DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER
Bethesda, Md. 20084

THE USE OF SEAKEEPING IN SHIP OPERATIONS: A STATUS REPORT

by

Susan Lee Bales

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SHIP PERFORMANCE DEPARTMENT

November 1976

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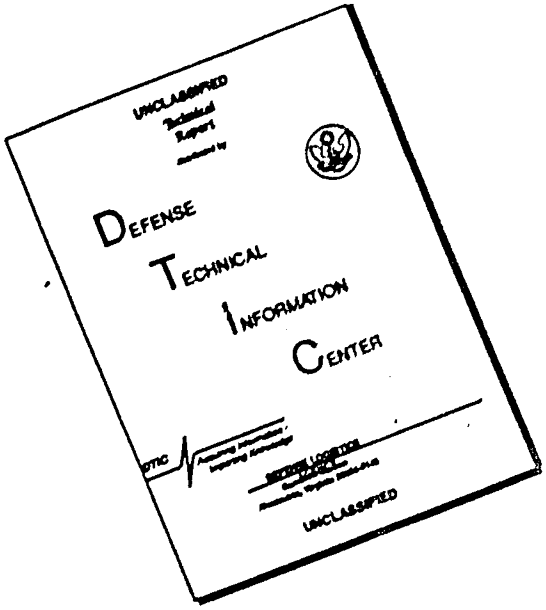

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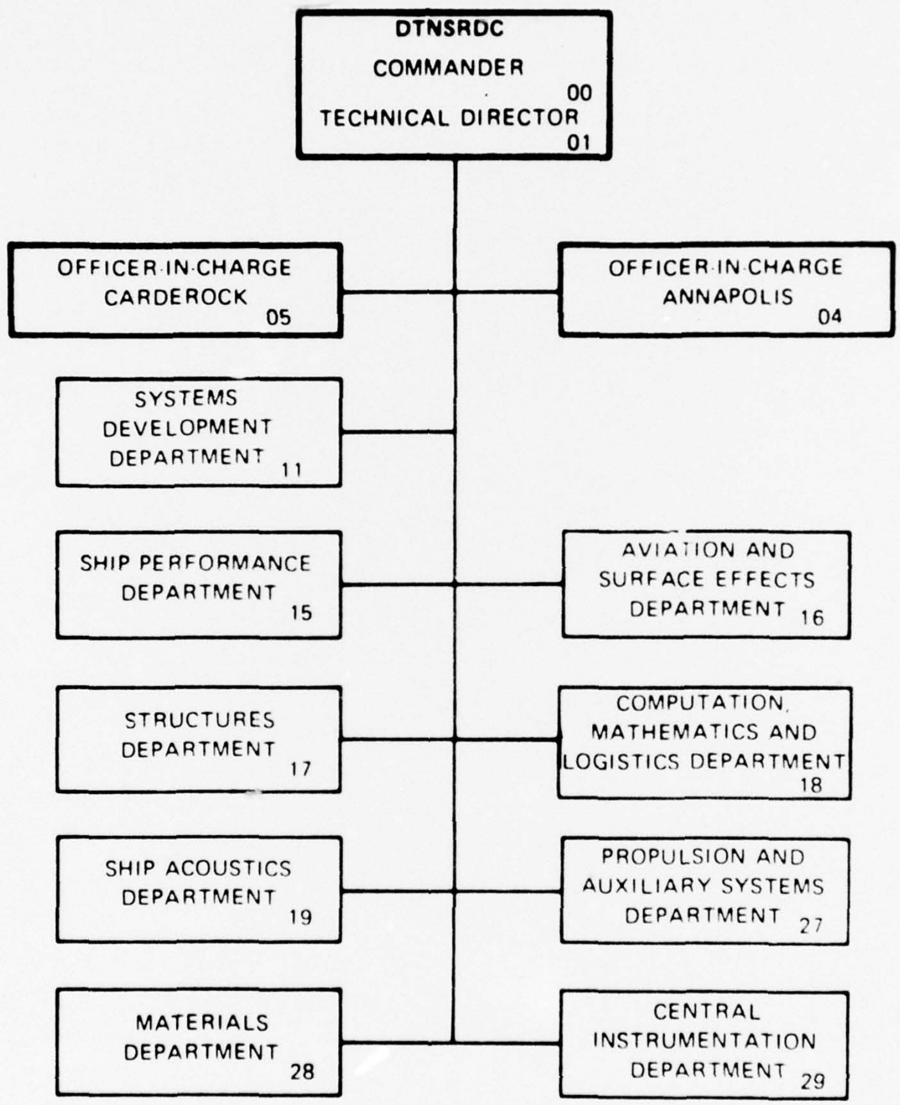

