

Naval Surface Warfare Center Carderock Division

West Bethesda, MD 20817-5700

NSWCCD-65-TR-2000/07 March 2000

Survivability, Structures, and Materials Directorate
Technical Report

User's Guide for SPECTRA: Version 8.3

by

Robert W. Michaelson

NSWCCD-65-TR-2000/07 User's Guide for SPECTRA: Version 8.3

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DEPARTMENT OF THE NAVY

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From: Commander, Naval Surface Warfare Center, Carderock Division

To: Commander, Naval Sea Systems Command (SEA 05R2)

Subj: PREDICTION OF EXTREME AND LIFETIME EXCEEDANCE PRIMARY HULL
GIRDER BENDING LOADS

Ref: (a) Program Element 0603563NB, Reliability Based Design Criteria for Surface Ships,
Project S2196-00, Subtask I-G for FY2000.

Encl: (1) NSWCCD-65-TR-2000/07, *User's Guide for SPECTRA: Version 8.3*

1. Reference (a) requested the Naval Surface Warfare Center, Carderock Division (NSWCCD) to document the SPECTRA computer program for predicting extreme and lifetime exceedance primary hull girder bending loads. Enclosure (1) contains the basic instructions for running SPECTRA program, with suggestions for suitable input data.

2. Comments or questions may be referred to Mr. Robert W. Michaelson, Code 651; telephone (301) 227-4200; e-mail, MichaelsonRW@nswccd.navy.mil.

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Enclosure (1)

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14. ABSTRACT SPECTRA is a Windows-based computer program for predicting extreme and lifetime exceedance primary hull girder bending loads. Extreme loads can be used for reliability-based strength design criteria, and exceedance loads can be used for fatigue strength design criteria. Loads are calculated based upon ship geometry, the sea conditions, and operating characteristics of the ship as specified by the user. This User's Guide contains the basic instructions for running SPECTRA program, with suggestions for suitable input data.					
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Administrative Information

The work reported herein was performed in the Structures and Composites Department (Code 65) of the Survivability, Structures, and Materials Directorate. This work was sponsored by the Naval Sea Systems Command under the direction of Mr. Jeffrey Hough (SEA 05R2). It is part of the Reliability Based Design Criteria for Surface Ships Task (PE63563N, Project S2196-00) and supports Subtask I-G.

Acknowledgements

The SPECTRA computer program represents many years of data gathering, processing, and formulating ship model tests and sea trials. This work began years before the author began working at Carderock, and hopefully will carry on. Mr. Jerome Sikora wrote the original version of SPECTRA over two decades ago, and continues to direct its development. Many people have contributed to the current version of SPECTRA, most notably Mr. Jack Birmingham, Mr. John Andrews, and Mr. Alfred Dinsenbacher. More recent contributors are Mr. Jeffrey Beach, Mr. Thomas Brady, Mr. John Dalzell, Mr. William Hay, Dr. David Kihl, and Mr. Richard Lewis. Finally, the support of Mr. Allen Engle (formerly of NAVSEA 05, now at the Carderock Division), Mr. Jeff Hough, and Mr. Mike Sieve of NAVSEA 05 is greatly appreciated.

Overview

SPECTRA computes vertical, lateral, and torsional moments applied to the hull girder of a monohull ship, as described by Sikora^{i,ii}. Computations are based on the input parameters specified by the user. All inputs are located in the left frame of a file window, and output is displayed in the right frames, as shown in the Figure 1. SPECTRA uses a Multiple Document Interface (MDI), so many files can be open simultaneously – which makes comparison of inputs easy.

Inputs describe the general characteristics of the ship, and the type of environment in which the ship will operate. Outputs can be displayed as a graph, text, or both, which show the expected loads, based on the specified inputs.

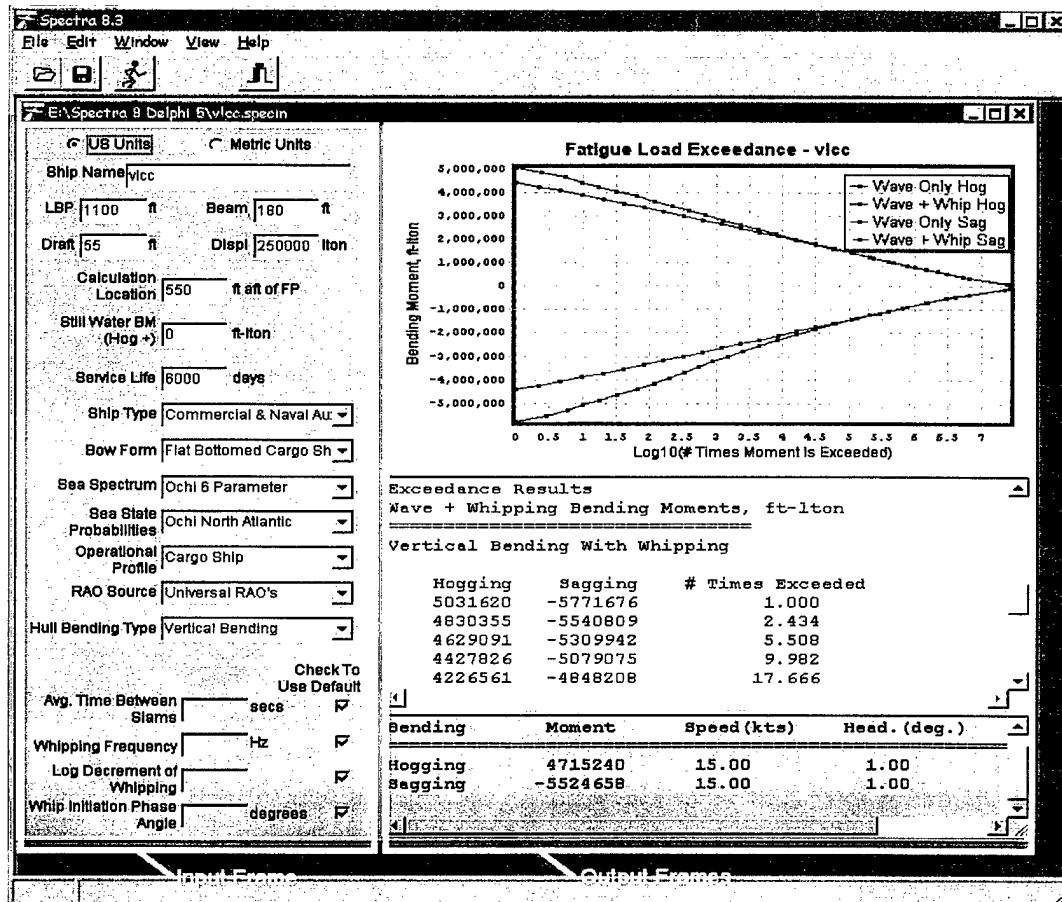


Figure 1 - SPECTRA User Interface

Installation

SPECTRA will run on Windows 95, 98, or NT – based PCs. For installation, contact either:

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SPECTRA Input

Ship Dimensions

Units: Select either U.S. or Metric.

LBP (ft. or m.): Length Between Perpendiculars – the length of the ship between the fore and aft perpendiculars. The fore perpendicular is the vertical line at the intersection of the fore side of the stem and the waterline. The aft perpendicular is the vertical line at the intersection of the summer load line and the aft side of the rudder post or sternpost, or the centerline of the rudder stock if there is no rudder post or stern post.

Beam (ft. or m.): The maximum breadth of the hull at or below the waterline.

Draft (ft. or m.): The depth of the ship below the waterline measured vertically to the lowest part of the hull proper (excluding sonar domes, appendages, etc.). For input into SPECTRA, this should be the mean draft of the hull (the average between the fore and aft drafts).

Displacement (lton. or mton.): The weight of the ship.

Calculation Location

The calculation location is the ship section at which the bending moments will be determined when SPECTRA is run. This location is specified as a distance (ft. or m.) aft of the forward perpendicular.

Still Water Bending Moment

The still water bending moment is the vertical bending moment of the ship in calm seas. The still water bending moment input for SPECTRA should coincide with the calculation location input. The still water bending moment is typically calculated

from programs such as Ship Hull Characteristics Program (SHCP).

Service Life

The service life is the expected number of days that the ship will be at sea. Historically, Navy ships have spent about one third of their life at sea. In the future, Navy ships are likely to spend about two thirds of their life at sea, due to fewer ships in the Fleet. So, for a 30-year ship life, about 7300 days will be spent at sea. If available, the ship's Operational Requirements Document should be consulted to determine service life and percent operability.

Commercial ships normally spend a higher percentage of their life at sea than Navy ships. This percentage can vary depending on the ship type and service. Typical service for commercial ships can be 300 or more days at sea per year.

With increasing sea time, the maximum lifetime bending moment does not increase much, but cycles at lower bending moments does. Thus fatigue cracks are more likely than hull girder failure if actual sea time exceeds the expected time at sea.

Ship Type

The ship type selection affects the magnitude of the wave-induced moments calculated within SPECTRA. Options of ship type listed within SPECTRA are:
Commercial & Naval Auxiliaries – typical commercial ships and Navy auxiliaries that operate at lower speeds and have a fuller hull form.

