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PREDICTION OF SHIP RESPONSES IN LONG-CRESTED IRREGULAR WAVES (COMPUTER PROGRAM SRIW)

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER



Bethesda, Md. 20084

PREDICTION OF SHIP RESPONSES IN
LONG-CRESTED IRREGULAR WAVES
(COMPUTER PROGRAM SRIW)

by

E. N. HUBBLE

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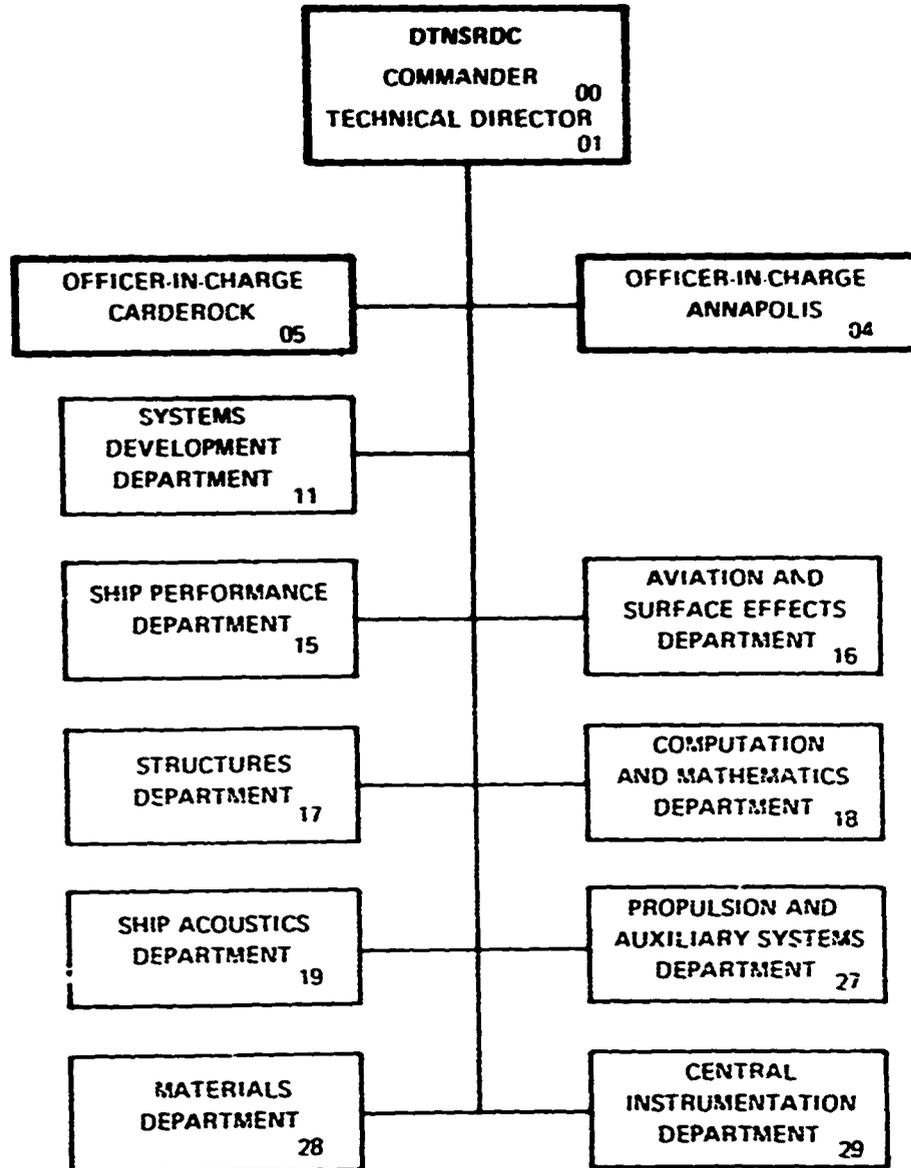
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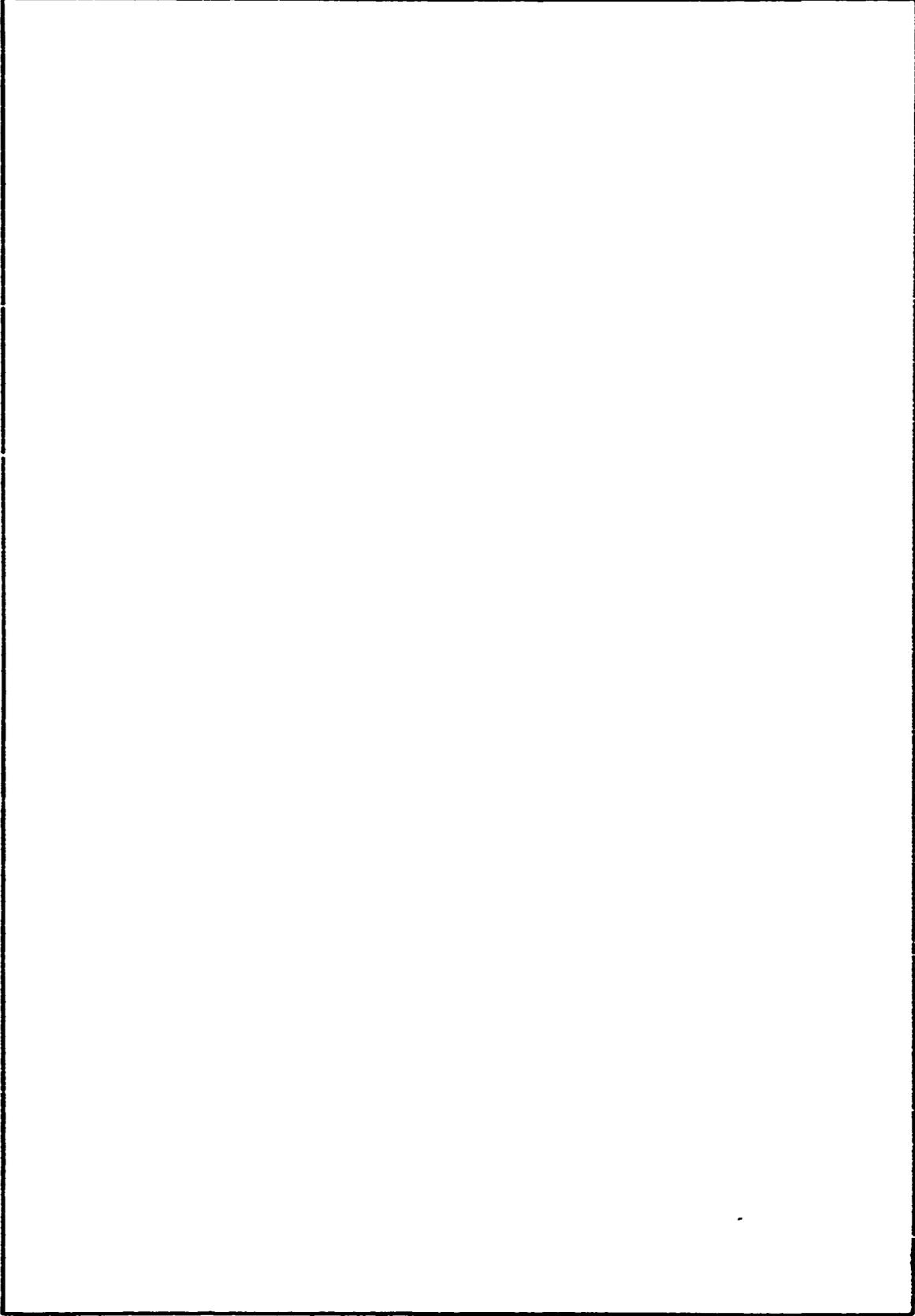
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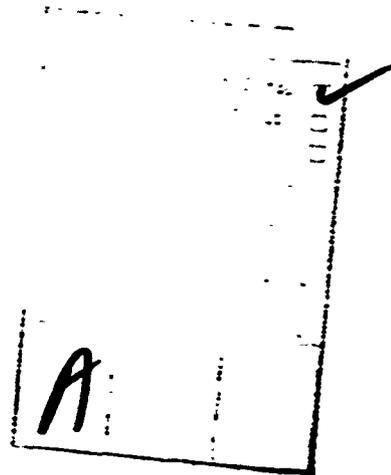
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ADMINISTRATIVE INFORMATION