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This report is the first in a series that will consider the inclusion of seakeeping in ship operations. The primary topic covered is the utilization of known ship performance data in the process of making operational decisions. State-of-the-art ship routing techniques are described and suggestions for improved routing techniques which reflect forecast wave conditions as well as the response characteristics (attainable speed) of the ship are given. The

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ABSTRACT

This report is the first in a series that will consider the inclusion of seakeeping in ship operations. The primary topic covered is the utilization of known ship performance data in the process of making operational decisions. State-of-the-art ship routing techniques are described and suggestions for improved routing techniques which reflect forecast wave conditions as well as the response characteristics (attainable speed) of the ship are given. The need for on-board seakeeping guidance of the fleet is illustrated and it is considered that the ongoing cooperative efforts of the research, design, and operations communities can now provide such guidance.

ADMINISTRATIVE INFORMATION

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BACKGROUND

During the past few years there has been an increasing amount of dialogue between the naval research, design, and operations communities. Perhaps the most enthusiastic dialogue occurred at the Seakeeping Workshop held at the United States Naval Academy in June 1975. The purpose of this workshop was to provide guidance in the formulation of an R&D program to develop and implement the required technology for a performance-oriented seakeeping design practice for naval ships. The major findings and recommendations of this workshop are presented in reference 1.*

The need for a continuing and productive dialogue between researchers, designers, and operators is stressed in reference 1, and this report summarizes the current joint efforts of the three groups to address, and hopefully solve, some of the real problems experienced by the fleet. The major item covered here is the inclusion of seakeeping in ship operations. Specifically, the topics covered are the use of seakeeping in ship routing and the provision of on-board seakeeping intelligence to ship operators.

THE PROBLEM

The behavior of a ship at sea is dependent primarily on its dynamic responses to the waves it encounters. The overall mission effectiveness of the ship is dependent on this wave induced dynamic behavior as well as on other environmental factors such as atmospheric electromagnetic properties which affect detection and defense systems reliability. Reference 2 provides a discussion of typical problems encountered by the fleet due to at-sea environment factors. The reference, a trip report by the Meteorological Officer of the now decommissioned USS Oriskany (CVA-34), reveals that waves (height, period, direction) were the most important factor affecting cruise planning and operations. The reference also reveals the great dearth of actual on-board knowledge regarding the ship's behavior in waves--though eventually of course some knowledge was gained simply through the experience of riding the ship.

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*A complete list of references is given on page 19.

The reference elaborates on the difficulties encountered in transiting, (i.e., loss of speed), in underway replenishment, in aircraft operations, etc., all of which were due to the environment and inadequate knowledge of its possible effects on the ship performance. Procedures for forecasting the local weather and how it was used for planning tactical operations are discussed. It is made quite clear that the limited on-board intelligence in the areas of ship behavior and local wave conditions could and did impact on the planning of tactical maneuvers, transits, etc., that improved knowledge in these areas could decrease the time spent in trying to carry out such operations, and thus improve overall mission effectiveness. It is also apparent that it may not be trivial to use existing, large scale weather (including oceanographic) forecasting programs available at Fleet Numerical Weather Central (FNWC) for local operational purposes due to the wide grid spacing inherent in the global programs and the sometimes slow (hours) turn-around in communications with FNWC.

The primary problem which this report addresses is that of the effects of wave environment on fleet operations as discussed and emphasized in reference 2. Specifically, the use of seakeeping in fleet operations is addressed, and some guidelines for providing seakeeping knowledge for the planning of tactical operations, ship routing, etc. are given. The report is not intended as a final report on the subject and attempts merely to discuss initial progress that has been made and to identify near future action items.

SOME SOLUTIONS

A one day workshop in the use of seakeeping in ship operations was held on 6 October 1976 at FNWC in Monterey, California. Participants in the workshop included representatives of FNWC, Naval Oceanographic R&D Activity (NORDA), Naval Environmental Prediction Research Facility (NEPRF), Naval Ship Engineering Center (NAVSEC), DTNSRDC, and Webb Institute of Naval Architecture. A list of attendees is given in the Appendix. The workshop consisted of a series of informal presentations and discussions by various members of the group.

The major topics of the day centered on the problem of providing on-board quantitative guidance to the ship operator regarding the behavior of the ship at speed in a seaway. This consisted of several major subtopics, including the use of predicted ship motions for forecasted wave conditions as an aid to the ship router, the use of on-board motion measuring devices as an aid to the ship operator in identifying increasingly severe sea conditions, and the use of previously generated or real time ship performance (i.e., attainable speed operating envelopes) data as an aid in making operator decisions such as heading and speed changes.

