theta) = -\pi e^{-kz}\cos ky + \int_0^\infty e^{-\upsilon y}\,\frac{\upsilon\sin\upsilon z + k\cos\upsilon z}{k^2+\upsilon^2}\,d\upsilon \qquad (52)$$

The mapped points y, z are obtained by applying the mapping equation at angle e (Equation(50)).

Since the integral in Equation (52) converges slowly it is evaluated by an alternative method. The method used follows the work of Sutherland and is known as the method of Laguerre-Gauss quadrature. It may be shown that the integral can be evaluated as in Equation (53):

$$\int_0^\infty e^{-\upsilon y}\,\frac{\upsilon\sin\upsilon z + k\cos\upsilon z}{k^2+\upsilon^2}\,d\upsilon = \sum \frac{w_i}{y}\left[\frac{\frac{s_i}{y}\sin\left(\frac{s_i z}{y}\right) + k\cos\left(\frac{s_i z}{y}\right)}{k^2 + \left(\frac{s_i}{y}\right)^2}\right] \qquad (53)$$

Where the weighting functions, w_i, and the abscissa, s_i, may be found in standard texts. Finally the f_{2m} terms are calculated for each multipole at each angle according to Equation (54):

$$f_{2m}(\theta) = \frac{y(\theta)}{\text{Half beam}}\,\psi_{2m}(\pi/2) - \psi_{2m}(\theta) \qquad (54)$$

with ψ_{2m}:

$$\psi_{2m} = \sin 2m\theta + ka_0\left[\frac{\sin(2m-1)\theta}{2m-1} + \sum_{n=1}^{N}(-1)^{n+1}\frac{(2n-1)a_{2n-1}\sin(2m+2n-1)\theta}{2m+2n-1}\right] \qquad (55)$$

where a_0, a_1, ... a_N are the conformal mapping coefficients.

Least squares solution to over-defined set of linear equations

In practice, Equation (49) is solved in a least squares sense: a number of angles, R, are chosen at which the ψ_c and ψ_s terms are evaluated from Equations (51) and (52). The number of multipoles, M, is chosen such that M < R, and the f_{2m} terms are evaluated, according to Equation (54), for each of the multipoles at each of the angles. Thus there are more linear equations than unknowns. It may be shown that the least squares solution to this system of equations may be expressed, in matrix form, as in Equation (51). This system may then easily be solved by Gauss elimination or any other matrix solving method, such as Gauss Seidel or SOR (successive over-relaxation).

$$\mathbf{A}^T\mathbf{A}\mathbf{x} = \mathbf{A}^T\mathbf{b} \qquad (56)$$

Calculation and integration of pressure functions around contour

Once the coefficients, p_{2m} and q_{2m}, have been found, it is necessary to calculate the terms M_0 and N_0. These are calculated according to Equation (57), where the functions are integrated over one quadrant of the section in the unit circle plane.

$$M_0 = \int_0^{\pi/2} \frac{a_0 M(\theta) W(\theta)}{\text{Half beam}} d\theta \qquad (57)$$
$$N_0 = \int_0^{\pi/2} \frac{a_0 N(\theta) W(\theta)}{\text{Half beam}} d\theta$$

The terms M(e), N(e) and W(e) are given in Equations (58):

$$M(\theta) = \Phi_s(\theta) + \sum_{m=1}^{M} q_{2m}\phi_{2m}(\theta)$$
$$N(\theta) = \Phi_c(\theta) + \sum_{m=1}^{M} p_{2m}\phi_{2m}(\theta) \qquad (58)$$
$$W(\theta) = \cos\theta + \sum_{n=1}^{N} (-1)^{n+1}(2n-1)a_{2n-1}\cos(2n-1)\theta$$

The terms Φ_s, Φ_c and ϕ_{2m} are calculated from Equations (59):

$$\Phi_c(\theta) = \pi e^{-kz}\cos ky$$
$$\Phi_s(\theta) = \pi e^{-kz}\sin ky - \int_0^{\infty} e^{-\upsilon y}\frac{\upsilon\cos\upsilon z - k\sin\upsilon z}{k^2+\upsilon^2}d\upsilon \qquad (59)$$
$$\phi_{2m} = \cos 2m\theta + ka_0\left[\frac{\cos(2m-1)\theta}{2m-1} + \sum_{n=1}^{N}(-1)^{n+1}\frac{(2n-1)a_{2n-1}\cos(2m+2n-1)\theta}{2m+2n-1}\right]$$

Again the integral in the Φ_s term is evaluated by Laguerre quadrature using Equation (60):