This program was authorized and funded by the Naval Ship Engineering Center Work Request Number N65197-75-PO-51314 and is identified as DTNSRDC Work Unit Number 1-1560-012.

INTRODUCTION

A ship's response in irregular waves may be derived from the irregular-wave spectrum and the regular-wave response by the linear superposition theory of St. Denis and Pierson.¹ The regular-wave transfer function may be obtained from experimental data or from analytical predictions provided by existing computer routines.^{2,3} In the past, idealized wave spectra such as the Pierson-Moskowitz formula for fully developed seas and the Bretschneider two-parameter sea formula have been used to represent irregular waves of various significant wave heights.

In recent years, DTNSRDC has obtained the data for 323 point spectra with significant wave height from 0.4 to 44.8 feet which were measured at Station INDIA in the North Atlantic.⁴ More recently, a series of mathematical wave spectra involving six parameters has been developed by Ochi⁵ in an attempt to systematically represent the variety of wave spectra shapes which may occur for any given significant wave height.

¹ St. Denis, M. and W.J. Pierson, "On the Motions of Ships in Confused Seas," SNAME Trans. Vol. 62 (1954)

² Frank, W. and N. Salvesen, "The Frank Close-Fit Ship-Motion Computer Program," NSRDC Report 3289 (1970)

³ Meyers, W.G., D.J. Sheridan, and N. Salvesen, "Manual, NSRDC Ship-Motion and Sea Load Computer Program," NSRDC Report 3376 (1975)

⁴ Miles, M., "Wave Spectra Estimated from a Stratified Sample of 323 North Atlantic Wave Records," N.R.C. Report LTR-SH-118-A (May 1972).

⁵ Ochi, M.K. and E.N. Hubble, "On Six-Parameter Wave Spectra," Proceedings of the Fifteenth Conference on Coastal Engineering (July 1976).

