700-2

~~CHURCH~~
-D. ~~CLARK~~
W. BUCKLEY

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON 7, D.C.

STRUCTURAL DESIGN LOADS AND CRITERIA FOR 500 TON HYDROFOIL SHIP

(A study of an approach to this goal)

STRUCTURAL MECHANICS LABORATORY
TECHNICAL NOTE
SML-700-2

March 18, 1963

Encl (1) to DTMB ltr
Ser 7

C 10

4

ABSTRACT

This study discusses the factors to be considered as they would apply to the structural design of a 500-ton, 90-knot ship. A second section covers suggestions for theoretical development to obtain an understanding of the phenomenon involved. The third portion discusses full scale test craft program objectives while the final section concerns materials for the hull and hydrofoils. The program envisioned to establish design loads will pursue development of theoretical predictions with verification by full scale tests.

INTRODUCTION

The Bureau of Ships assigned to the Model Basin the task for development of structural design loads and design criteria as applied to a 500-ton, 90-knot hydrofoil ship. A research program is presently underway to explore some aspects of this problem. The following review was carried out as a background study to be used for amplifying the present program, reference 4, and modifying it where it would appear necessary.

DESIGN CONCEPT

After the PCH demonstrates its capability, it is probably that operational requirements will be developed for both larger and faster hydrofoil ships. The design of such ships will require a refinement in the assumptions and criteria used to permit optimizing performance with a rational design procedure. Report, reference 1, presents a theoretical discussion of such structural design requirements based, in part, on airplane design practices. Paper, reference 2, gives an abbreviated summary of these considerations. Paper, reference 3, is still another note on the many new considerations in design of hydrofoil ships in contrast to present surface ship methods. All of these reports indicate an urgent need for reliable load data. A principle objective of this program is to obtain verification of these procedures.

The concept for a 500-ton, 90-knot ship is still vague. The actual mission of such a ship will influence the design criteria. For instance, the sea state to be negotiated at a given speed, and possibility of topside weapons and electronics will effect the structures through the hydrodynamic stability requirements. However, this program to develop criteria is to be broad so that these variables can be covered by the data to be obtained. The concept of the 500-ton, 90-knot ship structure in this report is developed to illustrate the relations of various parameters and will be subject to changes to suit a particular set of requirements.

The general characteristics of a 500-ton ship capable of 90 knots have to be established, based on existing designs and test results. Incidental data on arrangements, weight of equipment, machinery, etc., can be derived from either or both the PCH and AGEH Contract plans, which are available. The hull structure and weight will have to be scaled and modified according to information developed by this program.

Some questions still exist as to the optimum hydrofoil configuration for the 500-ton ship. The SEA LEGS and PCH have the main lifting surface aft and supported by two struts.

The AGEH design has hydrofoils port and starboard, just forward of amidship, to support most of the weight. The AGEH also has a large hull overhang forward which may be unacceptable. This test program will help to provide a basis to establish an acceptable design for the 500-ton ship.

The hydrofoil configuration might be scaled from an alternate high speed supercavitating foil design required for the AGEH under the rules for awarding contract by Bureau of Ships. The supercavitating foil design could also be based on tests carried out by the Bureau of Ships test craft "FRESH I" for evaluating supercavitating hydrofoils. The Hydrodynamics Laboratory can assist with this selection.

The structural design for the lifting foils and the supporting struts is limited by hydrodynamic considerations which will present very serious problems for a 90-knot "supercavitating" ship. Considerable problems also arise in the shafting inside the struts during turns when struts are highly loaded and deflect, bending the shafts. The connections between the struts and lifting foils have to be made compatible with minimum drag design and the propulsion gearing has to be incorporated at this point also. This location at the juncture between foil and strut is usually the highest stressed material. It can be seen that any structural study of these members has to follow and be closely coordinated with hydrodynamic design criteria.

The structural design loads and design criteria to be developed must accomplish the following:

a. It must be possible to analyze the hull and hydrofoil structures developed for the 500-ton, 90-knot craft. These calculations are to cover normal operating loads in waves as determined by theoretical approach such as in report, reference 1, and verified by test program.

b. It must be possible to calculate ship survival from unusual loads such as impact with non-yielding obstacles while flying and from underwater explosions;

c. Procedures are to be included for approximate checks of hydroelastic and vibration problems during the preliminary design formative stages of ship. Use of exact procedures for these calculations shall be indicated where developed and the relative accuracy noted.