Amphibious Assault – ships such as LHA, LHD, LPD classes.

Aircraft Carriers – aircraft carriers such as CV and CVN classes.

Frigates – Navy frigates such as FFG and FF classes.

DD-963 & CG-47 Class – specifically for the DD-963 or CG-47 classes.

DDG-51 Class – specifically for the DDG-51 class.

Other Destroyers & Cruisers – destroyers or cruiser not of the DD-963, DDG-51, or CG-47 classes.

Bow Form

The bow form selection affects the whipping of the ship. Waves impacting on the bow of the ship can cause whipping. Thus, the shape of the bow, and the presence of

bulbs or sonar domes can affect the magnitude of whipping moments for vertical and lateral bending.

Options of bow form listed within SPECTRA are:

Fine Bow Frigate with V-Bow - ships such as FFG-7 class.

Fine Bow Frigate or Destroyer with Bow Dome - ships with fine bows and bulbs or domes at the bow.

Flared Bow Cruiser with Bow Dome - ships such as CG-47 class.

Flat Bottomed Cargo Ship - typical form of a tanker, oiler, or bulk carrier.

Amphibious Ship with Large Bow Flare - ships such as the LHD-1 and LHA-1 classes.

Aircraft Carrier with Large Bow Flare - aircraft carriers.

Sea Spectrum

The sea spectrum is a mathematical description of the seaway in which the ship will operate. A sea spectrum characterizes the height and length of the waves in the frequency domain. Options of sea spectrum listed within SPECTRA are:

Pierson-Moskowitz – The Pierson-Moskowitz spectrum represents a "fully-developed" sea, meaning that fetch and duration are large, and there is no contamination from additional swells in the area. This sea spectrum is probably not appropriate for design use. It may be appropriate for extreme storm conditions.

Ochi 6 Parameter – The six parameters of the Ochi formulation generate a family of eleven spectral shapes for a given wave height. These shapes depict rising and fully developed seas as well as double-peaked spectra that occur when fresh, high-frequency seas occur in the presence of low-frequency swells. The Ochi spectrum was derived from North Atlantic data; it is recommended for design and for determining likely bending moments of ship structures in use in the North Atlantic.

North Atlantic 2 Parameter – The North Atlantic 2 Parameter spectrum is a form of the Bretschneider spectrum, with modal wave periods determined within the SPECTRA program. There are nine spectral shapes, each with an associated modal period for each wave height. The spectral shapes have the same area under the spectrum, but different peak energies. The North Atlantic 2 parameter spectrum has

the same limitations of the Bretschneider spectrum.

Bretschneider – The Bretschneider spectrum allows for input of joint probabilities of wave height and modal period. The Bretschneider input form (Figure 2) appears, when the Bretschneider option is chosen from the sea spectrum drop-down list.

		Modal Wave Period (seconds)							
		3.25	7.79	10.39	12.99	15.58	18.18	20.78	23.38
Number of wave periods: (20 max)	0.5	0.0209	0.0118	0.0046	0.0022	0.0005	0.0001	0.0000	0.0006
	1.5	0.0728	0.1311	0.0631	0.0173	0.0024	0.0003	0.0001	0.0008
	2.5	0.0212	0.1264	0.1183	0.0302	0.0037	0.0005	0.0001	0.0006
	3.5	0.0033	0.0496	0.0927	0.0330	0.0055	0.0007	0.0001	0.0003
	4.5	0.0005	0.0162	0.0444	0.0223	0.0048	0.0011	0.0001	0.0003
	5.5	0.0001	0.0043	0.0173	0.0129	0.0031	0.0006	0.0001	0.0000
	6.5	0.0001	0.0029	0.0099	0.0089	0.0030	0.0006	0.0001	0.0000
	7.5	0.0000	0.0014	0.0045	0.0052	0.0019	0.0004	0.0000	0.0000
	8.5	0.0000	0.0011	0.0026	0.0039	0.0020	0.0005	0.0000	0.0000
	9.5	0.0000	0.0005	0.0014	0.0023	0.0015	0.0007	0.0002	0.0000
	10.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
	11.5	0.0000	0.0000	0.0000	0.0001	0.0002	0.0001	0.0000	0.0000
	12.5	0.0000	0.0001	0.0000	0.0001	0.0002	0.0001	0.0000	0.0000
	13.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000
	14.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
	15.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 2 - Bretschneider Input Form

Some details of the Bretschneider input form:

- Number of Wave Periods - The number of wave periods must be defined before the modal periods can be input.
- Modal Period - The modal period is the most likely wave period for a given wave height. Modal wave periods should be entered in the top row.
- Joint Probabilities - The joint probabilities represent the probability of a wave height and modal period occurring simultaneously. Ideally, the sum of all the probabilities should be one. However, SPECTRA does not explicitly check this. Joint probabilities of wave height and modal period should be entered in the body of the table.
- File Open and Save - Bretschneider files can be saved and re-opened for future

use. The “File” drop-down menu has file open and save choices.

The Bretschneider sea spectrum can be useful if the joint wave height and modal period probabilities are known for the operating area. However, it is limited in its ability to model seas in which high frequency waves (such as recently generated wind waves) occur in conjunction with long swells from a distant disturbance, which happens frequently.

Sea State Probabilities

Sea state probabilities represent the likelihood of the occurrence of certain wave heights. Within SPECTRA, wave heights are divided into 16 bands at 1-meter intervals. Thus the wave height bands in meters are, 0-1, 1-2, 2-3,...,15-16. Each wave height band is assigned a probability of occurrence, with the sum of the 16 probabilities being equal to 1. Ship operational requirements will dictate this choice, and should be consulted if available. SPECTRA has the following options for choosing sea state probabilities:

Ochi North Atlantic - Probabilities were obtained from wave buoy data at Station-I in the North Atlantic in the Greenland-Iceland gap. This is a severe set, with high probabilities for large waves.

General Atlantic - Probabilities are a combination of the Ochi North Atlantic with data from the Caribbean, Mediterranean, and Atlantic between the U.S. east coast, and Spain.

General Pacific - Probabilities assume equal amounts of time off the U.S. west coast, Hawaiian Islands, south of the Aleutian Islands, and around Japan.

NATO North Atlantic - Probabilities based on expected convoy routes between U.S. and Europe.

Data File - The user can recall a data file where previously saved wave height probabilities are stored.

User Input - The user can interactively input wave height probabilities, and save them to a file if desired.

Sea state probability files are simple text files that can be created or modified in an ASCII text editor. Below is a sample of a sea state probability file.

Spectra 8.0 Sea State Probabilities
 0.087
 0.192
 0.220
 0.157
 0.124
 0.080
 0.052
 0.039
 0.025
 0.013
 0.007
 0.004
 0.000
 0.000
 0.000
 0.000

Each wave height band is assigned a probability. The wave height probabilities are assigned sequentially within the program. So, for the above file:

0.087 is the probability of waves 0-1 meter high occurring,
 0.192 for waves 1-2 meters,
 0.220 for waves 2-3 meters, and so on.

If desired, you can input your own sea state probabilities. The input form (Figure 3) will pop-up if "User Input" is chosen in the Sea State Probabilities list box. Fill in the probability associated with each wave height, so that all of the probabilities sum to one. Once you have input the probabilities, you can save them to a sea state probability file for reuse.

Wave Ht-meters	Probability	Wave Ht-meters	Probability
0-1	<input type="text"/>	8-9	<input type="text"/>
1-2	<input type="text"/>	9-10	<input type="text"/>
2-3	<input type="text"/>	10-11	<input type="text"/>
3-4	<input type="text"/>	11-12	<input type="text"/>
4-5	<input type="text"/>	12-13	<input type="text"/>
5-6	<input type="text"/>	13-14	<input type="text"/>
6-7	<input type="text"/>	14-15	<input type="text"/>
7-8	<input type="text"/>	15 plus	<input type="text"/>

Figure 3 – Sea State Probability User Input Form

The built-in sea state probability options within the SPECTRA program should offer enough flexibility to model typical operating areas. The "User Input" and "Data File" choices give the

option for the user to add custom sea state probabilities if necessary.

Operational Profile

SPECTRA requires information on how a ship operates, given specific sea conditions. This information is provided in the operational profile. The ship's operation is divided into cells of ship speed, ship heading relative to wave direction, and wave height. Each cell is assigned a probability, which represents the fraction of the ship's life that will be spent in that operational cell. SPECTRA includes a number of built-in operational profiles. The user can also recall an operational profile data file of his/her choice if desired.

The choices within SPECTRA are listed below:

Combatant, Cargo Ship, Aircraft Carrier - Based on dialogue with ship operators on how the operators felt their ships operate in certain wave conditions. Headings relative to the waves are at 45-degree intervals (i.e., head, bow, beam, quartering, and following seas).

30-60 headings, 5-15-25 speeds - Modified combatant profile to include headings relative to the wave direction of 30 and 60 degrees. Lateral bending and torsion are most severe at a wave direction of 60 degrees. If calculating lateral bending or torsion of a combatant, this is the recommended operational profile.