This report describes a computer program for deriving long-crested irregular-wave responses by the method of linear superposition using the Station INDIA sea spectra and/or the six-parameter wave spectra. The Pierson-Moskowitz spectra may also be used for comparison. The program, entitled SRIW, is written in FORTRAN for operation on the CDC 6700 computer at DTNSRDC. Calcomp plots of the results may also be obtained.

PROCEDURE

Any irregular-wave response -- pitch, heave, roll, yaw, sway, surge, relative motion, forces, moments, etc. -- may be calculated if the regular-wave transfer function or response amplitude operator is available in one of the formats specified in the Appendix. The program computes significant values of the response, most probable extreme values, and extreme values for design consideration. In addition, responses such as relative velocity, deck wetnesses, slams, etc., may be derived from relative vertical motion. Vertical and lateral accelerations may also be derived from absolute vertical motion and roll, respectively. Results are tabulated, and plotted if desired, as a function of significant wave height. A sample plot is shown in Figure 1.

SIGNIFICANT VALUES

Variances and significant values, i.e., average of highest 1/3, are derived in the following manner. Integration is performed in the wave frequency ω domain with limits of 0 to 2.0 rad/sec as suggested in Reference 6.

⁶Hubble, E.N., and J.B. Hadler, "Prediction of Ship Motion in Regular and Irregular Head Seas," NSRDC Report SPD-623-01 (April 1975)

(1) Wave frequency in rad/sec: $\omega = \sqrt{2\pi g/\lambda}$

(2) Encounter frequency in rad/sec: $\omega_e = \omega - \omega^2 \cos \mu V/g$

where g = gravitational acceleration in ft/sec²

λ = wave length in ft

V = ship speed in ft/sec

μ = heading angle, 180 deg for head seas, 90 deg for beam seas,

0 deg for following seas

$$\omega = \frac{-1 + \sqrt{1 - 4 \cos \mu \frac{V}{g} \omega_e}}{-2 \cos \mu \frac{V}{g}} \quad \text{for } 90^\circ < \mu < 270^\circ$$

(3) Response amplitude operator at V , ω_e , and μ transformed to ω :

$$\text{R.A.O.} = X(\omega) = \left(\frac{\text{regular-wave response amplitude}}{\text{wave amplitude in ft}} \right)^2$$

(4) Irregular-wave spectral ordinate at ω in $\frac{\text{ft}^2}{\text{rad/sec}}$:

$S(\omega)$ -- Values from Reference 4 for Station INDIA Spectra

$S(\omega)$ -- Values derived from equation and constants in Reference 5

for Ochi six-parameter spectra

(5) Variance of displacement:

$$E_d = m_0 = \int_0^{2.0} X(\omega) S(\omega) d\omega$$

(6) Variance of velocity:

$$E_v = m_2 = \int_0^{2.0} \omega_e^2 X(\omega) S(\omega) d\omega$$

(7) Variance of acceleration:

$$E_a = m_4 = \int_0^{2.0} \omega_e^4 X(\omega) S(\omega) d\omega$$

(8) Significant value of the response, i.e., displacement:

$$X_{1/3} = 2.0025 \sqrt{E_d}$$

(9) Significant velocity: $V_{1/3} = 2.0025 \sqrt{E_v}$

(10) Significant acceleration: $A_{1/3} = 2.0025 \sqrt{E_a}$

EXTREME VALUES

Extreme values are derived from the following relationship given by Ochi.⁷

(11) Extreme value of the response:

$$X_{\text{extreme}} = \sqrt{E_d} \sqrt{2 \ln \frac{3600 T}{2 \pi \alpha}} \sqrt{E_v/E_d}$$

where $\alpha = 1.0$ for most probable extreme value

$\alpha = 0.01$ for extreme value for design use

with 99 percent assurance

T = maximum duration time in hours for waves of given wave height (see Figure 2, extracted from Reference 8)

SUPPLEMENTARY RESPONSES

Additional statistical responses may be derived from relative vertical motion R.A.O.'s as follows:⁹

(12) Number of deck wetnesses, water contacts on catamaran cross-structure, or hydrofoil broachings per hour:

$$N_c = \frac{3600}{2\pi} \sqrt{E_v/E_d} e^{-C_o^2/(2E_d)}$$

⁷Ochi, M.K., "On Prediction of Extreme Values," Journal of Ship Research, Vol. 17, No. 1 (1973)

⁸Ochi, M.K., and Motter, L.E., "Prediction of Extreme Ship Responses in Rough Seas of the North Atlantic," Proceedings of the Symposium on the Response of Marine Vehicles and Structures in Waves, Univ. College London, (1974)

⁹Ochi, M.K., "Prediction of Occurrence and Severity of Ship Slamming at Sea," Proceedings of the 5th Symposium on Naval Hydrodynamics, Office of Naval Research (1964)

where E_d = variance of relative vertical displacement in ft^2
 E_v = variance of relative vertical velocity in $(\text{ft}/\text{sec})^2$
 C_o = absolute vertical distance in ft from water surface
 (running in still water) to appropriate structure

(13) Number of slams per hour

$$N_s = \frac{3600}{2\pi} \sqrt{E_v/E_d} e^{-[C_o^2/(2E_d) + \dot{r}_{\pm}^2/(2E_v)]}$$

where \dot{r}_{\pm} = threshold relative velocity in ft/sec

(14) Significant pressure on catamaran cross-structure in psi:

$$P_{1/3} = 2.1 k (2E_v)$$

where k = coefficient dependent upon cross-structure section
 shape

PERCENTAGE EXCEEDANCE

Cumulative statistics are applied to the Station INDIA data, if desired, to predict the probability of occurrence of the response over a one-year period in the North Atlantic. Since the Station INDIA spectra do not necessarily represent an average of the real ocean environment, each spectra is given a weighting factor. These weights were derived from meteorological data presented by Hogben and Lumb¹⁰ for Area 2 which represents the Eastern half of the North Atlantic and encompasses Station INDIA. The results are presented as percentage exceedance of the response. Sample plots are shown in Figure 3.