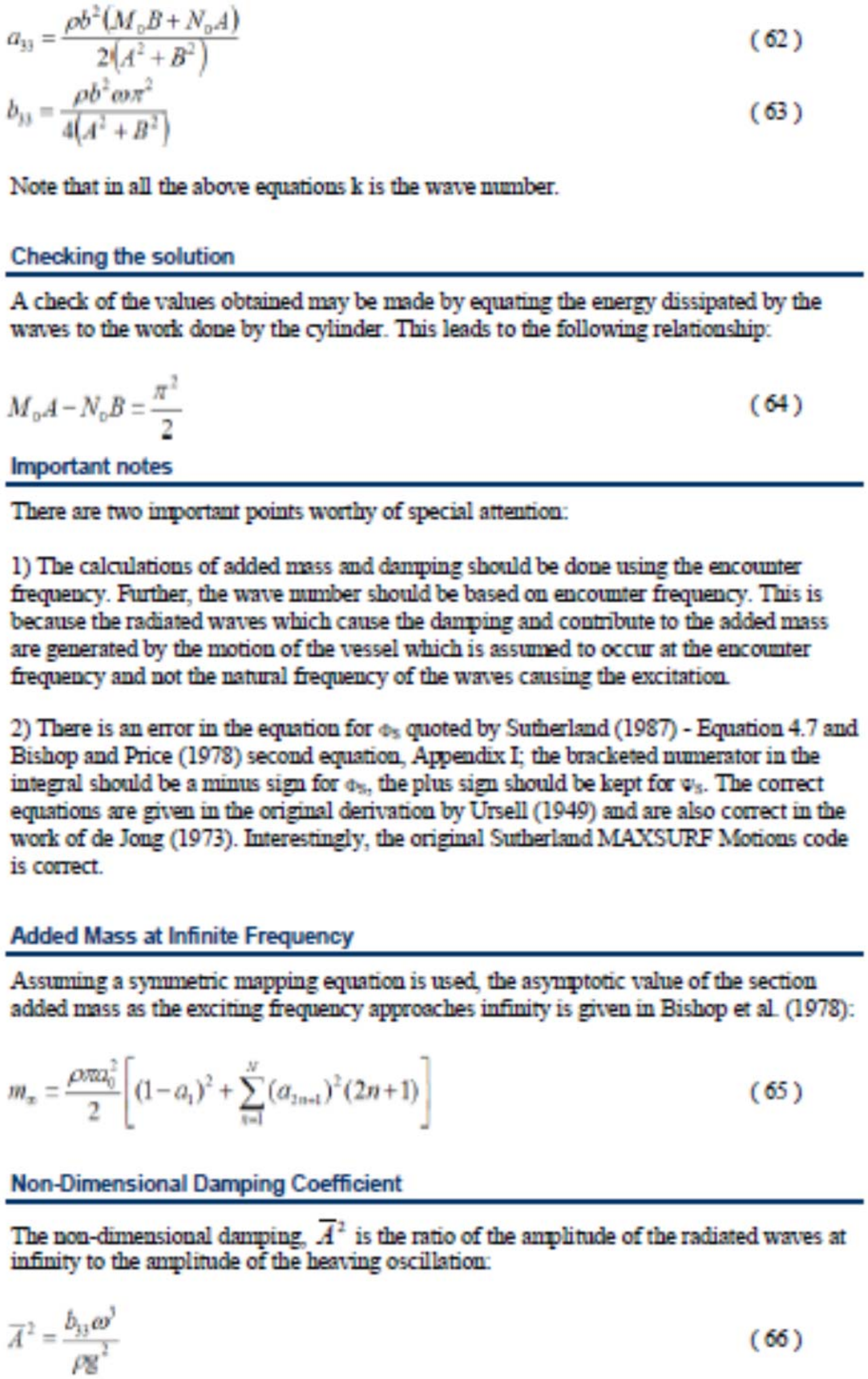
$$\int_0^{\infty} e^{-\upsilon y}\frac{\upsilon\cos\upsilon z + k\sin\upsilon z}{k^2+\upsilon^2}d\upsilon = \sum \frac{w_i}{y}\left[\frac{\frac{s_i}{y}\cos\left(\frac{s_i z}{y}\right) - k\sin\left(\frac{s_i z}{y}\right)}{k^2 + \left(\frac{s_i}{y}\right)^2}\right] \qquad (60)$$

Additional terms A and B are calculated from Equation (61):

$$A = \Psi_c(\pi/2) + \sum_{m=1}^{M} p_{2m}\psi_{2m}(\pi/2) \qquad (61)$$
$$B = \Psi_s(\pi/2) + \sum_{m=1}^{M} q_{2m}\psi_{2m}(\pi/2)$$

Evaluation of hydrodynamic coefficients

Finally, the section added mass, a_{33}, and the section damping, b_{33}, may be calculated from Equations (62) and (63) respectively.



$$a_{33} = \frac{\rho b^2 (M_0 B + N_0 A)}{2(A^2 + B^2)} \qquad (62)$$

$$b_{33} = \frac{\rho b^2 \omega \pi^2}{4(A^2 + B^2)} \qquad (63)$$

Note that in all the above equations k is the wave number.

Checking the solution

A check of the values obtained may be made by equating the energy dissipated by the waves to the work done by the cylinder. This leads to the following relationship:

$$M_0 A - N_0 B = \frac{\pi^2}{2} \qquad (64)$$

Important notes

There are two important points worthy of special attention:

1) The calculations of added mass and damping should be done using the encounter frequency. Further, the wave number should be based on encounter frequency. This is because the radiated waves which cause the damping and contribute to the added mass are generated by the motion of the vessel which is assumed to occur at the encounter frequency and not the natural frequency of the waves causing the excitation.

2) There is an error in the equation for ϕ_S quoted by Sutherland (1987) - Equation 4.7 and Bishop and Price (1978) second equation, Appendix I; the bracketed numerator in the integral should be a minus sign for ϕ_S, the plus sign should be kept for ψ_S. The correct equations are given in the original derivation by Ursell (1949) and are also correct in the work of de Jong (1973). Interestingly, the original Sutherland MAXSURF Motions code is correct.