Integrated Profiles for Combatant, Amphibious or Fast Cargo, Carrier, Auxiliary or Slow Cargo - These operational profiles are based on the operational profiles compiled by Michaelson with some "engineering judgement." The lower sea states assume random distribution of ship heading relative to the waves. The higher sea states use some interpretation, since there are very little data in higher sea states to form definitive conclusions. The integrated profiles adhere to the probabilities of the speed ranges from the Michaelson report.

Michaelson Profiles for Combatant, Amphibious or Fast Cargo, Carrier, Auxiliary or Slow Cargo - Michaelsonⁱⁱⁱ compiled over 90,000 shipboard weather observations taken by ship personnel on a variety of U.S. Navy ships. These observations were processed into operational profiles, with fairly strict adherence to the observed data.

Data File - The user can select an operational profile for further customization. Operational profile files are simple text files that can be created or modified using an

ASCII text editor. Below is a sample operational profile file.

```

Spectra Operational Profile Data
'Auxiliaries and Commercial Ships
'number of speeds
2
'number of headings
5
'number of wave heights
3
'mean speeds - knots
5, 15
'mean headings - degrees off bow - 0 is head seas
0, 45, 90, 135, 180
'wave ht band definitions -
'wave hts defined in meters, up to 16 meters high max
'in 1 meter intervals (integers)
'band 1 -
1,5
'band 2 -
6,10
'band 3 -
11,16
'operational probabilities
'speed, heading, prob per wave height-
'given that the ship is operating in the given wave height,
'what is the probability of operating at the specified
'speed and heading
'spd hdg wvht1 wvht2 wvht3
5, 0, 0.0100, 0.1250, 0.1750
5, 45, 0.0200, 0.1250, 0.1750
5, 90, 0.0200, 0.0625, 0.0875
5, 135, 0.0200, 0.1250, 0.1750
5, 180, 0.0100, 0.0625, 0.0875
15, 0, 0.1150, 0.1250, 0.0750
15, 45, 0.2300, 0.1250, 0.0750
15, 90, 0.2300, 0.0625, 0.0375
15, 135, 0.2300, 0.1250, 0.0750
15, 180, 0.1150, 0.0625, 0.0375

```

In the above file, lines that begin with an apostrophe (') are comments that will be disregarded by SPECTRA. The order of data in the file is important, and should be adhered to as the comments in the listing above describe.

The operational profile is probably the most ambiguous entry in SPECTRA. The operational profiles from Michaelson represent the most thorough attempt at determining this piece in the puzzle. However, the source of the data (shipboard weather observations) is by its nature open to human interpretation, and thus some judgement and possible modification of this data may be warranted. The "integrated" operational profile options represent a "best guess" interpretation of the Michaelson profiles. Without further study, the manner in which ships actually operate in various sea conditions will remain open to scrutiny.

Response Amplitude Operators (RAOs)

Response amplitude operators are transfer functions dependent upon the ship and operating conditions. The seaway provides input into the ship. Output from the system is the ship loads. RAOs mathematically represent the means by which the input (seaway) produces the output (bending moments).

Two choices for RAO source are listed - Universal RAOs, or Data File. Currently, SPECTRA only allows the use of Universal RAOs. The Universal RAOs are generated from algorithms that are based on data from model tests and full-scale trials.

The data file option is still under construction.

Bending Type

Ships can be bent in the vertical (hog and sag) and lateral planes of the hull girder.

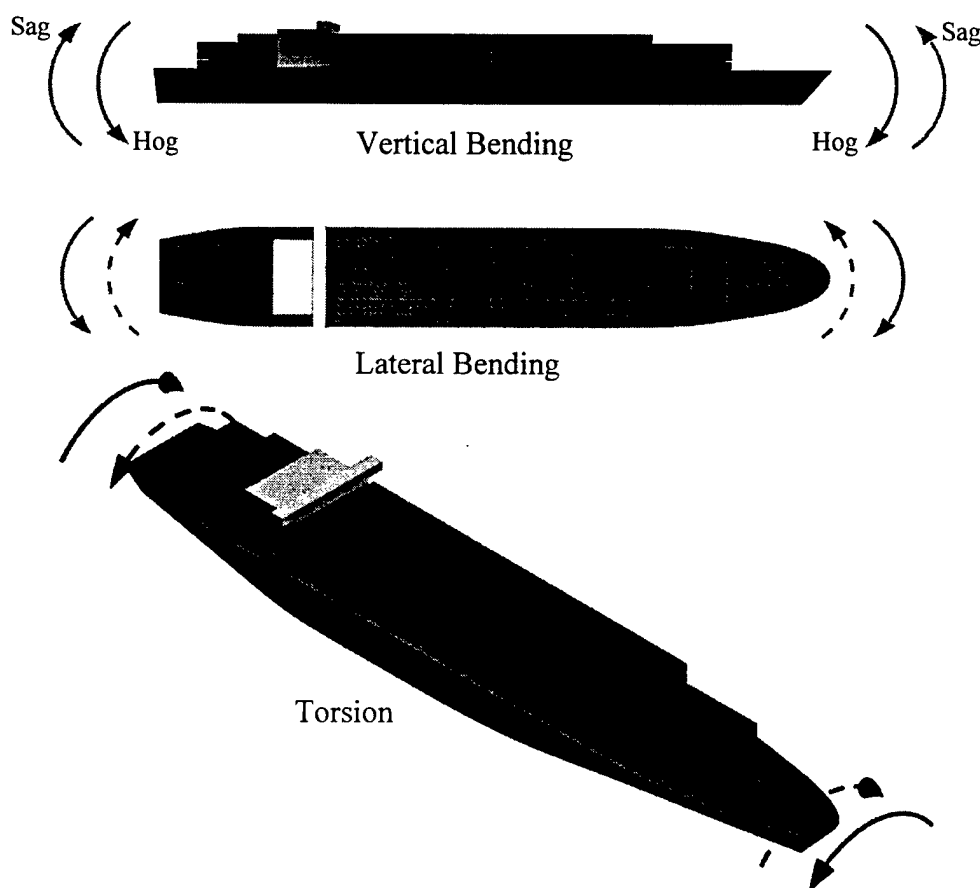


Figure 4 – Bending Moment Types

Also, the ship can be twisted about its longitudinal axis (torsion). SPECTRA has choices for determining vertical, lateral and torsional bending moments on the ship hull girder. Figure 4 shows the direction of the bending moment types.

Whipping

Hull girder whipping is a vibration of the overall hull girder due to waves slamming on the bow of the ship. SPECTRA can calculate the whipping contribution to ship loads for vertical and lateral bending. Torsional whipping has not been found to be significant and thus is not included in SPECTRA.

Bottom Slamming: One typical slam event occurs from the sea impacting on the bottom of the ship at the bow, after the bow has emerged from the water during severe pitching. Ships with a flat bottom far forward tend to have more severe bottom slamming compared to ships with a V-shaped bow.

Bow Flare Slamming: Another slam event occurs from waves hitting the flared portion of the bow above the waterline as the bow pitches down into the waves. Ships with large bow flare will have more severe bow-flare slamming than ships with a fine bow above the waterline. The presence of a bow bulb or sonar dome at the bow can also affect the magnitude of whipping bending moments. The Bow Form input has several options that characterize the bow shape.

SPECTRA allows for manual input of several items for control of the whipping parameters, which are listed below.

Average Time Between Slams

The average time between slams is the amount of time between slam events, provided that the ship is operating in conditions where slamming can occur.

SPECTRA will compute an average time in seconds between slam events unless one is input here. Slam rates can vary from about 20 to 40 slams per hour, depending on the ship and operating conditions.

Whipping Frequency

After a slamming event, the hull girder will vibrate at its natural frequency.

SPECTRA will estimate the hull girder natural frequency if the user does not provide one.

Vertical Bending: SPECTRA uses a simple equation based on length:

$$f_v = 302 / L^{0.884} = \text{vertical bending natural frequency (hertz)}.$$

A more sophisticated equation based on beam theory for vertical bending is:

$$f_v = 2.7 (EI_L g / (\Delta L^3))^{0.5} = \text{vertical bending natural frequency (hertz)}.$$

E = modulus of elasticity of the material (long tons per in²)

I = vertical moment of inertia of the hull girder (in²ft²)

g = acceleration due to gravity = 32.2 ft/sec²

Δ = displacement (long tons)

In the preliminary design stages, the designer does not usually know the moment of inertia, though. If "I" is known, then the user can input the calculated f_v .

Lateral Bending: As with vertical bending, SPECTRA uses a simple equation based on length:

$$f_L = 400 / L^{0.884} = \text{lateral bending natural frequency (hertz)}.$$

A more sophisticated equation based on beam theory for lateral bending is:

$$f_L = C_L (EI_L g / (\Delta L^3))^{0.5} = \text{vertical bending natural frequency (hertz)}.$$

C_L = lateral frequency coefficient, taken as 2.55ⁱ

E = modulus of elasticity of the material (long tons per in²)

I_L = lateral moment of inertia of the hull girder (in²ft²)

g = acceleration due to gravity = 32.2 ft/sec²

Δ = displacement (long tons)

Log Decrement of Whipping

The log decrement of whipping quantifies the decrease of the hull girder whipping vibration with time, due to damping (mainly hydrodynamic).