The purpose of this report is to summarize the major topics discussed during the workshop and to list the recommendations and action items identified by the group.

WAVE DATA - FORECAST

FNWC provides the U.S. Navy (and others) with forecasts of global weather patterns that are transmitted to four smaller naval weather centrals for refinement and transmission to the fleet. Four large-capacity digital computers are available at FNWC to provide the required meterological forecasts.

In addition, oceanographic data for the Northern Hemisphere in the form of directional wave spectra are generated several times a day for up to 72 hours in the future. The spectra are forecast by the Spectral Ocean Wave Model (SOWM), see reference 3, which is based primarily on the work of Professor Willard J. Pierson. The most important input to SOWM consists of wind velocity fields which are developed from as many as 1400 separate daily data sources. The daily reported data from these 1400 stations consists of at least wind direction and speed, sea level pressure, air and sea temperature, and wave height. All but the wave/swell and sometimes the wind direction/speed data are measured by standard instruments.

Other meteorological predictions are also made using an ANALOG system. The ANALOG or "weather-typing" system consists of matching present weather conditions with similar conditions which previously occurred in order to forecast future weather conditions. Somewhat tedious and not truly accurate, the ANALOG model is more reliable in fall and winter than in spring and summer.

The Optimum Track Ship Routing Group (OTSR) provides, on the basis of the forecasted conditions, ship routing which is available to all naval ships and selected commercial cargo carriers under contract to Military Sealift Command (MSC).* Two criteria are currently used by OTSR to provide routing guidance. The primary one is based on the optimum path work of James, see reference 4, and utilizes ship speed versus wave height as a function of ship heading and ship type, see Figure 1 adopted from reference 5. The James data is derived from ship logs and thus provides a combined voluntary/involuntary speed loss criterion for each ship type. The James data appears in various analytic models, see reference 5, though unfortunately the data has not been compiled for any naval combatants and no commercial ships designed and put into operation since 1957.

The second criterion currently used in ship routing constrains ships from operating in areas where sea conditions exceed predetermined values. The criterion is used as a supplement to James's work, is based solely on past years of experience (to avoid damage), and is admittedly conservative especially for the newer, faster, longer commercial carriers and naval combatants. Figure 2, adopted from reference 6, is illustrative of this routing technique which frequently uses a 12-foot significant wave height constraint. The contours are for significant wave height and the shading indicates areas where the forecasted significant wave height exceeds 12 feet. Track A is the shortest route, e.g., great-circle track between the two ports of New York and Southampton, England. Track B is the route, following the 12-foot wave height contour, that would be recommended by OTSR. Although the shortest distance track is Track A, ships proceeding along it would encounter 28-foot waves.

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*For example, naval ships conducting trans-Atlantic transits in excess of 1500 miles during October to April must proceed at latitudes in the lower 30's unless an alternative route is provided by OTSR.

This may necessitate severe reduction of speed in order to avoid severe storm damage from green water and slamming (bow-to-head-seas) or a loss of stability (beam-to-quartering-to-following-seas) could be experienced. Though longer in distance, Track B could be transitted in less time than A with little likelihood of severe storm damage to either the ship or cargo. All ships, regardless of size, or type, would be routed along Track B. The success of the routing technique is heavily dependent on the assumption of the accuracy of the wave contours. The assumption that a 12-foot significant wave height is the limiting value at all relative ship headings for all ship types may severely penalize ships such as the more recent cargo carriers and naval combatants which can transverse 12-foot seas reasonably comfortably.

The casualty reported in reference 7 indicates that at least one contributing cause of the disaster was FNWC's inability to predict the severe storms which the ship encountered during 25 to 26 December 1969 in the North Pacific. Traditionally, the wave height contours of Figure 2 have been developed from charts of predicted wind speeds and directions. Now, FNWC has the capability of developing them from the forecast directional wave spectra provided by SOWM. Reference 3 demonstrates FNWC's improved ability to forecast storm as well as moderate sea conditions via SOWM. Coupling these forecasts with a knowledge of the behavior of individual ships in waves similar to that developed by James could potentially provide a much more realistic basis on which to route ships. This coupling could include the effects of wave period and wave direction, identified to be as important as wave height, on ship behavior by reference 2.

Thus a consensus on what is now needed to enhance the use of SOWM in ship operations (routing) is

1. further validation of the SOWM model,
2. marriage of the model with a ship motion model which includes some criteria for predicting attainable speed envelopes and thus will provide more reliable and realistic routing guidance to the operators, e.g., based on a knowledge of the dynamic behavior of the ship in a seaway.