Added Mass at Infinite Frequency

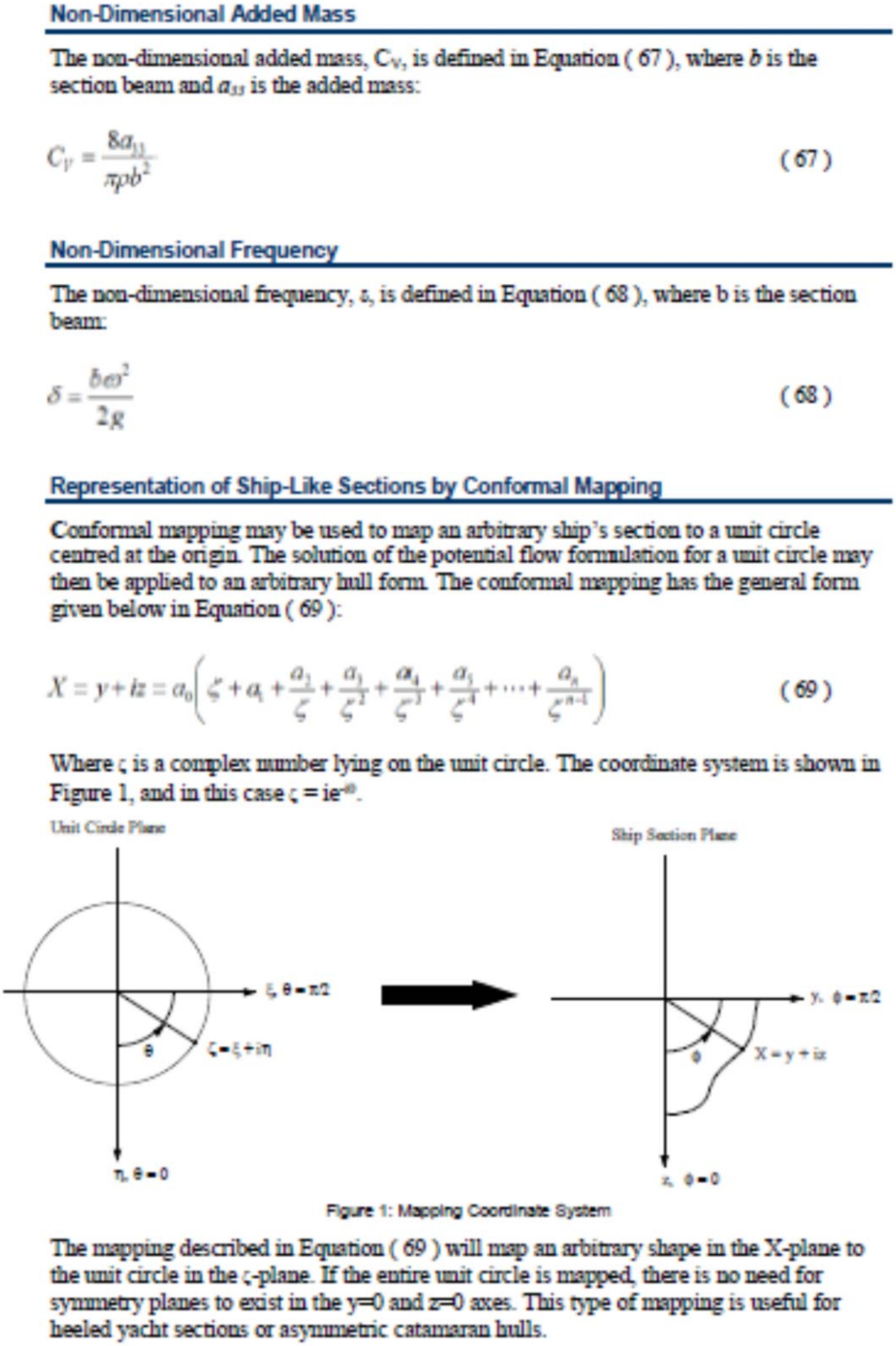
Assuming a symmetric mapping equation is used, the asymptotic value of the section added mass as the exciting frequency approaches infinity is given in Bishop et al. (1978):

$$m_\infty = \frac{\rho \pi a_0^2}{2} \left[(1 - a_1)^2 + \sum_{n=1}^{N} (a_{2n+1})^2 (2n+1) \right] \qquad (65)$$

Non-Dimensional Damping Coefficient

The non-dimensional damping, $\overline{A}^2$ is the ratio of the amplitude of the radiated waves at infinity to the amplitude of the heaving oscillation:

$$\overline{A}^2 = \frac{b_{33} \omega^3}{\rho g^2} \qquad (66)$$



Non-Dimensional Added Mass

The non-dimensional added mass, C_V, is defined in Equation (67), where b is the section beam and a_{33} is the added mass:

$$C_V = \frac{8a_{33}}{\pi\rho b^2} \qquad (67)$$

Non-Dimensional Frequency

The non-dimensional frequency, δ, is defined in Equation (68), where b is the section beam:

$$\delta = \frac{b\omega^2}{2g} \qquad (68)$$

Representation of Ship-Like Sections by Conformal Mapping

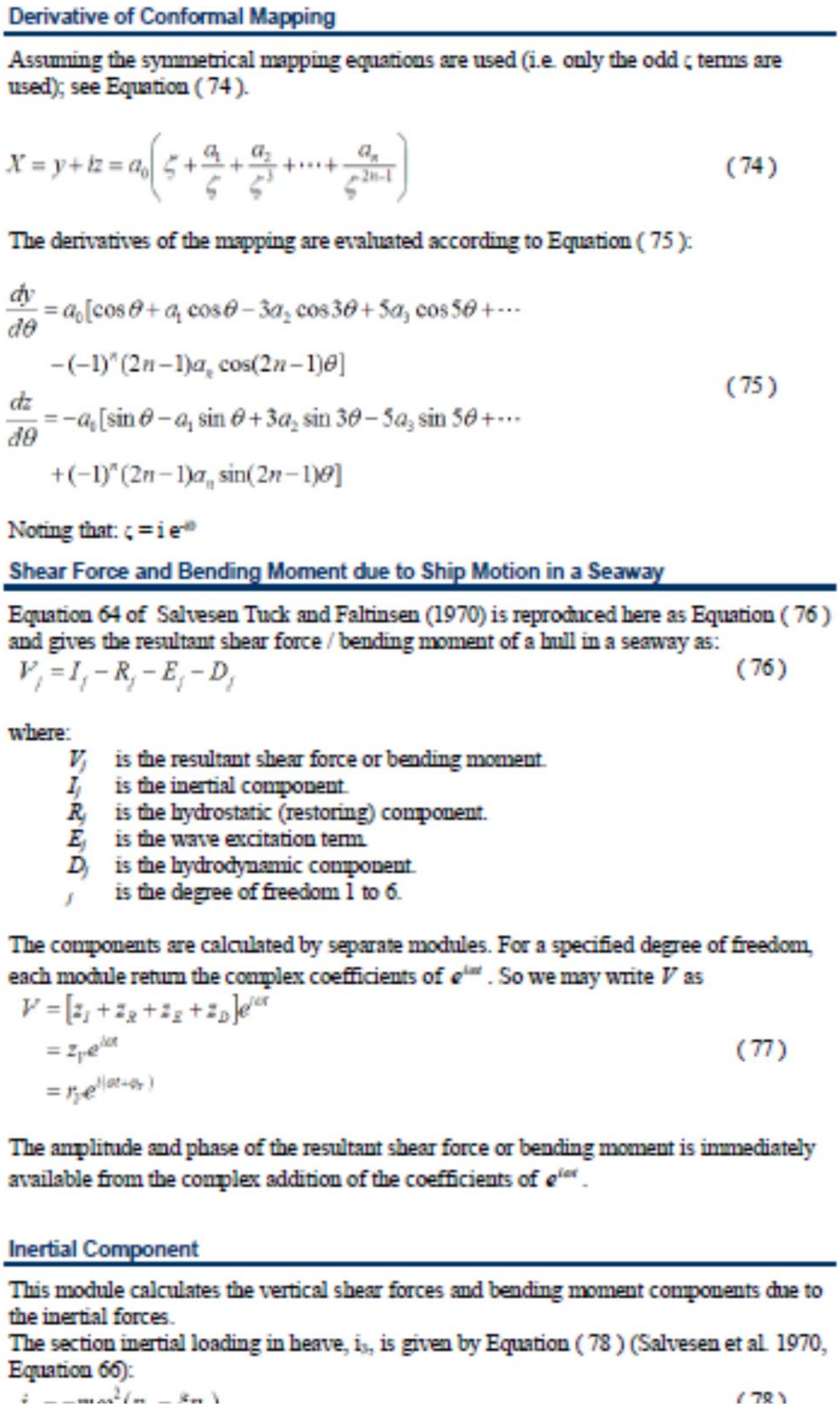
Conformal mapping may be used to map an arbitrary ship's section to a unit circle centred at the origin. The solution of the potential flow formulation for a unit circle may then be applied to an arbitrary hull form. The conformal mapping has the general form given below in Equation (69):

$$X = y + iz = a_0\left(\zeta + a_1 + \frac{a_2}{\zeta} + \frac{a_3}{\zeta^2} + \frac{a_4}{\zeta^3} + \frac{a_5}{\zeta^4} + \cdots + \frac{a_n}{\zeta^{n-1}}\right) \qquad (69)$$

Where ζ is a complex number lying on the unit circle. The coordinate system is shown in Figure 1, and in this case $\zeta = ie^{-i\theta}$.

Figure 1: Mapping Coordinate System

The mapping described in Equation (69) will map an arbitrary shape in the X-plane to the unit circle in the ζ-plane. If the entire unit circle is mapped, there is no need for symmetry planes to exist in the y=0 and z=0 axes. This type of mapping is useful for heeled yacht sections or asymmetric catamaran hulls.



Derivative of Conformal Mapping

Assuming the symmetrical mapping equations are used (i.e. only the odd ζ terms are used); see Equation (74).

$$X = y + iz = a_0\left(\zeta + \frac{a_1}{\zeta} + \frac{a_2}{\zeta^3} + \cdots + \frac{a_n}{\zeta^{2n-1}}\right) \qquad (74)$$

The derivatives of the mapping are evaluated according to Equation (75):

$$\begin{aligned}\frac{dy}{d\theta} &= a_0[\cos\theta + a_1\cos\theta - 3a_2\cos 3\theta + 5a_3\cos 5\theta + \cdots \\ &\quad - (-1)^n(2n-1)a_n\cos(2n-1)\theta] \\ \frac{dz}{d\theta} &= -a_0[\sin\theta - a_1\sin\theta + 3a_2\sin 3\theta - 5a_3\sin 5\theta + \cdots \\ &\quad + (-1)^n(2n-1)a_n\sin(2n-1)\theta]\end{aligned} \qquad (75)$$

Noting that: $\zeta = i\,e^{-i\theta}$

Shear Force and Bending Moment due to Ship Motion in a Seaway

Equation 64 of Salvesen Tuck and Faltinsen (1970) is reproduced here as Equation (76) and gives the resultant shear force / bending moment of a hull in a seaway as:

$$V_j = I_j - R_j - E_j - D_j \qquad (76)$$

where:

V_j is the resultant shear force or bending moment.
I_j is the inertial component.
R_j is the hydrostatic (restoring) component.
E_j is the wave excitation term.
D_j is the hydrodynamic component.
j is the degree of freedom 1 to 6.