An explanation of the use of the data presented is to be shown as it would apply to the 500-ton ship. It is recommended that upon completion of this assignment, sample design calculations for this ship be included in the appendix.

The summary or appendix is to have a series of charts, tables, or other means of showing data so that the the designer can enter them with operational requirements such as limiting acceleration, speed, deadrise of hull, and determine parameters like hull clearance or wave induced hull pressures for a range of sea states. If the data is presented in form of equations, they should be solveable by use of desk calculating machines and without use of complicated mathematics.

THEORETICAL CONSIDERATIONS

Paper, reference 1, presents a proposed rational procedure for the ship structural design. Further information needs to be developed on the actual ship environment and related response of the ship with the loading involved.

Additional areas needing theoretical investigation are actual foil spanwise lift distribution, autopilot control, impacts with objects in water, weapons effects, and vibration considerations.

<u>Hull</u>

During take-off and landing operations, and on occasions when ship meets waves larger than the design height, the hull of the ship will slice through waves and crests. An autopilot failure could cause the hull to be "dropped" back into the water at high speeds, either on even keel or at some inclination. During take-off and landing operations, in large seas, the ship will ship "green water" aboard. The loadings from these conditions (load distribution) have to be established.

Various size and weight of objects may be at the water surface in harbors. A procedure is required to permit assessing of damage to hull which would result when such objects are hit by the hull or the struts. As an example, what mass (size) would displace the hull-strut foundation structure beyond elastic deformation? Impact loads from such objects need to be estimated.

The impact forces on the hull passing through wave crests need to be defined in terms of both magnitude, distribution, and duration. As an example, it should be possible to predict the load on a panel of shell plating and the total force at the bow and the duration of this condition. With this data, a method for determining the overall effect on the hull girder is to be shown with a procedure for estimating the whipping stresses along the hull.

Hydrofoils

The steady-state lift and drag forces on hydrofoils and their supporting struts are determined by hydrodynamic calculations. Forces on the hydrofoils and the struts (lateral areas) during turns are also primarily hydrodynamic calculations. However, the exact spanwise distribution of these loadings and possible variations in turns, which are not steady state normally, is not established and makes further development of hydrodynamic procedures desirable.

The loading on foils will not be steady state when the ship is proceeding through waves. The ship commander will have an option in autopilot adjustment to regulate the vertical accelerations of the ship and so control foil lift (through foil flaps) and optimize ship operation under existing wave conditions. This acceptable acceleration value has been considered to be less than one-half G for personnel operation efficiency. With this control, wave impacts on hull will be a function of sea state and designed hull clearance of ships.

Dynamic Factors

Based on the given steady-state loading of foils, a procedure has ~~been~~ to be developed to determine the dynamic factor to account for operation in random seas. This dynamic action will come about whenever the nominal wave heights become greater than the designed hull clearance plus about one-half foil submergence. The results of this study should show in form of tables, graphs, or nomographs, the variation of "G" loading under various sea states and hull clearance with an approximate number of each "G" during a given period.

The maximum strut loads will be during turning of ship. Based on hydrodynamic data to be requested, charts, tables, graphs or other means should be developed to show the factors above static load, which will result in turns of various radii and at different speeds. This data will have to include both the side load on the struts and the increased loads transmitted to the strut by hydrofoils in turns.

Hydrofoil Explosive Loading

A combat operational ship will be subject to explosive loadings from its own weapons or enemy action. The effects of these possibilities need to be evaluated for underwater weapons with respect to:

a. The effect on the foil structure and foil lift.

b. The effect on struts and hull foundations.

The hydrofoil lift is developed by flow circulation around the selected shape and by a cavity for the supercavitating type foil. With the hollow foil construction (used for PCH and AGEH), the foil plating and possibly the whole foil could be deformed. A method to predict the extent of such damage, and in case of the supercavitating foil, the effect of collapse of the cavity needs to be developed.

The explosive loads on the foils will be transmitted to the hull structure. This combined foil lift change and strut column force prediction procedure will be required to determine the requirements for the strut-hull foundation design.

The results of this investigation must be condensed to procedure for predictions of high explosives or nuclear weapons effects for the full range of possible attack severity. To assess the lift change it will be necessary to predict the extent of foil damage or distortions also.