One difficulty to overcome in doing either of these is the fact that grid points for which spectral forecasts are made are up to about 190 nautical miles apart. Thus, exact comparisons of measured and forecast data will be difficult to perform, except in specific areas and for ships equipped with instrumentation, and instead perhaps long-term trends or statistical distributions across transits should be compared. Much of the rest of this report is devoted to a discussion of the two requirements (validation of SOWM, marriage of SOWM with ship motions) described above.

SHIP MOTION DATA - PREDICTED

The state-of-the-art in ship motion predictions is summarized in reference 5. It is now possible to join the ship motion models with SOWM to predict ship motions in a directional seaway by techniques [for example integration of the product of the "averaged frequency and direction" ship response amplitude operators (RAO's) and the SOWM output directional energy bands] originally presented in reference 8. DTNSRDC can provide FNWC with the proper RAO data bases for specified ships such that on-line ship motion predictions using the SOWM forecasts could be generated for use in ship routing. Figure 3, adopted from reference 3, provides a typical output of SOWM for a grid point in the North Pacific. The matrix of data consists of the energy bands for wave frequencies f from 0.39 to .164 herz* and for round-the-clock directions in 30-degree increments. Matrices of averaged response amplitude operators can be generated in a similar manner such that the root mean square ship response is calculable from the product of the two matrices.

In order to use such raw motion data for routing, however, it is necessary to establish some performance criteria as a function of ship type that is easily used by OTSR. One such criterion that is suggested is the use of upper bound shoring loads, as developed in reference 5, to establish limits on ship operations when cargo sliding or free fall situations occur at various positions

*The current frequency range used is from .039 to .308 herz. This corresponds to the range of wave frequencies to which conventional surface ships respond.

in the ship. Though a usable criterion, this one may provide limits that are much too high for say cargo ship operations because it was originally developed as a design tool and the values produced may not be refined enough for operational use.

The need for well-defined speed limiting criteria, for example those limits that interfere with mission performance, is considered essential and one such approach is suggested. Figure 4, from reference 9, presents, as a polar plot, the attainable ship speeds as a function of ship heading in order for aircraft to be launched, recovered, and cycled below deck. The plot, actually an operational envelope for a specified significant wave height, gives a quick view of the operating conditions (speed and heading combinations) which will produce ship motions, e.g., roll, that may limit aircraft operations. Given that such speed-induced motion limits are known, such graphs can be constructed for various missions (e.g., mobility, antisubmarine warfare, etc.) and used as a guideline in evaluations of performance effectiveness.

Two uses of these plots are immediately obvious in the context of ship operations. The first is to develop as complete a data base as possible of such graphs, called say an ADVISORY PACKAGE, for on-board use by the ship operator. This package could be constructed for specified sea conditions defined by theoretical wave spectra, and on ships equipped with sufficient computer capacity, software could be developed to assist the ship operator in accessing and interpreting the data through an interactive graphics display.* Ships with ample computer capacity, e.g., flagships, could access

*Tables of predicted ship responses for a wide range of ship speeds, ship headings and sea conditions are provided in reference 5. Attempts to use these types of tables, during full-scale trials such as described in reference 10, as a guide for making heading and speed changes such that aircraft could be operated have not been entirely successful. This is true for at least two possible reasons. One, it is difficult to determine the ship speed, and two it is difficult to match the occurring wave period and height to a theoretically defined wave spectrum for which calculations have been done. Perhaps the use of a more realistic wave spectral definition, together with some easily used interpolation schemes can improve this situation and be used with speed limits to produce the polar plots.

their own data base of RAO's, and, given the proper environmental descriptions transmitted from FNWC, construct their own real-time operational envelopes for local conditions such as shown in Figure 4 based on the aforementioned speed limits. The second use of this type of graph would be in conjunction with SOWM and for purposes of ship routing. This technique could provide a way to provide transit routings based on either very high or extreme ship motion levels or on motion levels that limit missions which the ship must perform in transit. Thus, the use of attainable speed envelopes is analogous to the present use of the James Attainable Speed Curves. Likewise, if on-line communications between FNWC and naval ships can be improved (from the viewpoint of turnaround time), it would seem possible that FNWC could participate in more local tactical routing by use of such graphs of attainable speed envelopes. Here again though, a difficulty to overcome rests in the sometimes wide spacing between grid points. A possible solution is interpolation between existing grid points, though in coastal areas this may not be sufficiently accurate. Another possibility is of course to increase the number of grid points in selected, strategically important areas.