¹⁰Hogben, N. and F.E. Lumb, "Ocean Wave Statistics," (1967)

RELATIVE BOW MOTION IN FEET SIGNIFICANT VALUES

HEADING=180.0 DEG L=220.0 FT V=10.0 KNOTS

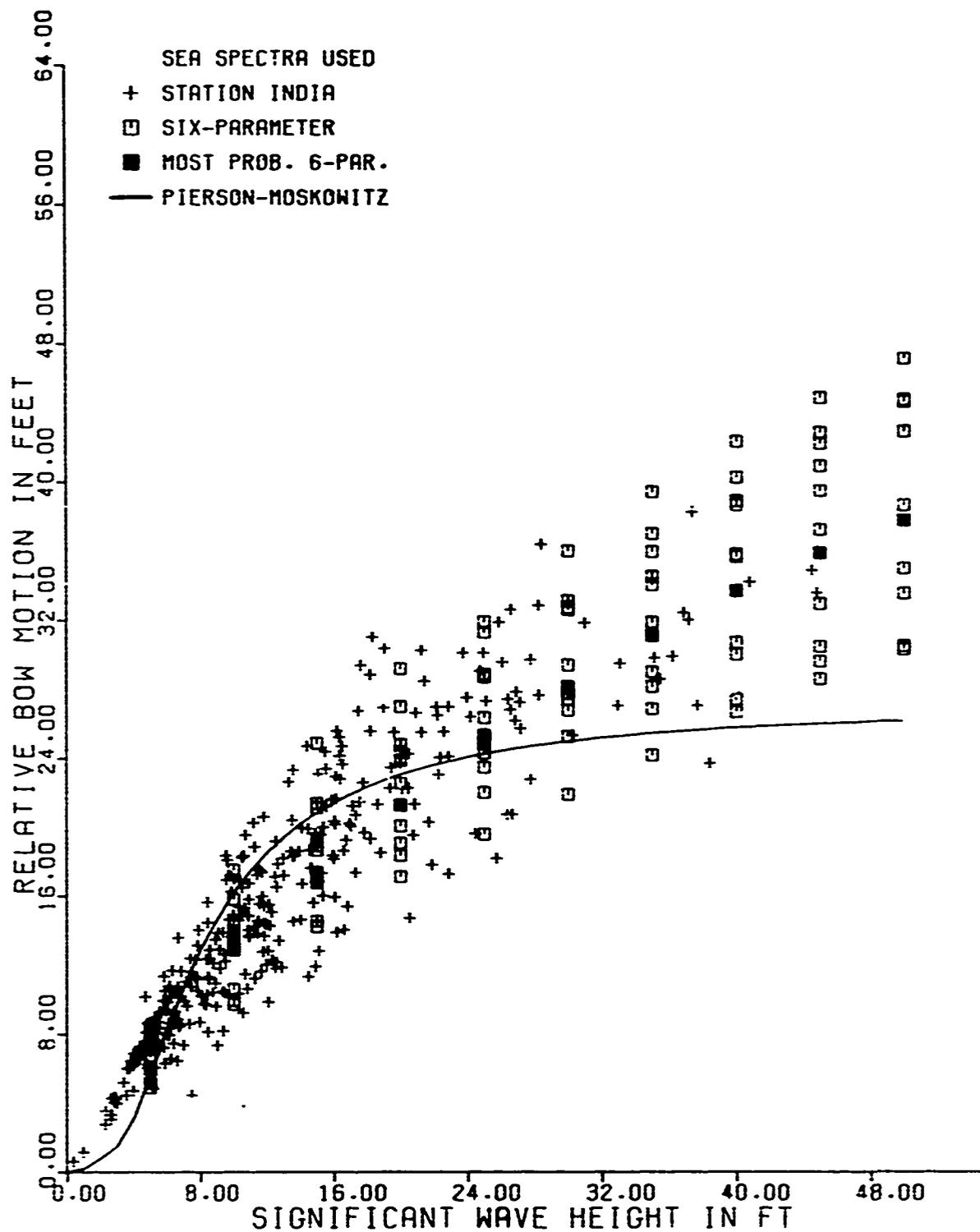


Figure 1 - Sample Plot of Irregular-Wave Response versus Significant Wave Height

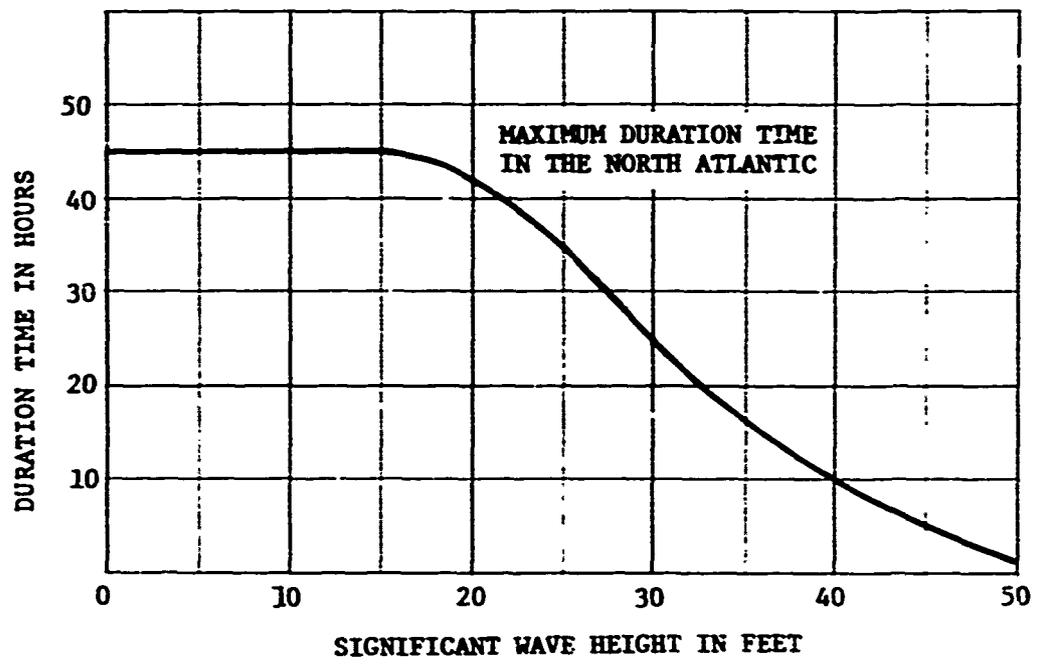


Figure 2
Maximum Duration Time of Waves in North Atlantic

RELATIVE BOW MOTION IN FEET

HEADING=180.0 DEG L=220.0 FT V=10.0 KNOTS

UPPER CURVE -- MOST PROBABLE EXTREME

LOWER CURVE -- SIGNIFICANT RESPONSE

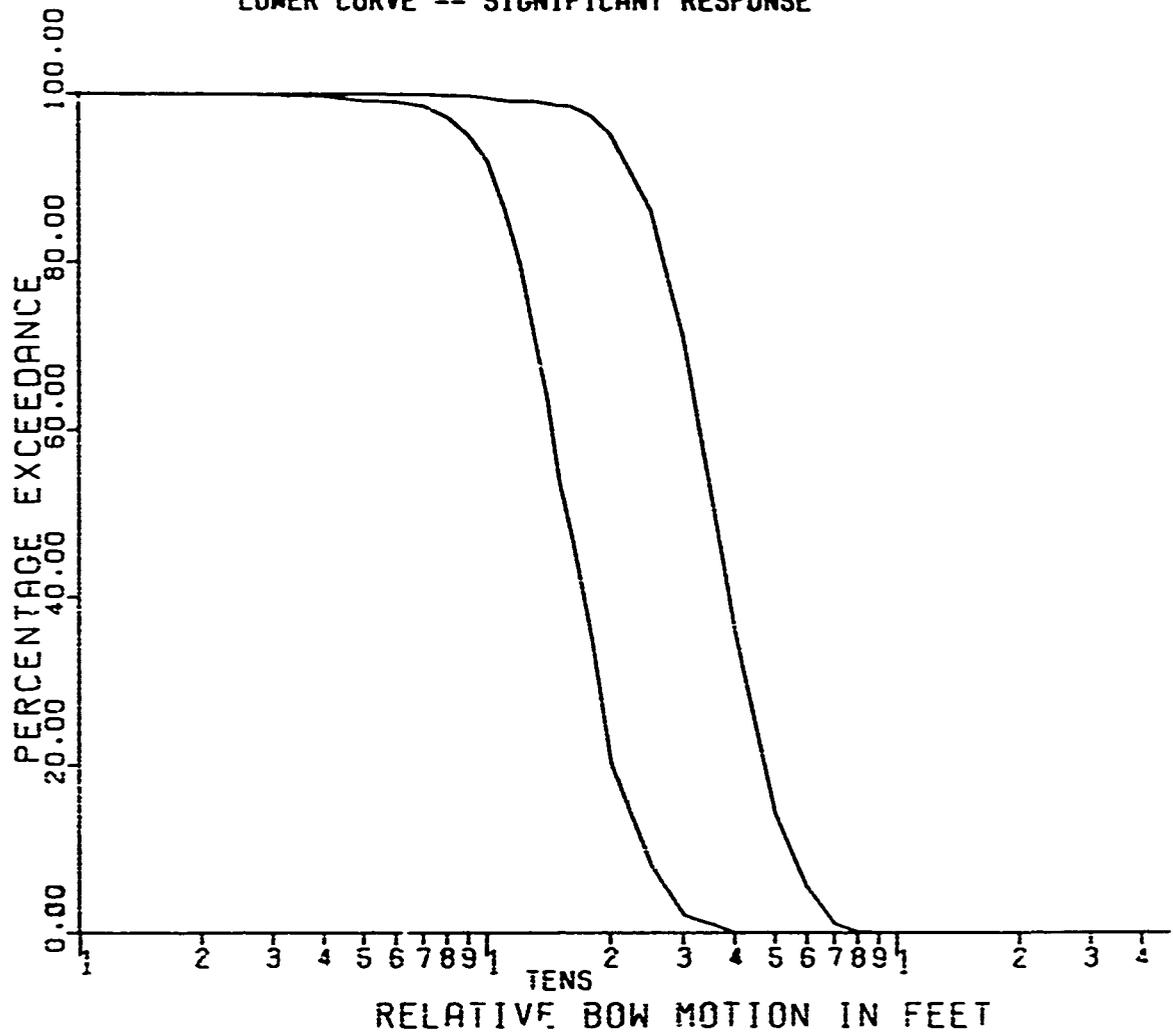


Figure 3

Sample Percentage Exceedance Design

APPENDIX

CONTROL CARDS AND INPUT

FOR

COMPUTER PROGRAM SRIW

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
1	1 - 3	I3	NSHIPS	Number of cases to be run; no limit
1	11-40	3A10	NAME	User's name, code, phone number
2	1 -40	4A10	SHIPN	Main title, such as ship name, etc.
2	41-70	3A10	RESP	Label for irregular-wave response to be computed, including dimensions.
Examples:				
PITCH AMPLITUDE IN DEGREES				
R. B.M. AT STATION 1.5 IN FEET				
2	75	I1	IRM	Set IRM to 1 if the response to be computed is relative motion. Otherwise, leave blank or set IRM to 0.
3	1 - 3	I3	IFORM	Code to identify form in which the transfer function is input