The components are calculated by separate modules. For a specified degree of freedom, each module return the complex coefficients of $e^{i\omega t}$. So we may write V as

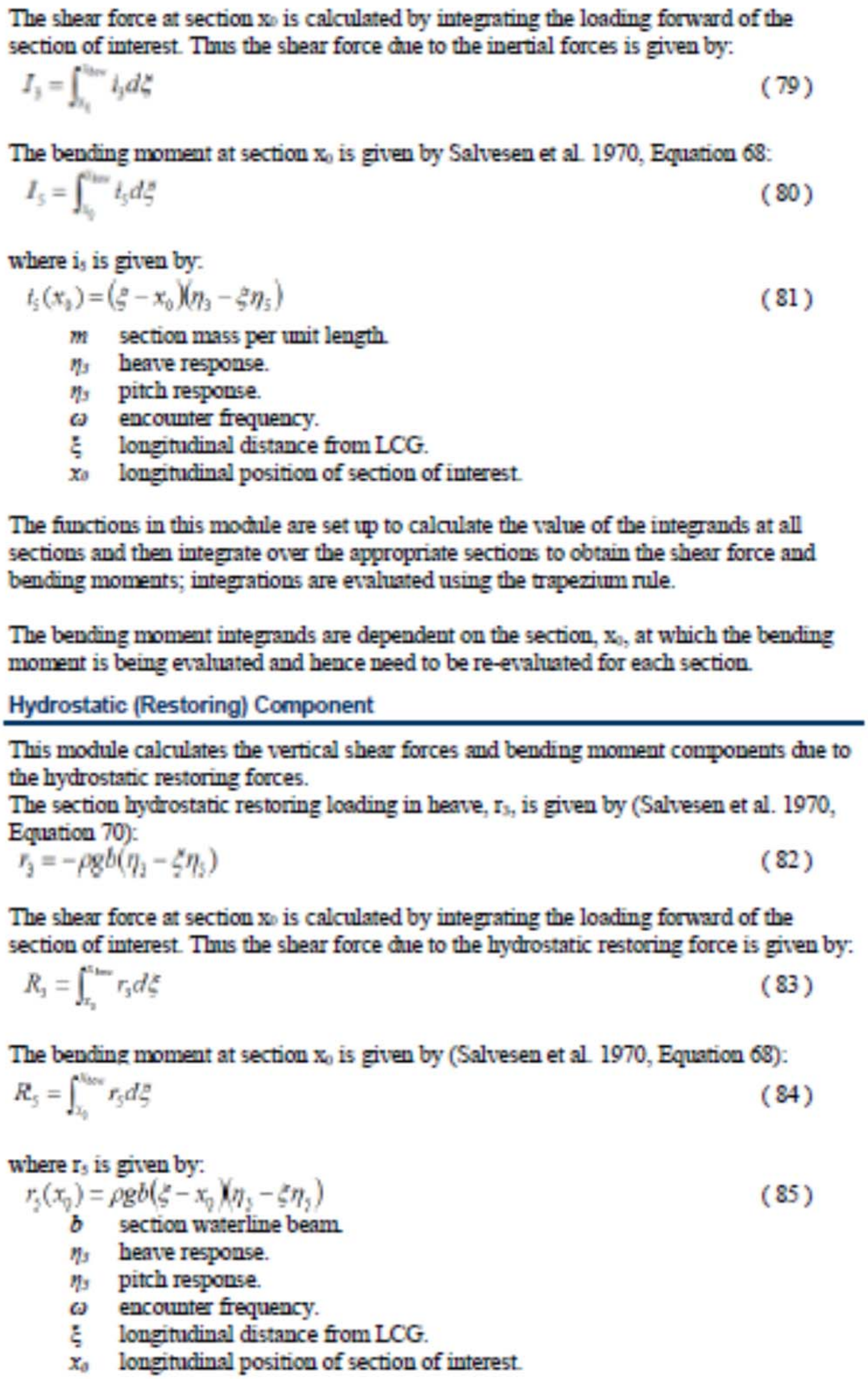
$$\begin{aligned}V &= [z_I + z_R + z_E + z_D]e^{i\omega t} \\ &= z_V e^{i\omega t} \\ &= r_V e^{i(\omega t + \theta_V)}\end{aligned} \qquad (77)$$

The amplitude and phase of the resultant shear force or bending moment is immediately available from the complex addition of the coefficients of $e^{i\omega t}$.

Inertial Component

This module calculates the vertical shear forces and bending moment components due to the inertial forces.
The section inertial loading in heave, i_3, is given by Equation (78) (Salvesen et al. 1970, Equation 66):

$$i_3 = -m\omega^2(\eta_3 - \xi\eta_5) \qquad (78)$$



The shear force at section x_0 is calculated by integrating the loading forward of the section of interest. Thus the shear force due to the inertial forces is given by:

$$I_3 = \int_{x_0}^{x_{bow}} i_3 d\xi \qquad (79)$$

The bending moment at section x_0 is given by Salvesen et al. 1970, Equation 68:

$$I_5 = \int_{x_0}^{x_{bow}} i_5 d\xi \qquad (80)$$

where i_5 is given by:

$$i_5(x_0) = (\xi - x_0)(\eta_3 - \xi\eta_5) \qquad (81)$$

m	section mass per unit length.
η_3	heave response.
η_3	pitch response.
ω	encounter frequency.
ξ	longitudinal distance from LCG.
x_0	longitudinal position of section of interest.

The functions in this module are set up to calculate the value of the integrands at all sections and then integrate over the appropriate sections to obtain the shear force and bending moments; integrations are evaluated using the trapezium rule.

The bending moment integrands are dependent on the section, x_0, at which the bending moment is being evaluated and hence need to be re-evaluated for each section.

Hydrostatic (Restoring) Component

This module calculates the vertical shear forces and bending moment components due to the hydrostatic restoring forces.
The section hydrostatic restoring loading in heave, r_3, is given by (Salvesen et al. 1970, Equation 70):

$$r_3 = -\rho g b(\eta_3 - \xi\eta_5) \qquad (82)$$

The shear force at section x_0 is calculated by integrating the loading forward of the section of interest. Thus the shear force due to the hydrostatic restoring force is given by:

$$R_3 = \int_{x_0}^{x_{bow}} r_3 d\xi \qquad (83)$$

The bending moment at section x_0 is given by (Salvesen et al. 1970, Equation 68):

$$R_5 = \int_{x_0}^{x_{bow}} r_5 d\xi \qquad (84)$$

where r_5 is given by:

$$r_5(x_0) = \rho g b(\xi - x_0)(\eta_3 - \xi\eta_5) \qquad (85)$$

b	section waterline beam.
η_3	heave response.
η_3	pitch response.
ω	encounter frequency.
ξ	longitudinal distance from LCG.
x_0	longitudinal position of section of interest.