SHIP MOTION DATA - MEASURED

The Heavy Weather Damage Avoidance System (HWDAS) is currently being used aboard the LASH ITALIA under joint sponsorship of the Maritime Administration, the National Maritime Research Center, Prudential Lines, and Edo Government Products Division. The LASH ITALIA has now made several trans-Atlantic crossings with the system which provides measures of bow accelerations and midship hull girder (longitudinal) strain in 15-minute intervals. The measurements, provided on the bridge, are displayed in terms of percentage increase or decrease between the current time interval and the previous one. Though there was, at least initially, some reluctance on the part of the ship's captain to consult it, the HWDAS has generally demonstrated its value as an on-board routing aid. Reference 11 provides further details on the use made of HWDAS during LASH ITALIA transits.

The use of HWDAS in conjunction with the SOWM wave forecasts in ship routing is attractive from the viewpoint of providing a validation of a combined SOWM and ship motion model. For example, full-scale measurements can be compared with ship motion predictions derived from SOWM wave spectra and DTNSRDC ship response amplitude operators. Also attractive of course is the fact that HWDAS provides the ship's operator with quantitative (percent change) real-time seakeeping guidance or intelligence for his own operating decisions.

The installation of HWDAS on a ship frequently routed by OTSR at FNWC would be desirable. One such candidate is a C-2 (FURMAN, C2-S-AP3) which frequently transits the Pacific between the West Coast and the Philippines under FNWC routing. An installation on this ship would permit FNWC one means of validating the use of SOWM in routing. The cost of such an installation is suggested to be at least $50,000 though less than $100,000.

There is some question as to whether or not HWDAS is required to perform this validation. For example, ship-board instrumentation, for purposes of developing long-term ship response distributions, has been in use for some years on various commercial carriers. This extensive effort, under Ship Structures Committee sponsorship, may be just as useful in validation of SOWM. Comparisons with ship responses predicted using wave hindcasts and measured over a given transit could be made.

Work by other, e.g., non-Navy, groups should be examined for any overlaps that may occur in the use of the spectral wave model. One such company, OCEANROUTES, provides forecasting of wave conditions in both the North Sea and the Gulf of Alaska for purposes of routing of oil rigs during mobilization and towing of barges or offshore structures. The spectral model used is apparently similar to SOWM though the grid spacing is reduced to 30 to 90 nautical miles. Further, dynamic vessel responses in spectral form are predicted, at least for the Gulf of Alaska model, and may be of interest for comparative purposes. Reference 12 gives more details on the OCEANROUTES model.

CONCLUDING REMARKS AND ACTION ITEMS

The progress made to date in solving one operational problem experienced by the fleet has been discussed and a list of near-term action items to carry out possible solutions will be given. The problem in a nutshell, concerns the dearth of seakeeping intelligence available for making real-time naval operational decisions. A knowledge of current environmental factors and their effect on the dynamic behavior of ships is required for both planning and carrying out fleet operations. Selecting optimum routes for oceanic transits, planning local tactical operations, carrying out underway replenishments, completing successful aircraft operations, etc. could all be enhanced by improved on-board seakeeping intelligence. The following items should be acted upon as soon as possible in order to make any further progress in this direction possible.

1. Determine means by which measured ship responses can be compared to predicted ones using SOWM directional spectra. Select existing measurements, such as those collected for the Ship Structures Committee, or determine a procedure for obtaining them anew. Installation of HWDAS is expensive ($50,000 - $100,000) and provides only certain information but it is thence permanently available on the ship. A full-scale trial may be comparably priced as well as provide a wider base of measured data, but the instruments are not permanently installed, and thus permanent future seakeeping guidance to the ship's operator is not provided. Validation may require data from a number of at-sea periods, so the use of fairly automated, unmanned instruments may be desirable.

2. Assuming new measurements are required, provide proper support personnel, cognizant of all aspects of the objectives, to be aboard the ship selected for the full-scale trials. A FNWC Navy officer familiar with routing strategies, etc. may be ideal as well as cost effective. Additionally, the ship selected should be one familiar to OTSR personnel such as the Pacific-based C-2 mentioned previously.

3. Determine suitable format for storing response amplitude operators (RAO's) of specified ship for use with SOWM directional spectra. Develop appropriate data base of RAO's and establish response sensitivities to ship load conditions. Develop software required to implement the procedure required to combine the RAO's, the SOWM spectra, and speed limits to produce attainable speed envelopes.

4. Develop machine tools to be used by OTSR group to simulate ship routings. One program to be developed should implement existing routing criteria such as the avoidance of seas with significant wave heights greater than 12 feet and the James speed reduction curves. A second program which contains criteria based on dynamic ship motion limits such as for roll, pitch, slams per hour, cargo loads, etc., should be developed in order to prepare attainable speed envelopes. Determine, evaluate, and compare the effects of the various criteria on the ship routes selected by the computer programs and the extreme motions therefore experienced by the ship.

5. Identify, and where possible quantify, appropriate ship motion limiting criteria for use in operations planning, ship routing, attainable speed envelopes.