SPECTRA computes the log decrement as $52 / L$ (L = length of the ship in feet) based on sea trial data, unless specified as input.

Whipping Phase Angle

The whipping phase angle defines the point along the time history of bending moment at which slam-induced whipping begins.

Vertical Bending: The reference point for the whipping initiation phase angle is taken

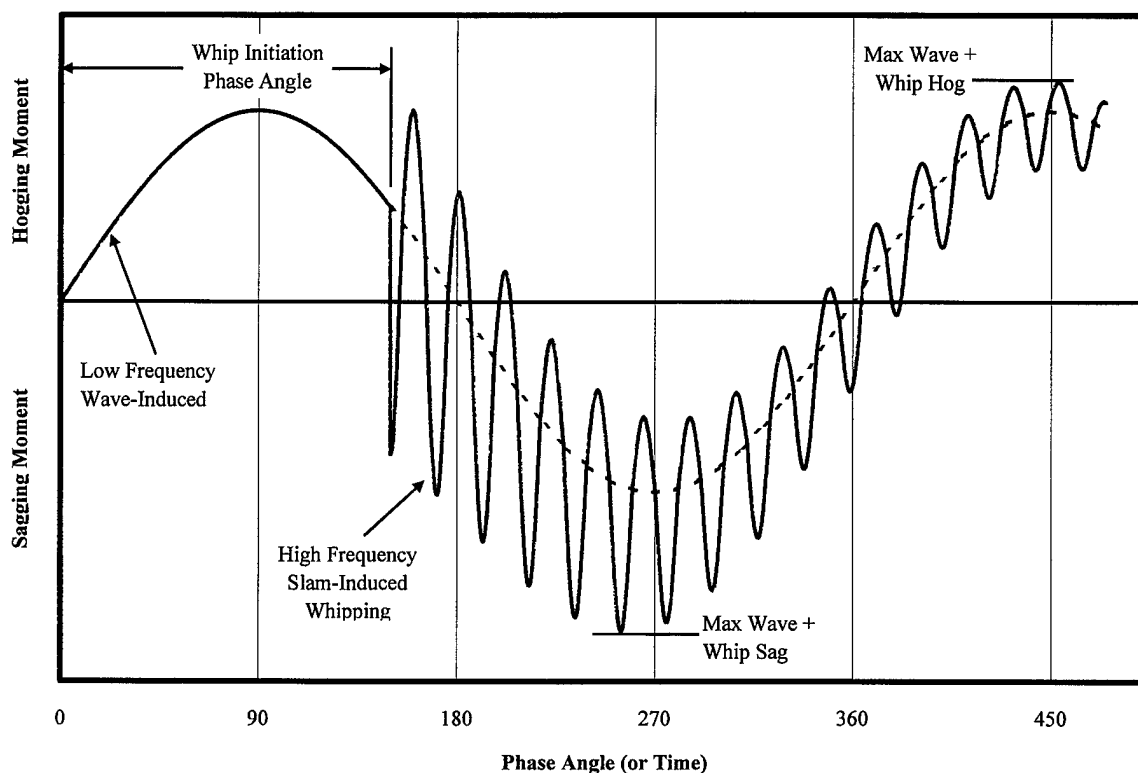


Figure 5 – History of Vertical Bending with Whipping

as the most recent zero up-crossing of the bending moment. Thus, in Figure 5, the whipping initiation phase angle is approximately 150 degrees.

Ship trials and model test data indicate that for hull bottom slamming, the whipping initiates at about 150 degrees. For bow flare slamming, a phase angle of 210 degrees may be appropriate. The default angle in SPECTRA is 150 degrees. Algorithms within SPECTRA are configured for vertical whipping initiation angles between 90 and 270 degrees. **If you input your own whip initiation phase angle, it should be between 90 and 270 degrees for vertical bending.**

Lateral Bending: The reference point for the whipping initiation phase angle is the most recent zero crossing of the bending moment. In Figure 6, the whipping initiation phase angle is roughly 70 degrees. There is little or no difference with the bending moment direction port to starboard as with vertical bending (hog vs. sag).

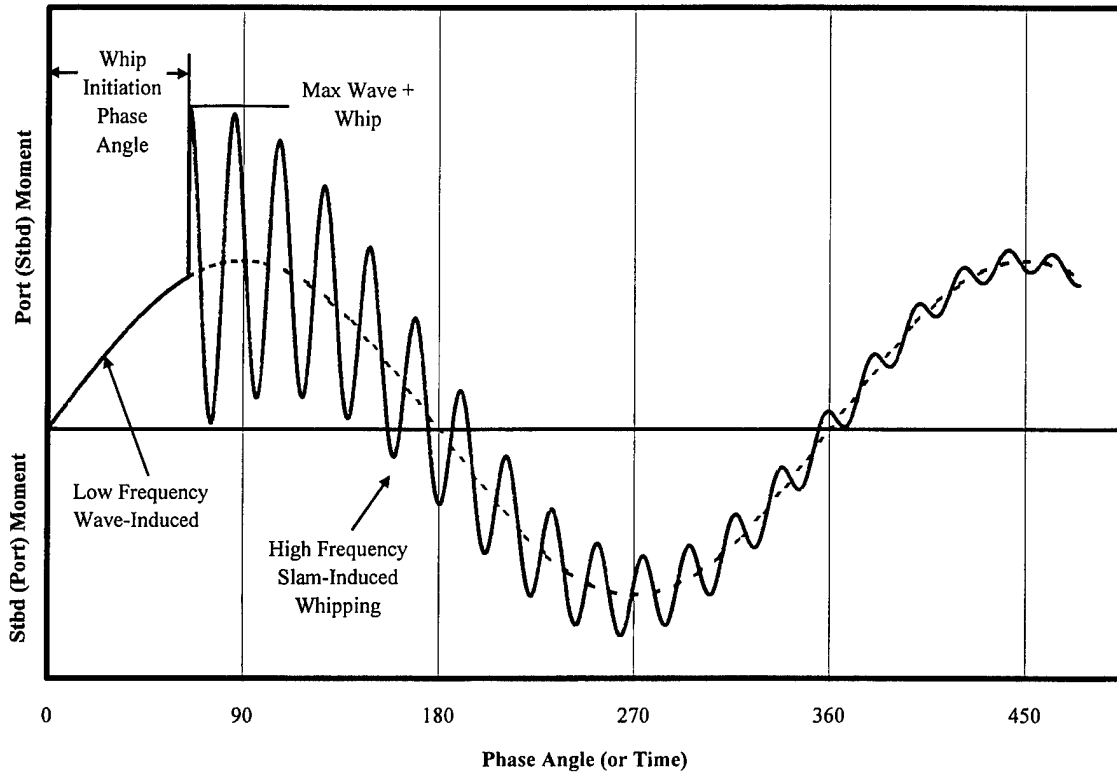


Figure 6 – History of Lateral Bending with Whipping

Ship trials and model test data show whipping initiation usually occurs just before the peak in a lateral bending moment cycle, with the default angle in SPECTRA being 68 degrees. **If you input your own whip initiation phase angle, it should be between 0 and 90 degrees for lateral bending.**

Running Input

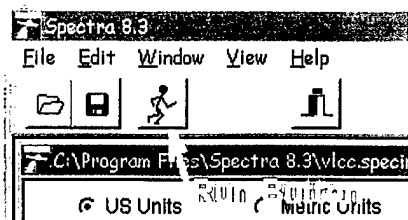


Figure 7 – Run Toolbar Buton

To perform calculations, the input data must be processed. Clicking the “running man” toolbar button at the top of the main window (Figure 7) generates output. If a change is made to the input, the output frames will be cleared, ensuring that

displayed output corresponds to the input. The input must also be complete for the run button to be activated.

SPECTRA Output

Output Overview

SPECTRA computes lifetime exceedance, histogram, and reliability information

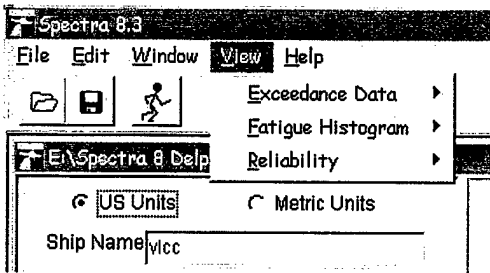


Figure 8 – View Menu for Output Selection

of hull girder bending moments. Exceedance and histogram results can be displayed in both graphical and text formats. The type of output to be displayed is designated from the View menu (Figure 8).