The functions in this module are set up to calculate the value of the integrands at all sections and then integrate over the appropriate sections to obtain the shear force and bending moments; integrations are evaluated using the trapezium rule. The bending moment integrands are dependent on the section, x_0, at which the bending moment is being evaluated and hence need to be re-evaluated for each section.

Wave Excitation Component

This module calculates the vertical shear forces and bending moment components due to the incident wave excitation forces.

The section wave excitation loading in heave, e_3, is given by (Salvesen et al. 1970, Equation 73):

$$e_3 = f_3 + h_3 \qquad (86)$$

Here the Froude-Krilov force, f_3, and the wave diffraction force, h_3, as calculated in the hydrodynamics module, include the wave amplitude and water density factor $\varsigma\rho$.

The shear force at section x_0 is calculated by integrating the loading forward of the section of interest and adding a speed dependent term. Thus the shear force due to the wave excitation is given by:

$$E_3 = \int_{x_0}^{x_{bow}} e_3 d\xi + \left[\frac{U}{i\omega} h_3(x_0)\right] \qquad (87)$$

The bending moment at section x0 is given by (Salvesen et al. 1970, Equation 74):

$$E_5 = \int_{x_0}^{x_{bow}} e_5 d\xi \qquad (88)$$

where e_5 is given by:

$$e_5(x_0) = (x_0 - \xi)(f_3 + h_3) + \frac{iU}{\omega} h_3 \qquad (89)$$

f_3	2D section Froude-Krilov wave force in heave.
h_3	2D section diffraction wave force in heave.
ω	encounter frequency.
ξ	longitudinal distance from LCG.
x_0	longitudinal position of section of interest.

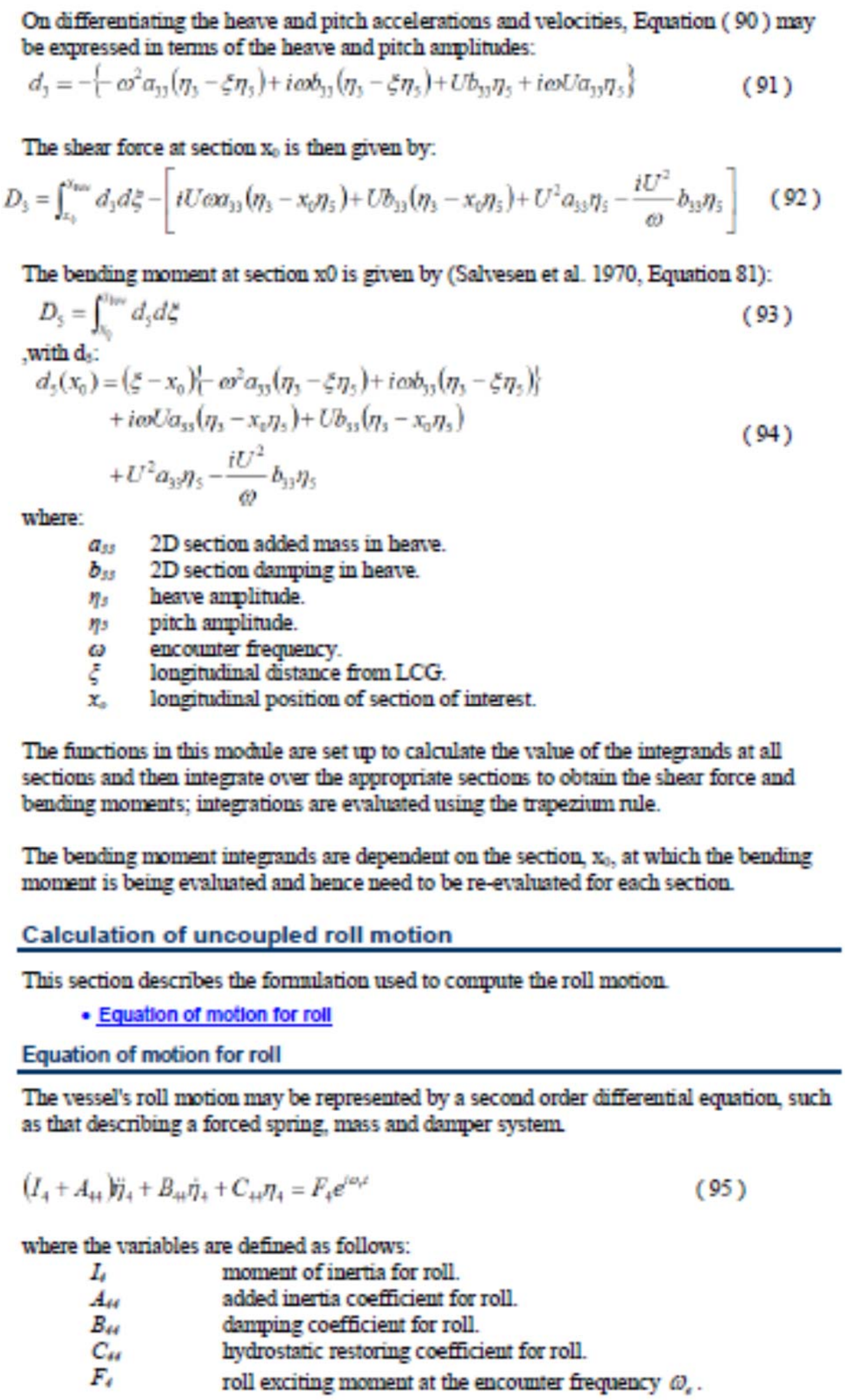
The functions in this module are set up to calculate the value of the integrands at all sections and then integrate over the appropriate sections to obtain the shear force and bending moments; integrations are evaluated using the trapezium rule.
The bending moment integrands are dependent on the section, x_0, at which the bending moment is being evaluated and hence need to be re-evaluated for each section.