6. Develop ADVISORY PACKAGE based on available ship motion limiting criteria for the ship to be instrumented (if one is) and educate ship operator on its meaning and applicability to operations. Determine the usefulness of this type of seakeeping presentation by trying to use it during any upcoming full-scale trials. Modify the PACKAGE format or contents to improve its generic and specific ship type usefulness in fleet operations.

7. Evaluate the progress made by other, e.g. non-Navy groups, in operational use of forecast directional spectra. Examine the effect of finer spaced grid points on operational use of SOWM for both local tactical and oceanic-transit routing.

8. Develop funding and milestone schedule for program. Determine lead code, agency for each task to insure a timely and orderly degree of accomplishment.

The items listed above, not necessarily in order of preference, provide a preliminary backbone for formulating a cohesive program for putting sea-keeping in the ship operations process. It is expected that a great deal of benefit to the fleet can be gained by a relatively small but joint effort by the naval agencies which participated in this workshop. Improved ship routing and operational planning are, of course, important to other than naval combatants--in fact, it would appear that initial investigation could most easily be completed for cargo carriers. Thus, it is worthwhile to invite other groups such as the Military Sealift Command and the Maritime Administration to help formulate and support the required technical programs.

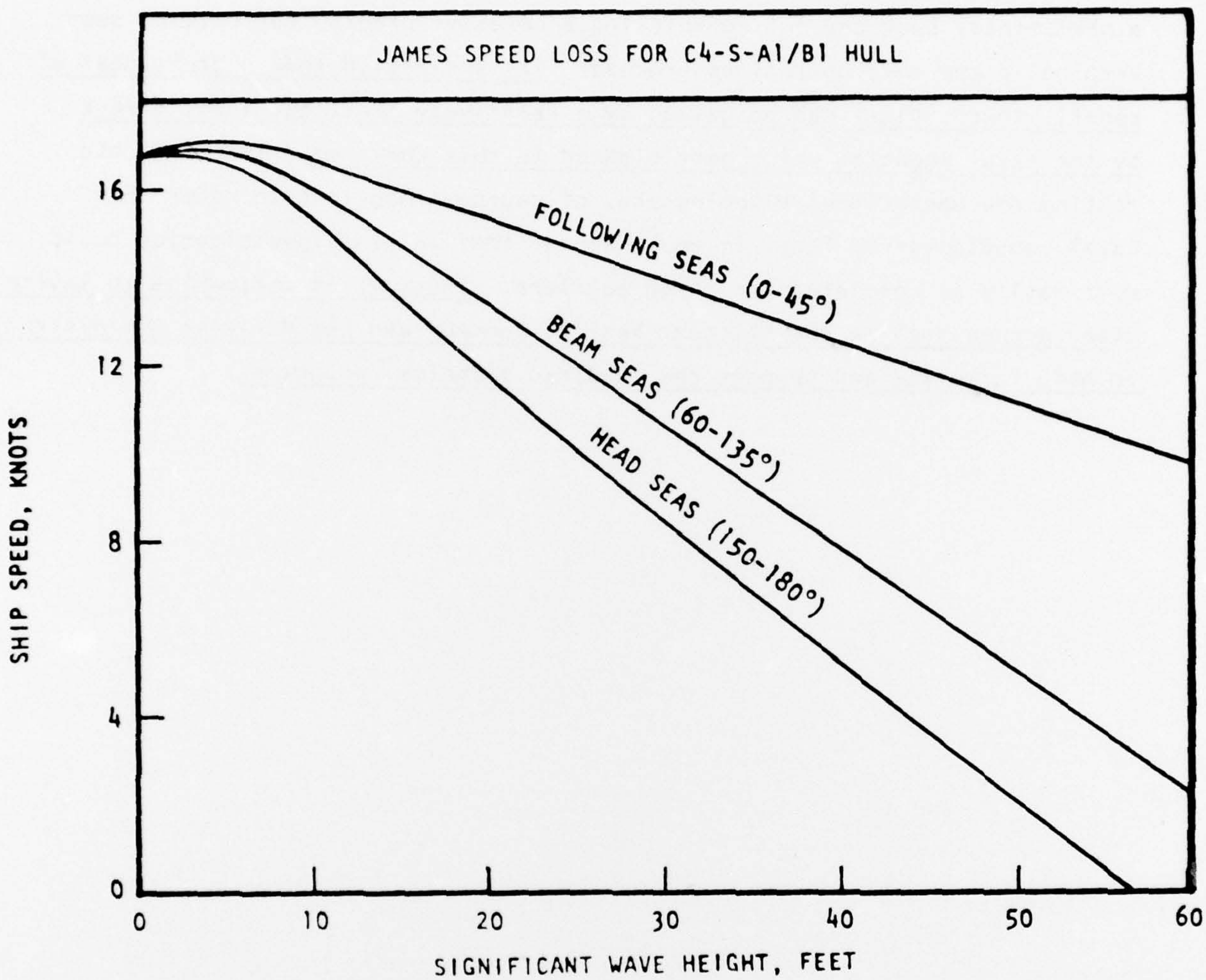