$$\text{IFORM}=1, \text{ if } TF = \left(\frac{1}{C}\right)\left(\frac{X}{R}\right) \text{ and } \left(\frac{X}{R}\right)^2 = (TF \cdot C)^2$$

$$\text{IFORM}=2, \text{ if } TF = \left(\frac{1}{C}\right)\left(\frac{X}{KR}\right) \text{ and } \left(\frac{X}{R}\right)^2 = (TF \cdot C \cdot \frac{2\pi}{\lambda})^2$$

$$\text{IFORM}=3, \text{ if } TF = \left(\frac{1}{C}\right)\left(\frac{X}{R}\right)^2 \text{ and } \left(\frac{X}{R}\right)^2 = (TF \cdot C)$$

Definitions:

- TF = input transfer function
- X = response amplitude in same dimensions specified on Card 2
- R = regular-wave amplitude in feet
- λ = regular-wave length in feet
- K = wave number = $2\pi / \lambda$
- KR = wave slope in radians = $2\pi R / \lambda$
- C = constant, input on Card 4
- $\left(\frac{X}{R}\right)^2$ = response amplitude operator

EXAMPLES OF POSSIBLE TRANSFER FUNCTION FORMS

<u>Irregular-Wave Response</u>	<u>Input Transfer Function (TF)</u>	<u>IFORM</u>	<u>C Value</u>
Heave in feet	$\frac{\text{Heave amplitude in feet}}{\text{Wave amplitude in feet}}$	1	1.0
Moment in ft-tons	$\frac{\text{Moment amplitude in ft-lbs} \times 10^{-6}}{\text{Wave amplitude in feet}}$	1	$\frac{10^6}{2240}$
Pitch in radians	$\frac{\text{Pitch amplitude in radians}}{\text{Wave slope in radians}}$	2	1.0
Roll in degrees	$\frac{\text{Roll amplitude in radians}}{\text{Wave slope in radians}}$	2	$\frac{360}{2\pi}$