Hydrodynamic Component

This module calculates the vertical shear forces and bending moment components due to hydrodynamic forces.

The section hydrodynamic loading in heave, d3, is given by (Salvesen et al. 1970, Equation 79):

$$d_3 = -\left\{a_{33}(\ddot{\eta}_3 - \xi\ddot{\eta}_5) + b_{33}(\dot{\eta}_3 - \xi\dot{\eta}_5) - \frac{U}{\omega^2} b_{33}\ddot{\eta}_5 + U a_{33}\dot{\eta}_5\right\} \qquad (90)$$



On differentiating the heave and pitch accelerations and velocities, Equation (90) may be expressed in terms of the heave and pitch amplitudes:

$$d_3 = -\left\{-\omega^2 a_{33}(\eta_3 - \xi\eta_5) + i\omega b_{33}(\eta_3 - \xi\eta_5) + U b_{33}\eta_5 + i\omega U a_{33}\eta_5\right\} \qquad (91)$$

The shear force at section x_0 is then given by:

$$D_3 = \int_{x_0}^{x_{bow}} d_3 d\xi - \left[iU\omega a_{33}(\eta_3 - x_0\eta_5) + U b_{33}(\eta_3 - x_0\eta_5) + U^2 a_{33}\eta_5 - \frac{iU^2}{\omega} b_{33}\eta_5 \right] \qquad (92)$$

The bending moment at section x0 is given by (Salvesen et al. 1970, Equation 81):

$$D_5 = \int_{x_0}^{x_{bow}} d_5 d\xi \qquad (93)$$

,with d_5:

$$\begin{aligned} d_5(x_0) = (\xi - x_0)&\left\{-\omega^2 a_{33}(\eta_3 - \xi\eta_5) + i\omega b_{33}(\eta_3 - \xi\eta_5)\right\} \\ &+ i\omega U a_{33}(\eta_3 - x_0\eta_5) + U b_{33}(\eta_3 - x_0\eta_5) \\ &+ U^2 a_{33}\eta_5 - \frac{iU^2}{\omega} b_{33}\eta_5 \end{aligned} \qquad (94)$$

where:

a_{33}	2D section added mass in heave.
b_{33}	2D section damping in heave.
η_3	heave amplitude.
η_5	pitch amplitude.
ω	encounter frequency.
ξ	longitudinal distance from LCG.
x_o	longitudinal position of section of interest.

The functions in this module are set up to calculate the value of the integrands at all sections and then integrate over the appropriate sections to obtain the shear force and bending moments; integrations are evaluated using the trapezium rule.

The bending moment integrands are dependent on the section, x_0, at which the bending moment is being evaluated and hence need to be re-evaluated for each section.

Calculation of uncoupled roll motion

This section describes the formulation used to compute the roll motion.

- Equation of motion for roll

Equation of motion for roll

The vessel's roll motion may be represented by a second order differential equation, such as that describing a forced spring, mass and damper system.

$$(I_4 + A_{44})\ddot{\eta}_4 + B_{44}\dot{\eta}_4 + C_{44}\eta_4 = F_4 e^{i\omega_e t} \qquad (95)$$

where the variables are defined as follows:

I_4	moment of inertia for roll.
A_{44}	added inertia coefficient for roll.
B_{44}	damping coefficient for roll.
C_{44}	hydrostatic restoring coefficient for roll.
F_4	roll exciting moment at the encounter frequency ω_e.

η_4	instantaneous roll displacement.
$\dot{\eta}_4$	instantaneous roll velocity.
$\ddot{\eta}_4$	instantaneous roll acceleration.

It may be shown that the solution to the above equation is given by:

$$\eta_4 = \frac{F_4}{\sqrt{\left(C_{44} - (I_4 + A_{44})\omega_e^2\right)^2 + B^2\omega_e^2}}\cos(\omega_e t + \varepsilon)$$

where: ε is the phase lag relative to the forcing function: $\tan\varepsilon = \dfrac{B_{44}\omega_e}{C_{44} - (I_4 + A_{44})\omega_e^2}$

This equation may be re-expressed in terms of the damping ratio,

$\beta_{44} = \dfrac{B_{44}}{2\sqrt{C_{44}(I_4 + A_{44})}}$, the natural frequency of the system, $\omega_0 = \sqrt{\dfrac{C_{44}}{(I_4 + A_{44})}}$, and

the tuning factor, $\lambda = \dfrac{\omega_e}{\omega_0}$.

As an aside, it may be shown (by differentiation of the RAO function) that the damped natural frequency is given by:

$$\omega_{0damped} = \omega_0\sqrt{1 - 2\beta^2}$$

The roll transfer function or response function is then assumed to be given by:

$$\mathrm{RAO}_{Roll} = \frac{\eta_4 C_{44}}{F_4} = \frac{1}{\sqrt{\left(1 - \lambda^2\right)^2 + 4\beta_{44}^2\lambda^2}}$$

Strictly speaking this is the roll motion transfer function with regard to wave force and not wave slope, however, the two are assumed to be the same.