Figure 1 - James Attainable Speed Curves

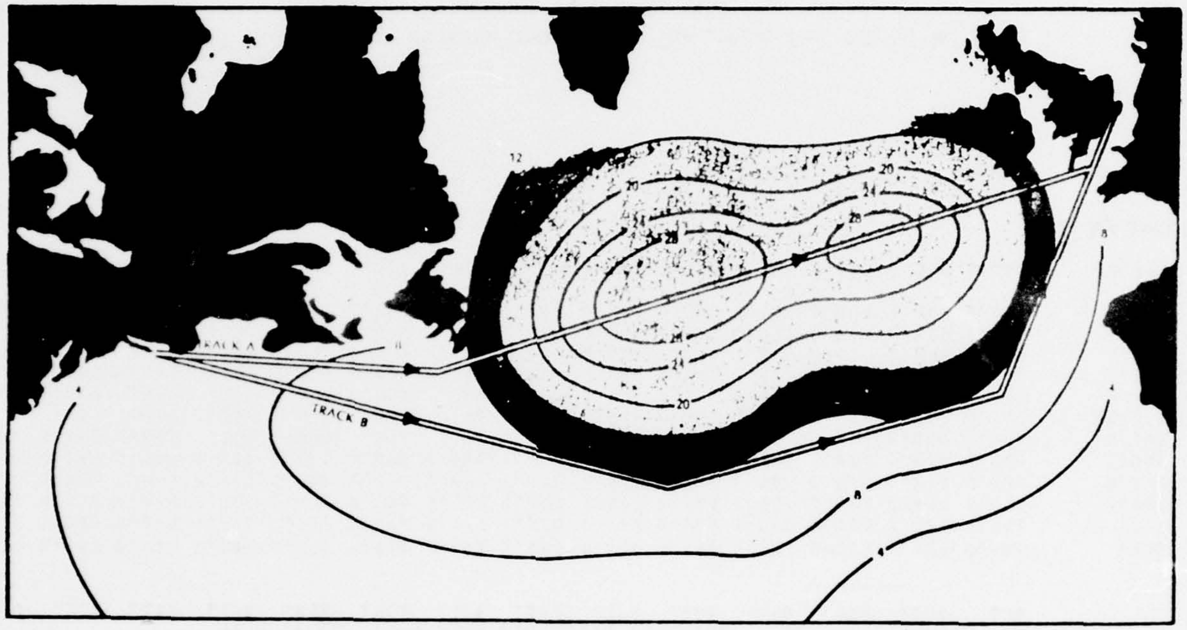

Figure 2 - Typical Optimum Track Ship Routing across the Northern Atlantic

UTG= 59120200 TAU= 0

TIME STEP 1 SUBPROJECTION 2 GRID PT 57 LAT 27.162 LONG (EAST) 203.396
WIND SPEED 7.49 WIND DIR 233.6 USTR .26

FREQ DIR	.164	.153	.133	.117	.103	.092	.083	.078	.072	.067	.061	.056	.050	.044	.039		(MET DIR)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.001	120.77
2	0.000	0.000	0.000	0.000	0.000	.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.001	90.77
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	60.77
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	30.77
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.77
6	0.000	0.000	0.000	.007	.005	.139	.032	.058	.026	.290	.196	.519	.997	1.669	.348	4.097	330.77
7	0.000	.011	.033	.097	.233	.659	.585	.765	1.147	1.638	2.846	3.917	6.685	6.845	3.817	29.277	300.77
8	.011	.254	.315	.450	.417	.395	0.000	.304	.193	.306	.535	0.000	0.000	0.000	0.000	2.874	270.77
9	.025	.254	.233	.245	.103	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.929	240.77
10	.028	.233	.364	.417	.102	.030	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.235	210.77
11	.011	.175	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.186	180.77
12	0.000	.007	.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.022	150.77
	.079	1.035	1.011	1.216	.858	1.123	.617	.828	1.366	2.145	3.577	4.436	7.683	8.514	4.165	38.622	

$\overline{H}$ 1/3=24.8 FT

Figure 3 - SOWM Two-Dimensional Wave Spectrum for 27.16°N, 156.29°W, December 2, 1969, 00Z