Yaw in degrees	$\frac{(\text{Yaw amplitude in deg})^2}{(\text{Wave amplitude in ft})^2}$	3	1.0
Force in tons	$\frac{(\text{Force amplitude in lbs})^2}{(\text{Wave amplitude in ft})^2}$	3	$\left(\frac{1}{2240}\right)^2$

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
3	4 - 6	I3	IFREQ	Code to identify frequencies at which transfer function is input
			IFREQ=1,	if exactly 80 values are input corresponding to wave frequencies $\omega = 0.25, .05, .075, \dots 1.975, 2.0$ rad/sec
			IFREQ=2	if 50 values or less are input corresponding to selected values of wave length/ship length (λ/L) input on Cards 6a, 6b, etc.
			IFREQ=3,	if 50 values or less are input corresponding to even increments of nondimensional encounter frequency ($\omega_e \sqrt{L/g}$) specified in Card 6. ²
			IFREQ=4	if 50 values or less are input corresponding to selected values of wave frequency ω input on Cards 6a, 6b, etc.
3	7 - 9	I3	NWL	Number of λ/L values input on Cards 6a, 6b, etc. when IFREQ=2, or number of ω values input on Cards 6a, 6b, etc. when IFREQ=4. Maximum value of NWL is 50. NWL not used when IFREQ=1 or IFREQ=2.
3	10-12	I3	ISR	Code for supplementing response to be computed in addition to the basic response identified on Card 2. ISR = 0 if no supplementary response is required.