The RAO is then modified for wave heading and apparent wave slope so that the RAO at off head seas is given by:

$$\mathrm{RAO}_{Roll}(\mu) = \mathrm{RAO}_{Roll}\sin(\mu)$$

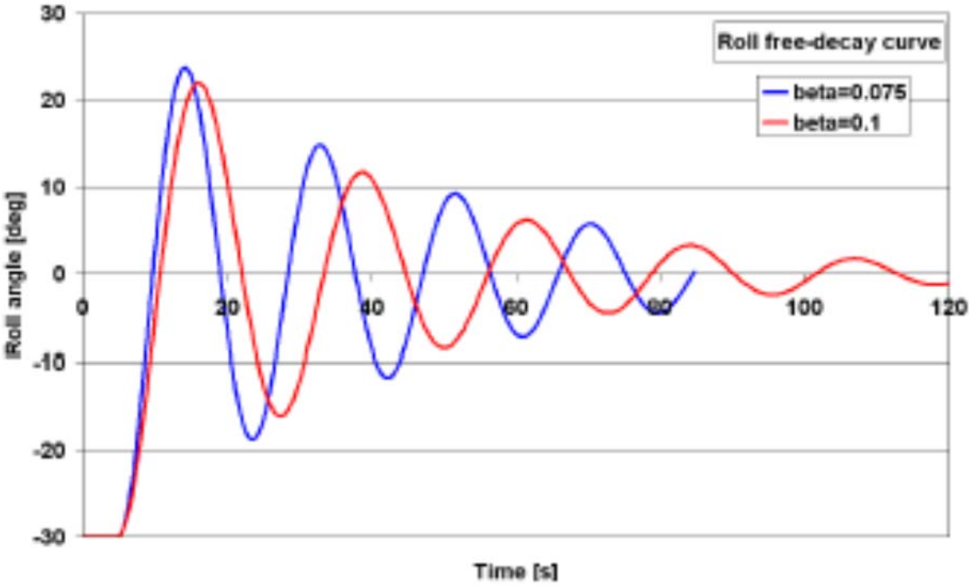
thus the roll RAO is zero in head and following seas and has a maximum in beam seas.

In MAXSURF Motions the required parameters are determined as follows:

I_4	mass inertia of vessel in roll $I_4 = k_{xx}^2\nabla\rho$, k_{xx} input by user
A_{44}	added inertia coefficient for roll $A_{44} = 0.3I_4$, this is an average of values from Vugts (1968) and Lloyd (1998)
β_{44}	Non-dimensional damping coefficient for roll, input by user.
C_{44}	hydrostatic restoring coefficient for roll $C_{44} = GM_t\nabla\rho g$, VCG input by user

Roll free-decay test

If experimental facilities are available, the roll damping can be obtained from a free-decay test of the roll motions. The vessel is heeled over to one side and released, the roll amplitude is measured and plotted against time. The figure below shows the theoretical free-decay of two vessels with different damping coefficients.



Free-decay time series for two vessels released from an initial heel angle of 30 degrees

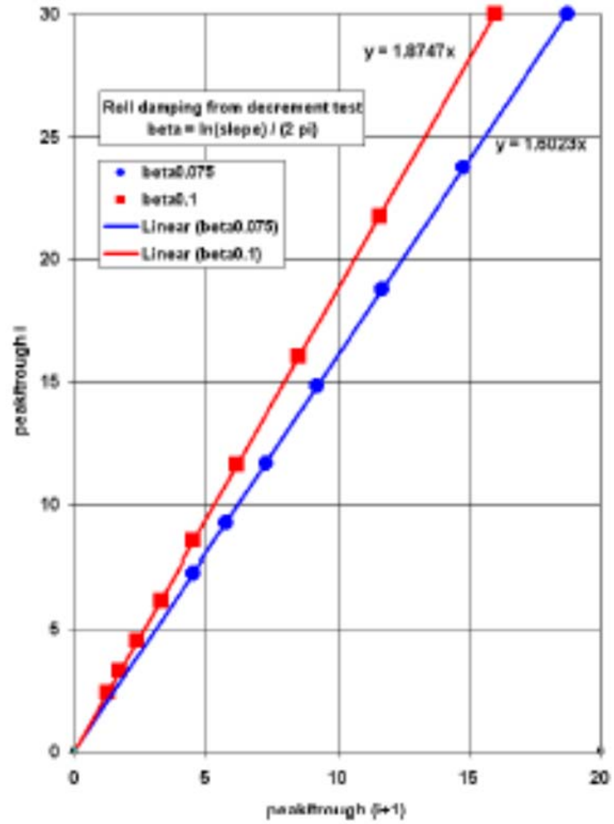
By plotting the value of one peak against the value of the next peak (the same can also be done for the troughs to obtain more data), the roll damping can be derived.

Peak/trough amplitudes for beta 0.075 vessel

beta0.075	peak/trough i	peak/trough i+1
trough 1	30.000	18.755
peak 1	23.752	14.808
trough 2	18.755	11.692
peak 2	14.808	9.231
trough 3	11.692	7.289
peak 3	9.231	5.754
trough 4	7.289	4.544
peak 4	5.754	
trough 5	4.544	

Peak/trough amplitudes for beta 0.1 vessel

beta0.1	peak/trough i	peak/trough i+1
trough 1	30.000	16.001
peak 1	21.745	11.646
trough 2	16.001	8.519
peak 2	11.646	6.183
trough 3	8.519	4.518
peak 3	6.183	3.285
trough 4	4.518	2.405
peak 4	3.285	1.747
trough 5	2.405	1.279
peak 5	1.747	
trough 6	1.279	



Plot of peak amplitude against peak amplitude of next peak. In this example, data for both peaks and troughs have been plotted

The non-dimensional roll damping parameter used in MAXSURF Motions, β_{44}, is given by:

$$\beta_{44} = \frac{\ln(\text{slope})}{2\pi}$$

Thus for the beta0.075 vessel, the slope is 1.6023, giving a damping of 0.075 (as expected); similarly for the beta0.1 vessel, the slope is 1.8747 giving a damping of 0.100.

The free-decay roll test can be simulated in MAXSURF Motions by choosing Roll decay simulation option in the Analysis | Calculate Wave Surface dialog, then choosing Display | Animate and saving the time-series to a file:

1