Obstacles

There have been reports of the Russian hydrofoils running aground in the rivers, backing off and continuing their trip. A Supramar hydrofoil (surface piercing with steel foils) hit a solid railroad tie and sliced it in half at 45-degree angle. In this case the pieces hit the propeller and bent it so as to cause excessive vibration. There were cases of the impacts where the Supramar hydrofoil ferry hit a floating log causing foils to be forced out of adjustment, but without destroying the foils. The LCVP hydrofoil test craft "Halobates" with submerged, pivoted, forward foils hit a dock and broke the foil pivot and lost the foil, probably without damage to the foil itself. It should be noted that the extent of foil or hull damage from immovable objects depends a great deal on how strong the foil-hull foundation is designed.

Unless the hydrofoil-strut is made retractable, it will project out beyond the confines of the hull. As in case of "Halobates", this will present a problem coming along side and going aground in shallow water as in the case of Russian experience. When the struts and foil are retractable, they are not as rigidly supported and will probably deflect if a large immobile object is hit. In this event it will require adjustment of foil, but will not mean that the ship will be lost.

Hydrofoil (Obstacles)

In addition to normal operating loads, the hydrofoils or supporting struts could hit floating objects in the water when the ship is foil borne. As such objects are more likely in harbors, these possibilities would be at less than normal speed. The effect of resultant impact is a function of the size of ship and direction of impact. A procedure is required to permit an estimate of the mass of a floating object and the resulting forces on hydrofoil structures from an impact.

The hydrofoils extend for a considerable distance below the bottom of ship's hull. This added draft makes it possible that the ship would run aground on occasion just before take-off in shallow harbors. It is possible that the ship will hit some fixed underwater obstruction when flying also. In the event that the bottom of channel is yielding, a method should be provided to determine the drag force on strut while the ship is being stopped. If the underwater object is unyielding, a procedure for an estimate of the impact force is needed to design the hull foundation of strut.

Hydrofoil (Vibration)

The basic design of hydrofoil structure has been different on each boat or ship built. There have not been any noticeable hydroelastic problems except on propellers. However, the experience is with subcavitating hydrofoil shapes which are not subject to as high loading as proposed on higher speed supercavitating type.

The supercavitating foil sections are also relatively thin and flexable.

A study of proposed hydrofoil designs using supercavitating shapes is required to determine natural frequency and relative flutter problems. On the basis of this survey either an exact, or a simple, short approximate procedure is to be developed to permit a check of proposed new designs for problem areas before the design has progressed too far.

Problems could arise on supercavitating foils during take-off before a stable cavity can develop. The procedure to be developed should permit a check of vibration with speed and to indicate if and what resultant transition conditions could exist. The effect of a preload as on foil strust is to be determined and included in the design method.

TEST PROGRAMS

There is an urgent need to obtain ship performance and environment data to check assumptions made in design and needed in theoretical procedures. Figure 1, gives the major areas involved. The test program has to include comprehensive data correlating loads and craft motions with a particular sea state and also long term accumulated information on operational histories to establish environment factors.

An example of loading assumption made and to be checked is frequency and steepness of waves and the direction of relative ship course, which strongly influences the critical landing loads at high speed. A rational design needs to establish the number and type of such loads expected during the lifetime of ships to determine proper fatigue factors. Further assumptions are the point of impact during landing and usual landing time and speeds to determine the number of impacts.

There are or will be six hydrofoil boats or ships which merit consideration for use in program to get the desired test information. These are:

1. SEA LEGS, a 28-foot submerged foil test craft
2. PCH, a 110-foot submerged foil ASW ship
3. FRESH-1, a 50-foot submerged foil supercavitating experimental boat.
4. AGEH, a 200-foot submerged foil, experimental ship.
5. LCVP (highlander), a 38-foot surface-piercing foil boat.
6. DENISON, a 100-foot, controlled, surface piercing foil boat.

Some tests have been made of the stresses in the craft hull and struts and pressure data on the SEA LEGS. If good wave heights and hull clearance data was or can be obtained, some relation between craft vertical motion and foil stress dynamic factors for an approximate wave height may be determined. This data would be of considerable help to designer in establishing strut lengths. SEA LEGS tests could also help to obtain verification of strut forces and moments during turning, especially in non-steady state conditions and in waves as compared to calm water conditions used in design calculations. If landing velocities can be obtained in tests, with associated hull impact on pressures and distributions, a check of hull pressure prediction procedure may be possible. Vibration information on this craft with the type of installed machinery and foil supports is not representative of U. S. Navy practice and is therefore of only academic interest.