²The option IFREQ=3 can be used only if $90^\circ < \mu < 270^\circ$ since this program is set up to convert from ω_e to ω only in this regime. See Equation (2) page 3.

<u>ISR</u>	<u>SUPPLEMENTARY RESPONSE TO BE COMPUTED</u>	<u>BASIC RESPONSE IDENTIFIED ON CARD 2</u>	<u>VALUE OF CLR REQUIRED</u>
1	Significant Relative Velocity in ft/sec	Relative Motion (R.M.) in feet	-
2	Significant Vertical Acceleration / g	Absolute Motion (A.M.) in feet	-
3	Significant Lateral Acceleration / g	Roll Angle in degrees	CG to Deck
4	Deck Wetnesses per hour	R.M. in feet, generally at the F.P.	WL to Deck
5	Hull Slams per hour	R.M. in feet, generally at Sta. 3	WL to Keel
6	Water Contacts per hour on Catamaran Cross-Structure (C-S)	R.M. in feet, at fwd end of C-S	WL to C-S
7	C-S Slams per hour	R.M. in ft, at C-S	WL to C-S
8	Significant Pressure on C-S in psi	R.M. in ft, at fwd end of C-S	-
9	Hydrofoil Broachings per hour	R.M. in ft, at hydrofoil	WL to top of foil

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
3	13-15	13	ISEA	Code for irregular-wave spectra to be used
			ISEA=1,	for Station INDIA spectra only
			ISEA=2,	for Ochi six-parameter spectra only
			ISEA=3,	for Station INDIA spectra and Pierson-Moskowitz spectra
			ISEA=4,	for Ochi six-parameter spectra and Pierson-Moskowitz spectra
			ISEA=5,	for all three sets of spectra
3	16-18	13	IPE	Set IPE to 1 if cumulative statistics are to be applied to the Station INDIA data to predict the probability of occurrence of the response over a one-year period in the North Atlantic. Results will be presented as percentage exceedance. If not required, set IPE to 0.
3	19-21	13	IPLLOT	Code for response(s) to be plotted
			IPLLOT=0,	if no plots are required
			IPLLOT=1,	if only significant values of the basic response are to be plotted
			IPLLOT=2,	if significant and most probable extreme values are to be plotted
			IPLLOT=3,	if only extreme values for design use are to be plotted
			IPLLOT=4,	if only the supplementary response designated by ISR is to be plotted

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
3	19-21	13	IPL0T=5,	if all computed responses are to be plotted
3	22-24	13	ISYMA ISYMA=3,	Code for symbol to be used when plotting data derived from INDIA spectra will produce the symbol † There will be one data point for each of the 323 INDIA spectra
3	25-27	13	ISYMB ISYMB=0,	Code for symbol to be used when plotting data for Ochi six-parameter spectra will produce the symbol □ There will be 11 data points for each wave height used.
3	28-30	13	ISYMC ISYMC=11,	Code for additional symbol to be used when plotting the most probable six-parameter data; one data point for each wave height will produce the symbol * Since the most probable six-parameter data is plotted twice, the resultant symbol is ⊠ if ISYMC=0 and ISYMC=11

Notes:

- (1) Responses are plotted as a function of significant wave height. In addition, percentage exceedance is plotted as a function of the basic response, if IPE=1.
- (2) Other symbols may be used if desired; see Calcomp manual.
- (3) Pierson-Moskowitz data is plotted as a solid line.

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
4	1-8	F8.2	BPL	Ship length (L_{gp}) in feet
4	9-16	F8.2	DISPL	Ship displacement in long tons (optional)
4	17-2	F8.2	VKT	Ship speed (V) in knots
4	25-32	F8.2	BETA	Heading angle (μ) in degrees BETA=180, for head seas BETA=90, for beam seas BETA=0, for following seas
4	33-40	F8.2	C	Constant for converting input transfer function to proper dimensions; see IFORM, Card 3.
4	41-48	F8.2	CLR	Vertical distance (absolute value) in feet required for calculation of supplementary response; see ISR, Card 3 Distances should be measured from the running waterline if possible
4	49-56	F8.2	ALPHA	Constant (α) required for calculation of extreme values for design use ALPHA=.01, for 99 percent assurance
4	57-64	F8.2	XKK	Constant (k) required for calculation of significant pressure on catamaran cross-structure, when $ISR = 8$. k is dependent upon the cross-structure section shape

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
4	65-72	F8.2	RDOT	Threshold velocity (\dot{r}_z) in ft/sec required for calculation of slams, when ISR=5 or ISR=7. If \dot{r}_z is not input, program will assign a value of $\dot{r}_z = 12.0 \sqrt{L_{BP} / 520}$
5	1-8	F8.2	YINC(1)	Scale for one inch on plots of significant values of basic response
5	9-16	F8.2	YINC(2)	Scale for one inch on plots of most probable extreme values
5	17-24	F8.2	YINC(3)	Scale for one inch on plots of extreme values for design use
5	25-32	F8.2	YINC(4)	Scale for one inch on plots of supplementary response, ISR

Notes: (1) If no plots desired, or if program is to set appropriate scales, leave Card 5 blank.

(2) Abscissa for basic plots is significant wave height; scale for one inch is 8 ft; abscissa is 7 inches long.