Figure 9 shows the typical output frames for vertical bending showing graphical and text

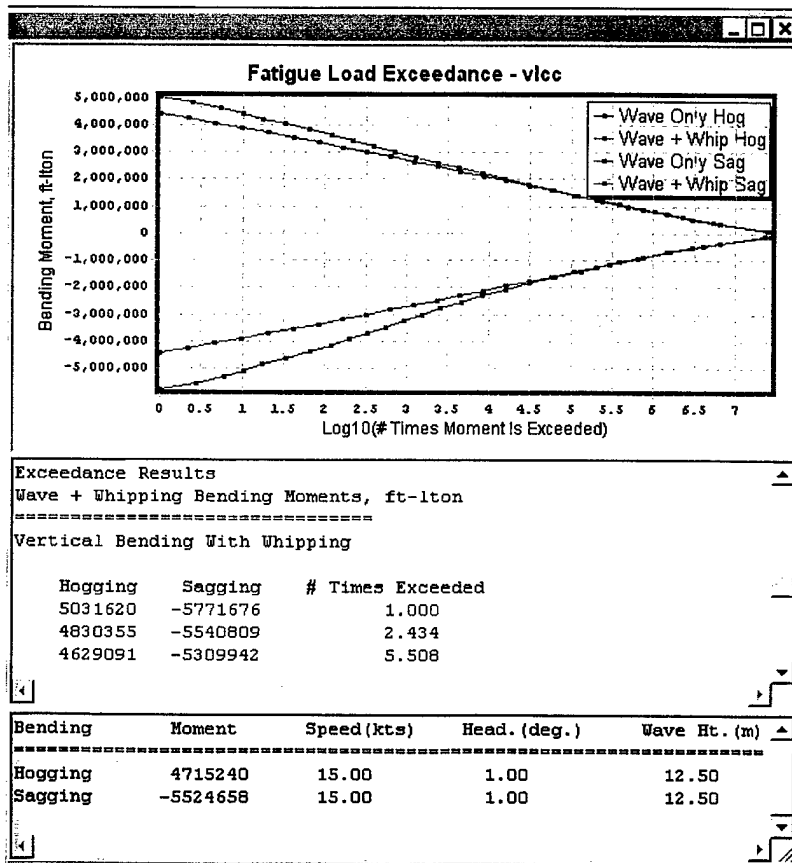


Figure 9 – SPECTRA Output

output. The bottom output frame always shows the operational cell in which the most severe bending moment occurs.

Exceedance Output

Exceedance output can be displayed graphically, as text, or both. Display of exceedance output is designated in the View menu of the main SPECTRA window

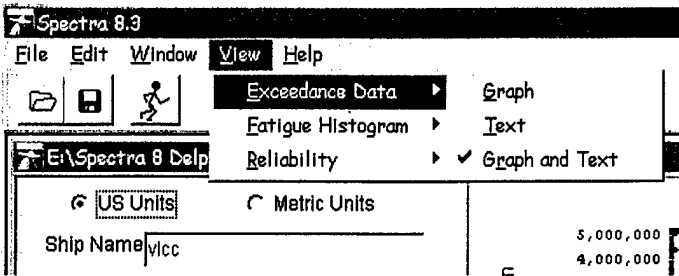


Figure 10 – Exceedance Output Menu Selection

(Figure 10). Exceedance output gives the number of times in the life of the ship that a bending moment is equaled or exceeded.

For vertical and lateral bending, wave-induced and wave plus whipping moments are displayed.

The screenshot shows a window titled 'Exceedance Results' with the following content:

```

Exceedance Results
Wave + Whipping Bending Moments, ft-lton
=====
Vertical Bending With Whipping

Hogging      Sagging      # Times Exceeded
5031620      -5771676      1.000
4830355      -5540809      2.434
4629091      -5309942      5.508
4427826      -5079075      9.982
4226561      -4848208      17.666
4025296      -4617341      32.565
3824031      -4386474      63.443
3622766      -4155607      119.614
3421502      -3924740      218.177
3220237      -3693873      390.743
3018972      -3463006      701.141
2817707      -3232139      1269.746
2616442      -3001272      2324.291
2415178      -2770405      4326.204
2213913      -2539537      8190.114
2012648      -2308670      15736.859
1811383      -2077803      30592.401
1610118      -1846936      60054.841
1408854      -1616069      118797.021
1207589      -1385202      237053.921
    
```

Below this table is a section titled 'Single Max Bending Cell - Vertical Bending' with the following table:

Bending	Moment	Speed (kts)	Head. (deg.)	Wave Ht. (m)
Hogging	4715240	15.00	1.00	12.50
Sagging	-5524658	15.00	1.00	12.50

Figure 11 – Exceedance Output, Text Format

For torsion, only wave-induced moments are output. Text output for exceedance is shown in Figure 11.

Fatigue Histogram Output

Fatigue histogram output can be displayed graphically, as text, or both. Display is designated in the View menu of the main SPECTRA window (Figure 12). Fatigue

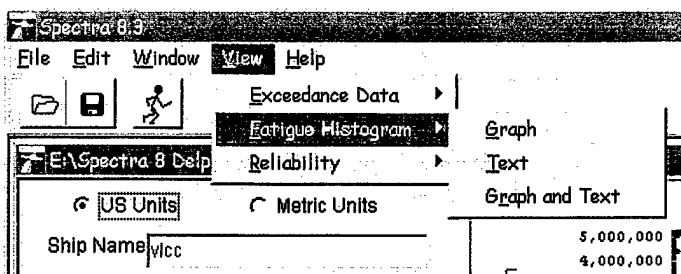


Figure 12 – Fatigue Histogram Output Menu Selection

histogram output gives the number of times in the life of the ship that a range of moments will occur, with the mid-range moment listed in the output. This is useful in predicting the fatigue behavior

Histogram Results				
Wave + Whipping Bending Moments, ft-lton				

Vertical Bending With Whipping				
Hogging	Sagging	# Cycles at Moment		
4930988	-5656243	1.434		
4729723	-5425376	3.074		
4528458	-5194508	4.474		
4327193	-4963641	7.684		
4125928	-4732774	14.899		
3924664	-4501907	30.878		
3723399	-4271040	56.171		
3522134	-4040173	98.563		
3320869	-3809306	172.566		
3119604	-3578439	310.398		
2918340	-3347572	568.605		
2717075	-3116705	1054.544		
2515810	-2885838	2001.913		
2314545	-2654971	3863.911		
2113280	-2424104	7546.745		
1912016	-2193237	14855.542		
1710751	-1962370	29462.440		
1509486	-1731503	58742.180		
1308221	-1500636	118256.900		
1106956	-1269769	244742.968		
905692	-1038902	532274.944		

Single Max Bending Cell - Vertical Bending				
Bending	Moment	Speed (kts)	Head. (deg.)	Wave Ht. (m)

Hogging	4715240	15.00	1.00	12.50
Sagging	-5524658	15.00	1.00	12.50

Figure 13 – Fatigue Histogram Output, Text Format

of the ship's hull girder using cumulative damage theory. For vertical and lateral bending, wave induced, and wave plus whipping moments are displayed. For torsion, only wave-induced moments are output. Text output for histogram data is shown in Figure 13.

Reliability Output

Reliability output can only be displayed as text. Display is designated in the View

menu of the main SPECTRA window (Figure 14).

Reliability output tabulates the probability that a given bending moment will **not** be exceeded. In addition, SPECTRA performs a Weibull

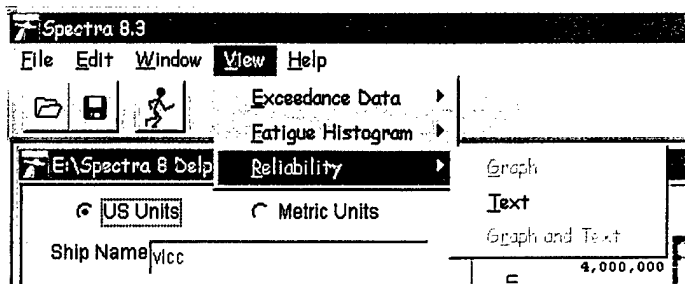


Figure 14 – Reliability Output Menu Selection

Reliability Results				
Lat ft-lton	Rel.	Weibull Fit		
2921314	0.367847	2917155		
3008953	0.719623	3007128		
3096592	0.901167	3100160		
3184232	0.968892	3189993		
3271871	0.990838	3276080		
3359511	0.997435	3359181		
3447150	0.999314	3440135		
3534790	0.999825	3519604		
3622429	0.999957	3598074		
3710068	0.999990	3675899		
3797708	0.999998	3753338		
Weibull Slope =		1.395		
Truncation Value =		2833674		
Scale =		145999		
Mean X =		133143		
Variance X =		9355954470		
Total wave encounters of all cells = 59857113				
Single Max Bending Cell - Lateral Bending				
Bending	Moment	Speed (kts)	Head. (deg.)	Wave Ht. (m)
Lateral	2810501	15.00	45.00	11.50

Figure 15 – Reliability Output

fit for the tabulated moments. The moment for a given probability, R , is given by:

$$M = (\text{Truncation Value}) + \text{Scale}(-\ln(1 - R))^{1 / (\text{Weibull Slope})}$$

Figure 15 is a sample of reliability output for lateral bending as computed by SPECTRA.

Copying and Printing Output

Both graphical and text output can be copied to the clipboard or printed to your system printer. Right-clicking the mouse on the graph or text output frames will pop-up a menu with options for copying or printing the graph or selected text output.

When copying or printing the graph, best results are obtained if the graph is as large as possible on your screen

ⁱ Sikora, J., "Cumulative Lifetime Loadings for Naval Ships", 1998 International Mechanical Engineering Congress & Exposition, Anaheim CA, USA, Nov. 1998.