The PCH is an operational ship, built for a specific operational ASW requirement. However, a limited test evaluation period has been assigned for it. The presently planned instrumented program should give much useful data on the Disturbance and Response questions as listed by Figure 1. However, there is some doubt on the availability of stress instrumentation and more pressure gages than now planned would be needed to obtain complete bow pressure distributions.

A further automatic recording program should be prepared for the ship to obtain a sample history of operational use loading on factors listed under "Environment" in Figure 1, with a few key response measurements (as done for all modern airplanes). In any event, special note should be made on the influence and adjustment of the autopilot on the resultant recorded data.

The AGEH experimental ship construction is starting. This ship is to be used to evaluate the benefit of hydrofoils for tasks to be determined. At the present time, there does not appear to be any USN program to obtain a record of hull and foil performance during this period or during initial tests. A program similar to the PCH program, but planned specifically for particular data such as needed in design and proposed by report, reference 1, has to be established. This program planning should be completed at the earliest time so as to permit an orderly planning and installation of test instrumentation on the ship while it is being built.

The FRESH-1 is a test craft for evaluation of supercavitating hydrofoil configurations. The equipment on this craft includes a very extensive recording apparatus for hydrodynamic and structural tests. The foils are supported by special balances to permit measuring forces and moments on the struts. However, to date, there does not appear to be any planned program to utilize this craft for obtaining structural data. The craft is being checked-out with cambered, parabolic, foils. The Grumman Aircraft Company is building a set of supercavitating foils for installation on this craft. It is understood that the lift control will be by foil rotation about a strut pivot.

This craft could be used in present vibration program to evaluate the performance of supercavitating foils by investigating possible flutter occurrence as from torsion and hinge pin support design. Further problems in fatigue may arise due to the relatively flexible shape of foil and the possible cavity instability at lower speeds in waves.

The LCVP has four surface piercing foils, designed to high stress levels. These foils are scaled-up versions of the "High-pockets" type previously tested by the David Taylor Model Basin. The tests of this boat's foils would provide useful data to check scale effects, dynamic factors on foil load in waves, and fatigue property of the aluminum foil material.

The Maritime Administration had an extensive test and evaluation program for the DENISON. This program and results should be monitored to check any data which would be useful to the designer.

Performance (Hull)

There are some basic criteria on the selection of hydrofoil ship design which requires a compromise between structural and hydrodynamic aspects.

The hydrodynamic shape of the hull has a large effect on magnitude of wave impact forces, but is of course, properly in the cognizance of hydrodynamics. It should be noted that the Saunders Roe group in England spent considerable time and effort in this area to determine the recommended hull form. This hull had a maximum beam forward and a rather narrow transom to reduce undesirable wave effects. The Saunders Roe investigations also disclosed that a large overhang of hull forward on a narrow hull as on AGEH resulted in greatly magnified "G" loadings near the bow from pitching motion coupled with heave. The relative merits of these considerations can be demonstrated by suitable tests of PCH and AGEH ships. The SEA LEGS has essentially no overhang and will not duplicate the sea loads from these added forces on bow structure of such overhangs. Also SEA LEGS is a "V" bottom hull, not similar to the PCH or the AGEH.

Various naval architects have expressed much concern for hydrofoil "crashes", indicating that a hydrofoil hull would experience large accelerations and impact forces on such occasions. Actual test craft operational experience has been otherwise. There have been experiences when an abnormal sea has come aboard while boat was foil borne and stove in reasonably strong windshield as with test craft (SEA LEGS). There does not seem to be any impact at unintentional landing such as some theoretical procedures indicate. However, a check of this condition would be helpful, if possible.

Performance of (Hydrofoil Structure)

A program to check the hydrodynamic loads predictions on hydrofoils under operational conditions should be carried out. The actual forces will be related to adjustments of autopilots controls, personnel comfort, and relative operational hull clearance of specific craft. In order to correlate this data, it will be necessary to select some basis for loads at a given vertical acceleration which is not too great from operational efficiency stand-point for personnel. Under this criteria, information such as the frequency and location of various stress levels and duration of any one maximum need to be determined. The stresses at critical points of foil and struts such as at cantilever support and strut connections have to be related to accelerations and wave conditions.