(3) Ordinate for basic plots is the appropriate response in dimensions specified on Card 2, or the fixed dimensions specified for supplementary responses; ordinate starts at 0.0 and is 8 inches long.

(4) Scales for percentage exceedance diagrams are set by program.

TRANSFER FUNCTION - OPTION 1 (IFREQ=1)

<u>CARD</u>	<u>COLUMNS</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
6	<p>There is no Card 6 when IFREQ = 1.</p> <p>Do not insert a blank card.</p> <p>Wave frequencies ω are set in program</p> <p>ω_i ($i = 1,81$) = 0, .025, .05, .075, 1.975, 2.0</p>		
7a	1-8	F8.3	TF(2) Transfer function at $\omega = .025$
	9-16	F8.3	TF(3) Transfer function at $\omega = .05$
	.	.	.
	.	.	.
	.	.	.
	.	.	.
	73-80	F8.3	TF(11) Transfer function at $\omega = .25$
7b	1-8	F8.3	TF(12) Transfer function at $\omega = .275$
	.	.	.
	.	.	.
	73-80	F8.3	TF(21) Transfer function at $\omega = .50$
7c	<p>Continue with same format; 8 cards total.</p> <p>TF(1) is set to zero in program.</p> <p>TF must be in form indicated by IFORM on Card 3.</p>		
7d			
7e			
7f			
7g			
7h	1-8	F8.3	TF(72) Transfer function at $\omega = 1.775$
	.	.	.
	.	.	.
	73-80	F8.3	TF(81) Transfer function at $\omega = 2.00$

TRANSFER FUNCTION - OPTION 2 (IFREQ=2)

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
6a	1-8	F8.3	WAVEL(1)	Values of $\frac{\text{wave length } \lambda}{\text{ship length } L}$ at which transfer function is input
	9-16	F8.3	WAVEL(2)	
	.	.	.	
	.	.	.	
	73-80	F8.3	WAVEL(10)	
6b	1-8	F8.3	WAVEL(11)	λ/L can be in either ascending or descending order, and need not be equally spaced.
Continue with 10 values per card. Max. is 5 cards.			.	
			.	
			.	
			.	
			WAVEL(NWL)	
7a	1-8	F8.3	TTF(1)	Values of transfer function corresponding to λ/L values on Cards 6a, 6b, etc.
	9-16	F8.3	TTF(2)	
	.	.	.	
	.	.	.	
	73-80	F8.3	TTF(10)	
7b	1-8	F8.3	TTF(11)	Transfer function must be in form indicated by IFORM on Card 3.
Continue same as 6a, 6b, etc.			.	
			.	
			.	
			TTF(NWL)	

TRANSFER FUNCTION - OPTION 3 (IFREQ=3)

<u>CARD</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>FORTRAN</u>	<u>EXPLANATION</u>
6	1-8	F8.3	TWMIN	Minimum, maximum, and increments of nondimensional encounter frequency $\omega_e \sqrt{L/g}$ at which transfer function is input
	9-16	F8.3	TWMAX	
	17-24	F8.3	TWINC	
7a	1-8	F8.3	TTF(1)	Transfer function at $\omega_e \sqrt{L/g} = TWMIN$ Transfer function for increments of $\omega_e \sqrt{L/g} = TWINC$
	9-16	F8.3	TTF(2)	
	.	.	.	
	.	.	.	
	73-80	F8.3	TTF(10)	
7b	1-8	F8.3	TTF(11)	$NTW = \frac{TWMAX - TWMIN}{TWINC} + 1$ Transfer function at $\omega_e \sqrt{L/g} = TWMAX$
	.	.	.	
	.	.	.	
	.	.	.	
	.	.	.	

Continue with
10 values per card.
Max. is 5 cards.

Note: The DTNSRDC Pitch-Heave Motion Program PHM (formerly designated YF17) has a provision for punching pitch, absolute motion, and relative motion transfer functions according to the Option 3 format.

TRANSFER FUNCTION - OPTION 4 (IFREQ=4)

CARD	COLUMNS	FORMAT	FORTRAN	EXPLANATION
6a	1-8	F8.3	YR(1)	Values of wave frequency ω at which transfer function is input Must be in ascending order.
	9-16	F8.3	YR(2)	
	.	.	.	
	.	.	.	
	.	.	.	
	73-80	F8.3	YR(10)	
	.	.	.	
	.	.	.	
	.	.	.	
	.	.	YR(NWL)	
<div style="border: 1px solid black; padding: 5px; width: fit-content;"> Continue with 10 values per card. Max. is 5 cards </div>				
7a	1-8	F8.3	TTF(1)	Values of transfer function corresponding to ω values on Cards 6a, 6b, etc.
	9-16	F8.3	TTF(2)	
	.	.	.	
	.	.	.	
	.	.	.	
	73-80	F8.3	TTF(10)	
7b	1-8	F8.3	TTF(11)	Transfer function must be in form indicated by IFORM on Card 3.
	.	.	.	
	.	.	.	
	.	.	.	
	.	.	TTF(NWL)	
<div style="border: 1px solid black; padding: 5px; width: fit-content;"> Continue with 10 values per card. Max. is 5 cards </div>				

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