ⁱⁱ Sikora, J., "Design Methodology for Seaway Loads", NSWCCD Report 65-TR-1999/16, September 1999.

ⁱⁱⁱ Michaelson, R. "Ship Operational Profiles Compiled from Shipboard Weather Observations of 40 U.S. Navy Ships", NSWCCD Report TR-65-96/07, June 1996.

Appendix A – Sample Input and Output

SPECTRA automatically installs three sample files during the program setup, “vlcc.specin”, “cargo.specin”, and “vlcc-metric.specin”. It is suggested that the user run the program using these files to ensure the program is operating correctly and to gain familiarity with its use. Input and output listings are provided below.

vlcc.specin:

Input:

```

US units
Ship Name= vlcc
LBP= 1100
Beam= 180
Draft= 55
Displacement= 250000
Calculation Location= 550
Still Water Bend.Moment= 0
Ship Type= Commercial & Naval Auxiliaries
Bow Shape= Flat Bottomed Cargo Ship
Service Life= 6000
RAO Source= Universal RAO's
Hull Bending= Vertical Bending
Sea Spectrum= Ochi 6 Parameter
Sea State Probabilities= Ochi North Atlantic
Operational Profile= Cargo Ship
Avg Time Between Slams= Default
Whipping Frequency= Default
Whipping Log Decrement= Default
Whipping Initiation Phase Angle= Default

```

Output:

```

Exceedance Results
Wave Induced Moments, ft-lton
=====
Vertical Bending

```

Hogging	Sagging	# Times Exceeded
4419337	-4419337	1.000
4242563	-4242563	2.179
4065790	-4065790	4.666
3889016	-3889016	9.822
3712243	-3712243	20.340
3535469	-3535469	41.473
3358696	-3358696	83.358
3181922	-3181922	165.417
3005149	-3005149	324.683
2828375	-2828375	631.649
2651602	-2651602	1220.489
2474829	-2474829	2346.617
2298055	-2298055	4495.581
2121282	-2121282	8587.119
1944508	-1944508	16353.539
1767735	-1767735	31037.539
1590961	-1590961	58686.102
1414188	-1414188	110604.347
1237414	-1237414	208224.723
1060641	-1060641	393508.075
883867	-883867	753291.096
707094	-707094	1479858.640

530320	-530320	3030887.368
353547	-353547	6622623.963
88387	-88387	26759677.078

Exceedance Results

Wave + Whipping Bending Moments, ft-lton

=====

Vertical Bending With Whipping

Hogging	Sagging	# Times Exceeded
5032133	-5772263	1.000
4830848	-5541373	2.434
4629563	-5310482	5.507
4428277	-5079592	9.980
4226992	-4848701	17.661
4025707	-4617811	32.555
3824421	-4386920	63.419
3623136	-4156030	119.574
3421851	-3925139	218.096
3220565	-3694248	390.595
3019280	-3463358	700.869
2817995	-3232467	1269.229
2616709	-3001577	2323.301
2415424	-2770686	4324.266
2214139	-2539796	8186.276
2012853	-2308905	15729.281
1811568	-2078015	30577.537
1610283	-1847124	60026.145
1408997	-1616234	118742.815
1207712	-1385343	236953.022
1006427	-1154453	481606.894
805141	-923562	1013709.998
603856	-692672	2235375.664
402571	-461781	5285415.875
100643	-115445	24942602.490

cargo.specin:Input:

Ship Name= cargo
 LBP= 800
 Beam= 105
 Draft= 44
 Displacement= 80000
 Calculation Location= 400
 Still Water Bend.Moment= 0
 Ship Type= Commercial & Naval Auxiliaries
 Bow Shape= Flat Bottomed Cargo Ship
 Service Life= 6000
 RAO Source= Universal RAO's
 Hull Bending= Vertical Bending
 Sea Spectrum= Ochi 6 Parameter
 Sea State Probabilities= General Atlantic
 Operational Profile= Cargo Ship
 Avg Time Between Slams= Default
 Whipping Frequency= Default
 Whipping Log Decrement= Default
 Whipping Initiation Phase Angle= Default

Output:Exceedance Results
Wave Induced Moments, ft-lton

=====

Vertical Bending

Hogging	Sagging	# Times Exceeded
1137274	-1137274	1.000
1091783	-1091783	2.135
1046292	-1046292	4.495
1000801	-1000801	9.340
955310	-955310	19.141
909819	-909819	38.695
864328	-864328	77.168
818837	-818837	151.857
773346	-773346	295.040
727855	-727855	566.411
682364	-682364	1075.677
636873	-636873	2023.747
591382	-591382	3778.095
545891	-545891	7011.102
500400	-500400	12954.630
454909	-454909	23870.155
409418	-409418	43925.373
363928	-363928	80865.501
318437	-318437	149313.972
272946	-272946	277588.666
227455	-227455	522939.843
181964	-181964	1009476.163
136473	-136473	2042119.795
90982	-90982	4508417.432
22745	-22745	21227087.381

Exceedance Results
Wave + Whipping Bending Moments, ft-lton

=====

Vertical Bending With Whipping

Hogging	Sagging	# Times Exceeded
1268719	-1498751	1.000
1217970	-1438801	2.494
1167221	-1378851	5.935
1116473	-1318901	11.448
1065724	-1258951	21.766
1014975	-1199001	41.769
964226	-1139051	77.493
913478	-1079101	139.096
862729	-1019151	245.549
811980	-959201	428.111
761231	-899251	748.577
710483	-839301	1315.223
659734	-779351	2324.892
608985	-719401	4158.758
558236	-659451	7530.803
507488	-599500	13796.008
456739	-539550	25594.947
405990	-479600	48176.430
355241	-419650	92350.064
304493	-359700	180827.914
253744	-299750	361966.822
202995	-239800	741808.744
152246	-179850	1587292.335
101498	-119900	3714980.088
25374	-29975	19910768.082

vlcc-metric.specin:

Input:

Ship Name= vlcc-metric
 LBP= 335.28
 Beam= 54.86
 Draft= 16.76
 Displacement= 254083
 Calculation Location= 167.64
 Still Water Bend.Moment= 0
 Ship Type= Commercial & Naval Auxiliaries
 Bow Shape= Flat Bottomed Cargo Ship
 Service Life= 6000
 RAO Source= Universal RAO's
 Hull Bending= Vertical Bending
 Sea Spectrum= Ochi 6 Parameter
 Sea State Probabilities= Ochi North Atlantic
 Operational Profile= Cargo Ship
 Avg Time Between Slams= Default
 Whipping Frequency= Default
 Whipping Log Decrement= Default
 Whipping Initiation Phase Angle= Default

Output:

Exceedance Results
 Wave Induced Moments, m-mton
 =====

Vertical Bending

Hogging	Sagging	# Times Exceeded
1368533	-1368533	1.000
1313792	-1313792	2.179
1259051	-1259051	4.666
1204309	-1204309	9.822
1149568	-1149568	20.340
1094827	-1094827	41.473
1040085	-1040085	83.358
985344	-985344	165.417
930603	-930603	324.683
875861	-875861	631.649
821120	-821120	1220.489
766379	-766379	2346.617
711637	-711637	4495.581
656896	-656896	8587.119
602155	-602155	16353.539
547413	-547413	31037.539
492672	-492672	58686.102
437931	-437931	110604.347
383189	-383189	208224.723
328448	-328448	393508.075
273707	-273707	753291.096
218965	-218965	1479858.640
164224	-164224	3030887.368
109483	-109483	6622623.963
27371	-27371	26759677.078

Exceedance Results
 Wave + Whipping Bending Moments, m-mton
 =====

Vertical Bending With Whipping

NSWCCD-65-TR-2000/07

Hogging	Sagging	# Times Exceeded
1558298	-1787493	1.000
1495966	-1715994	2.434
1433634	-1644494	5.507
1371302	-1572994	9.980
1308970	-1501494	17.661
1246638	-1429995	32.555
1184306	-1358495	63.419
1121974	-1286995	119.574
1059643	-1215496	218.096
997311	-1143996	390.595
934979	-1072496	700.869
872647	-1000996	1269.229
810315	-929497	2323.301
747983	-857997	4324.266
685651	-786497	8186.276
623319	-714997	15729.281
560987	-643498	30577.537
498655	-571998	60026.145
436323	-500498	118742.815
373991	-428998	236953.022
311660	-357499	481606.894
249328	-285999	1013709.998
186996	-214499	2235375.664
124664	-142999	5285415.875
31166	-35750	24942602.490

Appendix B – Sea Spectra

SPECTRA includes four built-in sea spectra. The formulations for these spectra are given below.