The test program planned for SEA LEGS and PCH will furnish such data. However, it is not necessary to use pressure gages in the foils for this program. There could be some variation from uniform, spanwise distribution (eliptical loading) hydrofoil loading, but this can be determined by use of strain gages. The pressure distribution in chordwise direction has an effect on foil twisting which would be of concern in design when the whole foil was adjustable or if hydroelastic problems are anticipated such as with supercavitating foil sections.

There is a need to check the magnitude of forces on the rudder and foil flap control mechanism. This would be required to design flap control rods and rudder stock. It is also useful to the designer of the servo control devices. An automatic recorder should be installed on the PCH to accumulate the cycles of loads above a certain value at critical points during operational evaluation. A structure test program such as on the PCH and the AGEH will be very useful in evaluating the relative merits of the foil configurations and design of basic foil strut supports.

MATERIALS

A review is to be conducted on the fabrication and performance of the hull and foil structures of hydrofoil craft. This investigation is to determine what the permissible stresses are and the limits which fabrication problems impose on the designers freedom in selecting materials. Under certain conditions, as in the installation of transmission and foil connections, optimum structure is not feasible. The problems of surface protection and galvanic interaction with installed equipment in hull is also more easily determined by inspecting and monitoring performances on the operational ships.

Principle objectives are to be:

1. Compile data on use of any problems in use of aluminum and other materials.

2. Prepare comparison of aluminum with alternate possibilities such as glass reinforced plastic or titanium.

3. Specify acceptable values of stress to be used for recommended material.

Hydrofoil Construction

The structural requirements for material increase with both size and speed. Use of aluminum appears to be acceptable for boats up to about 15 tons and 37 feet in length. Larger craft require material of higher stress levels and stiffness than provided by alloys of aluminum that can be immersed in salt water. High strength steels and certain titanium alloys have possible use provided fabrication techniques are developed for them.

Continuous efforts should be carried on to explore the various alloys and construction techniques for fabricating of foils to determine the one best suited for the highly stressed supercavitating foil application. It may be that welding will be impractical in all parts of assembly and some joints will require bonding. The frictional resistance will predominate at 90-knot speeds so that a great deal of care will be necessary to obtain a smooth surface which will remain smooth. The protective coating being used for the protection of the steel PCH foils is understood to be quite rough. A 90-knot speed would also wear off coatings so that titanium appears to be the preferred material for foils and struts of the 500-ton ship. Answers to these questions need to be coordinated with the Hydrodynamics Laboratory. If this is the case, much needs to be done to learn of requirements for fabrication and allowable stresses at joints.

The ultimate objective of hydrofoil material program is to develop a low weight to strength ratio material compatible with material used on ship hull and which can be readily fabricated. This material should not be effected by salt water and have excellent fatigue characteristics to permit use of minimum safety factors in design.

The program should tabulate the permissible design stress of this material and fabrication techniques which should be followed (in shipyards) as part of the results.

The performance of the material on test craft is to be monitored periodically for evaluation of influence of salt water and any failures which may occur. Reports of research programs such as the Titanium Bonded Design at North American Aviation with the Bureau of Ships are to be reviewed for use in further efforts which may become desirable in those areas.

REFERENCES

1. Martin Company, Hydrofoil Craft Structural Design Study. CONFIDENTIAL

2. Stevens, Banko, and Arrone, Bureau of Ships, Structural Load Criteria for Hydrofoil Ships

3. Merritt, R. G., Boeing Airplane Co., Structural Design for Safety in High Speed Ships

4. DTMB Technical Note SML-760-17, Progress Report No. 1, An Investigation of Loadings Experienced by Hydrofoil Craft. Progress Report No. 1 DTMB Technical Note SML-760-17