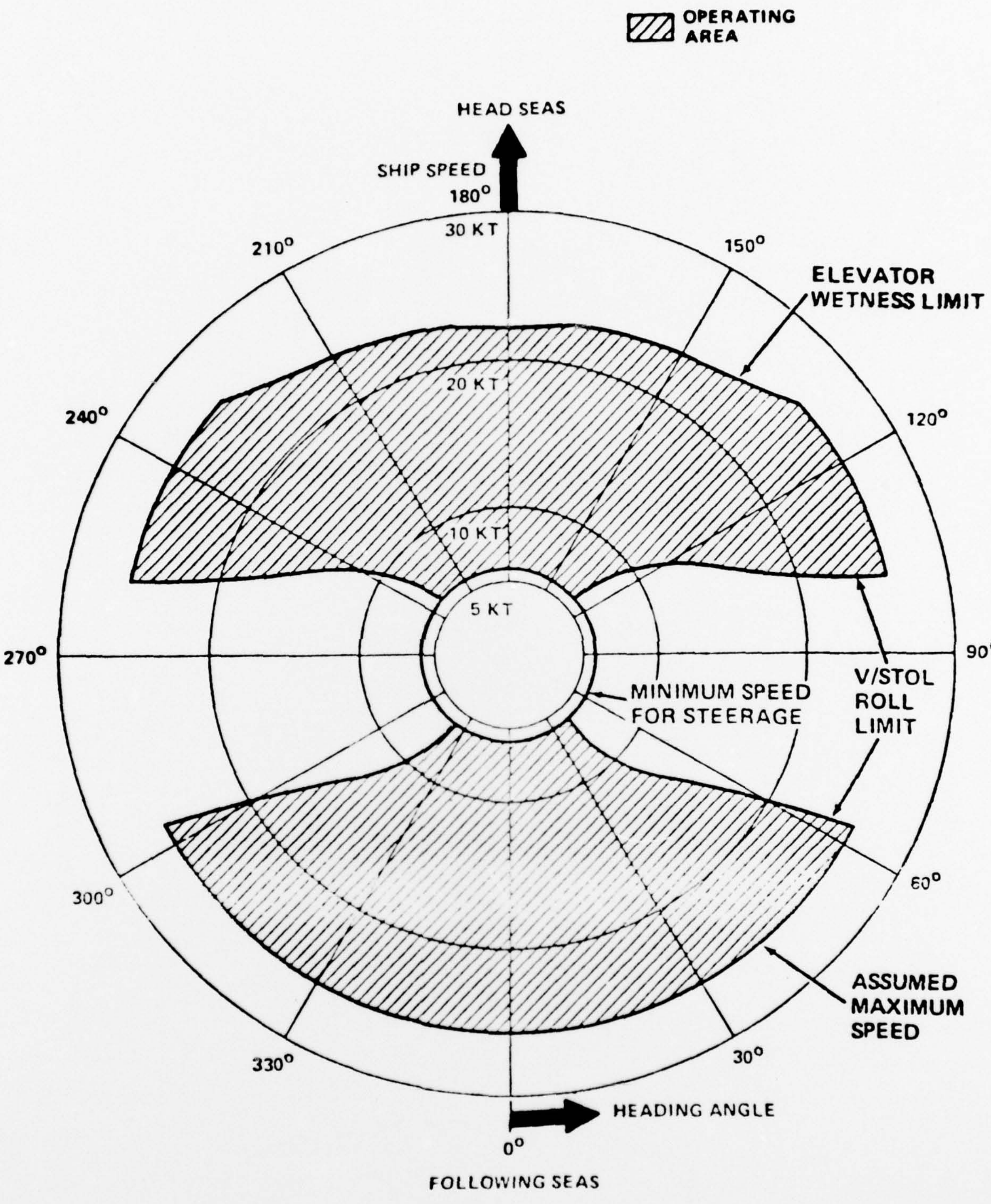

Figure 4 - Attainable Speed Envelope for V/STOL Support Ship "A" in Significant Wave Height of 11.48 Feet

APPENDIX

LIST OF ATTENDEES

	Name	Organization	Telephone
1.	A. E. Baitis	DTNSRDC 1568	202/227-1107
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6.	J. Hayes	FNWC	408/646-2817
7.	D. Hoffman	Webb	516/671-2356
8.	S. M. Lazanoff	NORDA	408/646-2817
9.	W. Reuter	NAVSEC 6120E	202/692-1899
10.	N. M. Stevenson	FNWC	408/646-2844
11.	LtCDR D. Sturr	FNWC	408/646-2817
12.	CDR J. B. Tupaz	NEPRF	408/646-2906
13.	LtCDR C. Workman	FNWC	408/646-2036

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