Pierson-Moskowitz

The Pierson-Moskowitz spectrum for fully developed seas can be used to generate one spectral shape for a given wave height by,

$$S(\omega) = 0.0081 \frac{g^2}{\omega^5} \exp\left(-0.032 \left(\frac{g}{H\omega^2}\right)\right)$$

where

$S(\omega)$ = spectral density function

g = acceleration due to gravity

ω = non - dimensional wave frequency, rad/sec

H = significant wave height

Ochi 6 Parameter

The Ochi 6 parameter spectrum is composed of 11 spectral shapes for a given wave height, with each spectral shape having its own probability of occurrence for a given wave height. The formulation is defined as:

$$S(\omega) = \frac{1}{4} \sum_{j=1}^2 \frac{\left(\frac{4\lambda_j + 1}{4} \omega_{mj}^4\right)^{\lambda_j}}{\Gamma(\lambda_j)} \cdot \frac{H_{sj}^2}{\omega^{4\lambda_j + 1}} \cdot \exp\left(-\frac{4\lambda_j + 1}{4} \left(\frac{\omega_{mj}}{\omega}\right)^4\right)$$

where

$S(\omega)$ = spectral density function

Γ = gamma function

λ = shape parameter

H_s = wave height parameter

ω = non - dimensional wave frequency, rad/sec

ω_m = modal frequency parameter

$j = 1$ or 2 for low and high frequency components

The six parameters, H_{s1} , H_{s2} , ω_{m1} , ω_{m2} , λ_1 , and λ_2 are listed in Table B1.

Table B1 – Six Ochi Parameters as Functions of Significant Wave Height

Spectral Shape	Probability	H_{s1}	H_{s2}	ω_{m1}	ω_{m2}	λ_1	λ_2
1	0.50	0.84ζ	0.54ζ	$0.70e^{-0.046\zeta}$	$1.15e^{-0.039\zeta}$	3.00	$1.54e^{-0.062\zeta}$
2	0.05	0.95ζ	0.31ζ	$0.70e^{-0.046\zeta}$	$0.50e^{-0.046\zeta}$	1.35	$2.48e^{-0.102\zeta}$
3	0.05	0.65ζ	0.76ζ	$0.61e^{-0.039\zeta}$	$0.94e^{-0.036\zeta}$	4.95	$2.48e^{-0.102\zeta}$
4	0.05	0.84ζ	0.54ζ	$0.93e^{-0.056\zeta}$	$1.50e^{-0.046\zeta}$	3.00	$2.77e^{-0.112\zeta}$
5	0.05	0.84ζ	0.54ζ	$0.41e^{-0.016\zeta}$	$0.88e^{-0.026\zeta}$	2.55	$1.82e^{-0.089\zeta}$
6	0.05	0.90ζ	0.44ζ	$0.81e^{-0.052\zeta}$	$1.60e^{-0.033\zeta}$	1.80	$2.95e^{-0.105\zeta}$
7	0.05	0.77ζ	0.64ζ	$0.54e^{-0.039\zeta}$	0.61	4.50	$1.95e^{-0.082\zeta}$
8	0.05	0.73ζ	0.68ζ	$0.70e^{-0.046\zeta}$	$0.99e^{-0.039\zeta}$	6.40	$1.78e^{-0.069\zeta}$
9	0.05	0.92ζ	0.39ζ	$0.70e^{-0.046\zeta}$	$1.37e^{-0.039\zeta}$	0.70	$1.78e^{-0.069\zeta}$
10	0.05	0.84ζ	0.54ζ	$0.74e^{-0.052\zeta}$	$1.30e^{-0.039\zeta}$	2.65	$3.90e^{-0.085\zeta}$
11	0.05	0.84ζ	0.54ζ	$0.62e^{-0.039\zeta}$	$1.03e^{-0.030\zeta}$	2.60	$0.53e^{-0.069\zeta}$

ζ = significant wave height.

North Atlantic 2 Parameter

The North Atlantic 2 parameter spectrum is composed of nine spectral shapes for a given wave height. The formulation is:

$$S(\omega) = 0.3125 \frac{\omega_m^4 H^2}{\omega^5} \exp\left(-1.25 \left(\frac{\omega_m}{\omega}\right)^4\right)$$

where

$S(\omega)$ = spectral density function

ω_m = modal wave period

ω = wave frequency, rad/sec

H = significant wave height

Thus this spectrum has two parameters, ω_m and H . For a given wave height, H , the modal period and spectral shape probability for this spectrum is shown in Table B2.

Table B2 – Modal Period and Spectral Shape Probability for North Atlantic 2 Parameter Sea Spectra

Spectral Shape	Probability	ω_m (rad/sec)
1	0.0500	$0.048(8.75 - \ln(H))$
2	0.0500	$0.054(8.44 - \ln(H))$
3	0.0875	$0.061(8.07 - \ln(H))$
4	0.1875	$0.069(7.77 - \ln(H))$
5	0.2500	$0.079(7.63 - \ln(H))$
6	0.1875	$0.099(6.87 - \ln(H))$
7	0.0875	$0.111(6.67 - \ln(H))$
8	0.0500	$0.119(6.65 - \ln(H))$
9	0.0500	$0.134(6.41 - \ln(H))$

Bretschneider

The basic form of the Bretschneider spectrum is the same as the North Atlantic 2 parameter, except that use of the Bretschneider spectrum, requires a tabulation of joint modal period and wave height probabilities. A sample of joint probabilities is given in Table B3.

Table B3 - Joint Wave Height and Modal Period Probabilities Sample

	Modal wave period (seconds)							
	3.25	7.79	10.39	12.99	15.58	18.18	20.78	23.38
0.5	0.02091	0.01179	0.00457	0.00224	0.00047	0.00006	0.00000	0.00060
1.5	0.07278	0.13108	0.06308	0.01726	0.00239	0.00033	0.00011	0.00077
2.5	0.02124	0.12641	0.11831	0.03024	0.00368	0.00047	0.00009	0.00056
3.5	0.00328	0.04960	0.09269	0.03299	0.00546	0.00068	0.00012	0.00027
4.5	0.00053	0.01619	0.04436	0.02228	0.00479	0.00114	0.00008	0.00029
5.5	0.00012	0.00434	0.01730	0.01289	0.00313	0.00056	0.00013	0.00004
6.5	0.00007	0.00290	0.00990	0.00886	0.00303	0.00059	0.00008	0.00003
7.5	0.00003	0.00139	0.00447	0.00522	0.00193	0.00038	0.00004	0.00004
8.5	0.00000	0.00109	0.00255	0.00392	0.00198	0.00050	0.00003	0.00002
9.5	0.00000	0.00054	0.00136	0.00226	0.00154	0.00068	0.00020	0.00004
10.5	0.00001	0.00001	0.00010	0.00011	0.00010	0.00005	0.00002	0.00000
11.5	0.00000	0.00000	0.00003	0.00008	0.00017	0.00006	0.00000	0.00000
12.5	0.00000	0.00005	0.00000	0.00014	0.00022	0.00006	0.00001	0.00000
13.5	0.00000	0.00002	0.00000	0.00007	0.00009	0.00003	0.00000	0.00001
14.5	0.00000	0.00000	0.00000	0.00002	0.00006	0.00002	0.00000	0.00001
15.5	0.00000	0.00002	0.00000	0.00001	0.00001	0.00002	0.00001	0.00001

SPECTRA will compute a sea spectral shape for each of the joint probabilities using the applicable modal periods and wave heights. Thus for Table B3, 128 spectral shapes would be computed using the same equation as for the North Atlantic 2 parameter spectra,

$$S(\omega) = 0.3125 \frac{\omega_m^4 H^2}{\omega^5} \exp\left(-1.25 \left(\frac{\omega_m}{\omega}\right)^4\right),$$

with each spectral shape being assigned its associated probability of occurrence. For example, one of the 128 spectral shapes would be calculated with $\omega_m = 3.25$ and $H = 0.5$, with the probability of occurrence being 0.02091.

Appendix C – Sea State Probabilities

SPECTRA includes four pre-defined sea state probability choices - Ochi North Atlantic, General Atlantic, General Pacific, and NATO North Atlantic (Table C1). The sea state probabilities represent the probability of occurrence of a given wave height.

Table C1 - Sea State Probabilities

Significant Wave Height (meters)	Ochi North	General		NATO North
	Atlantic	Atlantic	General Pacific	Atlantic
< 1	0.050300	0.369200	0.225411	0.087000
1 - 2	0.266500	0.330300	0.384911	0.192000
2 - 3	0.260300	0.148000	0.230511	0.220000
3 - 4	0.175700	0.072300	0.094511	0.157000
4 - 5	0.101400	0.035500	0.030341	0.124000
5 - 6	0.058900	0.018100	0.017361	0.080000
6 - 7	0.034600	0.011000	0.006761	0.052000
7 - 8	0.020900	0.006600	0.003911	0.039000
8 - 9	0.012000	0.003600	0.003131	0.025000
9 - 10	0.007900	0.002470	0.001781	0.013000
10 - 11	0.005400	0.001380	0.000591	0.007000
11 - 12	0.002900	0.000740	0.000321	0.004000
12 - 13	0.001600	0.000400	0.000321	0.000000
13 - 14	0.000740	0.000190	0.000111	0.000000
14 - 15	0.000450	0.000120	0.000021	0.000000
>15	0.000410	0.000100	0.000000	0.000000

Appendix D – Operational Profiles

SPECTRA includes 12 operational profiles which describe a ship's operational characteristics with respect to speed, wave height, and heading relative to wave direction (0 degrees is head seas). These operational profiles are listed in the tables below.