Prepared by John Bader
John Bader

Approved by
CDR Peter Beierl, USN

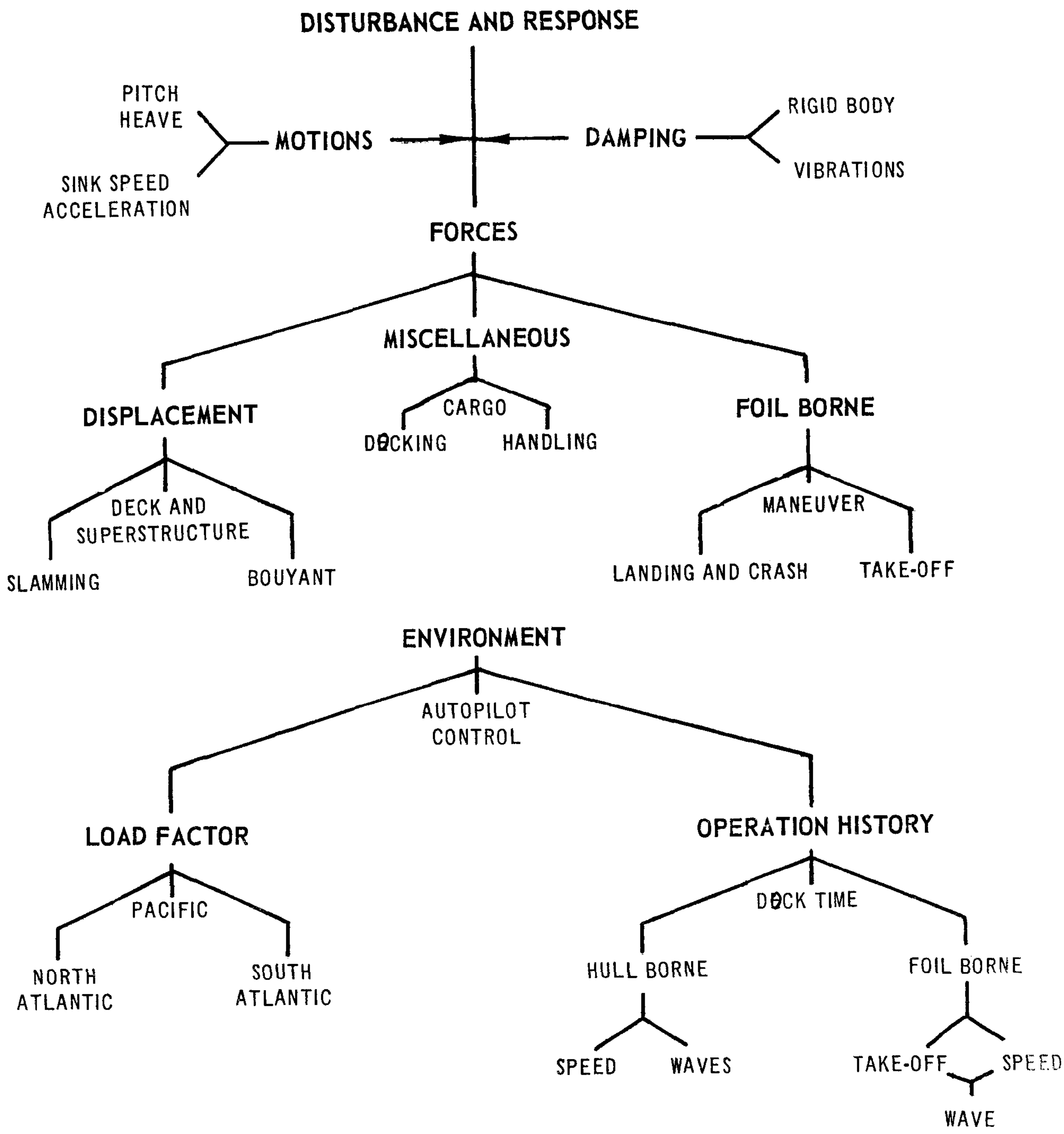
DISTURBANCE AND RESPONSE
PITCH
HEAVE
SINK SPEED
ACCELERATION
MOTIONS
DAMPING
RIGID BODY
VIBRATIONS
FORCES
MISCELLANEOUS
CARGO
DOCKING
HANDLING
DISPLACEMENT
DECK AND SUPERSTRUCTURE
SLAMMING
BOUYANT
FOIL BORNE
MANEUVER
LANDING AND CRASH
TAKE-OFF
ENVIRONMENT
AUTOPILOT CONTROL
LOAD FACTOR
PACIFIC
NORTH ATLANTIC
SOUTH ATLANTIC
OPERATION HISTORY
DOCK TIME
HULL BORNE
FOIL BORNE
SPEED
WAVES
TAKE-OFF
SPEED
WAVE

FIGURE 1