Table D1 - Operational Profile: Combatant

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.01250	0.02500	0.00000
5	45	0.02500	0.37500	0.80800
5	80	0.02500	0.05000	0.00000
5	135	0.02500	0.05000	0.04200
5	180	0.01250	0.02500	0.00000
15	0	0.08750	0.02300	0.00000
15	45	0.17500	0.33750	0.14200
15	90	0.17500	0.00000	0.00000
15	135	0.17500	0.04450	0.00800
15	180	0.08750	0.02250	0.00000
25	0	0.02500	0.00250	0.00000
25	45	0.05000	0.03750	0.00000
25	90	0.05000	0.00000	0.00000
25	135	0.05000	0.00500	0.00000
25	180	0.02500	0.00250	0.00000

Table D2 - Operational Profile: Cargo Ship

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.01000	0.12500	0.17500
5	45	0.02000	0.12500	0.17500
5	90	0.02000	0.06250	0.08750
5	135	0.02000	0.12500	0.17500
5	180	0.01000	0.06250	0.08750
15	0	0.11500	0.12500	0.07500
15	45	0.23000	0.12500	0.07500
15	90	0.23000	0.06250	0.03750
15	135	0.23000	0.12500	0.07500
15	180	0.11500	0.06250	0.03750

Table D3 - Operational Profile: Aircraft Carrier

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.01000	0.12500	0.17500
5	45	0.02000	0.12500	0.17500
5	90	0.02000	0.06250	0.08750
5	135	0.02000	0.12500	0.17500
5	180	0.01000	0.06250	0.08750
15	0	0.09600	0.11500	0.07500
15	45	0.19200	0.11500	0.07500
15	90	0.19200	0.05750	0.03750
15	135	0.19200	0.11500	0.07500
15	180	0.09600	0.05750	0.03750
25	0	0.01900	0.01000	0.00000
25	45	0.03800	0.01000	0.00000
25	90	0.03800	0.00500	0.00000
25	135	0.03800	0.01000	0.00000
25	180	0.01900	0.00500	0.00000

Table D4 - Operational Profile: 30-60 headings, 5-15-25 speeds

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.00417	0.01400	0.08000
5	30	0.00833	0.03850	0.16000
5	60	0.00833	0.02450	0.04000
5	90	0.00833	0.01050	0.00000
5	120	0.00833	0.01050	0.00000
5	150	0.00833	0.02800	0.08000
5	180	0.00417	0.01400	0.04000
15	0	0.01667	0.06600	0.12000
15	30	0.03333	0.18150	0.24000
15	60	0.03333	0.11550	0.06000
15	90	0.03333	0.04950	0.00000
15	120	0.03333	0.04950	0.00000
15	150	0.03333	0.13200	0.12000
15	180	0.01667	0.06600	0.06000
25	0	0.06250	0.02000	0.00000
25	30	0.12500	0.05500	0.00000
25	60	0.12500	0.03500	0.00000
25	90	0.12500	0.01500	0.00000
25	120	0.12500	0.01500	0.00000
25	150	0.12500	0.04000	0.00000
25	180	0.06250	0.02000	0.00000

Table D5 - Operational Profile: Combatant - integrated

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.04100	0.07600	0.06000
5	45	0.08200	0.08400	0.76000
5	89	0.08200	0.02750	0.00000
5	135	0.08200	0.05400	0.03000
5	179	0.04100	0.03300	0.00000
15	0	0.07100	0.11600	0.00000
15	45	0.14300	0.28700	0.09200
15	89	0.14300	0.04550	0.00000
15	135	0.14300	0.11500	0.00800
15	179	0.07100	0.06000	0.05000
25	0	0.01300	0.00700	0.00000
25	45	0.02500	0.01900	0.00000
25	89	0.02500	0.01900	0.00000
25	135	0.02500	0.01900	0.00000
25	179	0.01300	0.03800	0.00000

Table D6 - Operational Profile: Amphibious or Fast Cargo - integrated

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.03800	0.04800	0.22900
5	45	0.07500	0.08200	0.25700
5	90	0.07500	0.05500	0.08450
5	135	0.07500	0.06700	0.11400
5	180	0.03800	0.03400	0.05700
15	0	0.08500	0.15200	0.05700
15	45	0.17000	0.21000	0.08600
15	90	0.17000	0.12400	0.02950
15	135	0.17000	0.13800	0.05700
15	180	0.08500	0.07000	0.02900
25	0	0.00200	0.00300	0.00000
25	45	0.00500	0.00500	0.00000
25	90	0.00500	0.00500	0.00000
25	135	0.00500	0.00500	0.00000
25	180	0.00200	0.00200	0.00000

Table D7 - Operational Profile: Carrier - integrated

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.05000	0.04800	0.15000
5	45	0.10300	0.19600	0.36800
5	90	0.10300	0.16000	0.05600
5	135	0.10300	0.09400	0.08000
5	180	0.05000	0.03000	0.01200
15	0	0.05600	0.04700	0.07500
15	45	0.11300	0.11800	0.11500
15	90	0.11300	0.11400	0.02800
15	135	0.11300	0.07200	0.07800
15	180	0.05600	0.02500	0.03800
25	0	0.01800	0.00800	0.00000
25	45	0.03500	0.01500	0.00000
25	90	0.03500	0.02900	0.00000
25	135	0.03500	0.03600	0.00000
25	180	0.01800	0.00800	0.00000

Table D8 - Operational Profile: Auxiliary or Slow Cargo - integrated

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 5	6 - 10	> 10
5	0	0.02500	0.03500	0.17500
5	45	0.05000	0.07500	0.17500
5	90	0.05000	0.05100	0.08700
5	135	0.05000	0.04200	0.17500
5	180	0.02500	0.01300	0.08800
15	0	0.10000	0.14900	0.07500
15	45	0.20000	0.20000	0.07500
15	90	0.20000	0.18500	0.03700
15	135	0.20000	0.17500	0.07500
15	180	0.10000	0.07500	0.03800

Table D9 - Operational Profile: Combatant - Michaelson
 Significant Wave Height (meters)

Speed (kts)	Heading	0 - 3	4 - 6	> 6
5	1	0.06884	0.06131	0.11111
5	45	0.09032	0.09045	0.08642
5	90	0.06641	0.04422	0.08642
5	135	0.07458	0.04422	0.02469
5	180	0.04791	0.02714	0.02469
15	1	0.10590	0.14975	0.16049
15	45	0.15724	0.19698	0.16049
15	90	0.10414	0.13970	0.09877
15	135	0.13127	0.09447	0.08642
15	180	0.07297	0.06131	0.04938
25	1	0.01583	0.01809	0.00000
25	45	0.02168	0.02714	0.01235
25	90	0.01473	0.01307	0.02469
25	135	0.01815	0.02412	0.01235
25	180	0.01004	0.00804	0.06173

Table D10 - Operational Profile: Amphibious or Fast Cargo - Michaelson
 Significant Wave Height (meters)

Speed (kts)	Heading	0 - 3	4 - 6	> 6
5	0	0.06345	0.06341	0.05714
5	45	0.10554	0.08696	0.08571
5	90	0.07840	0.03261	0.05714
5	135	0.08544	0.03442	0.05714
5	180	0.04984	0.02174	0.02857
15	0	0.11891	0.16304	0.22857
15	45	0.17500	0.27899	0.25714
15	90	0.10585	0.12681	0.05714
15	135	0.13125	0.12681	0.11429
15	180	0.07650	0.03804	0.05714
25	0	0.00174	0.01268	0.00000
25	45	0.00190	0.01087	0.00000
25	90	0.00190	0.00000	0.00000
25	135	0.00269	0.00000	0.00000
25	180	0.00158	0.00362	0.00000

Table D11 - Operational Profile: Carrier - Michaelson

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 3	4 - 6	> 6
5	0	0.07428	0.10083	0.03846
5	45	0.11625	0.09991	0.30769
5	90	0.08851	0.08973	0.11538
5	135	0.09484	0.06383	0.07692
5	180	0.05235	0.04625	0.00000
15	0	0.07585	0.06846	0.03846
15	45	0.12624	0.15171	0.11538
15	90	0.09001	0.11193	0.15385
15	135	0.09321	0.07031	0.03846
15	180	0.05196	0.06105	0.00000
25	0	0.02285	0.01943	0.00000
25	45	0.03721	0.03608	0.00000
25	90	0.02728	0.04163	0.07692
25	135	0.03055	0.02405	0.03846
25	180	0.01860	0.01480	0.00000

Table D12 - Operational Profile: Auxiliary or Slow Cargo - Michaelson

Speed (kts)	Heading	Significant Wave Height (meters)		
		0 - 3	4 - 6	> 6
5	0	0.04278	0.05491	0.04938
5	45	0.06082	0.04439	0.11111
5	90	0.04243	0.03271	0.02469
5	135	0.04486	0.03271	0.03704
5	180	0.03393	0.02220	0.00000
15	0	0.15471	0.19042	0.19753
15	45	0.20694	0.26636	0.19753
15	90	0.14620	0.13318	0.18519
15	135	0.15957	0.14836	0.14815
15	180	0.10777	0.07477	0.04938
