DEPARTMENT OF THE NAVY

TAYLOR MODEL BASIN
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HYDROMECHANICS

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STRUCTURAL MECHANICS

APPLIED MATHEMATICS

A METHOD FOR PREDICTING THE PROBABLE NUMBER AND SEVERITY OF COLLISIONS BETWEEN FOILBORNE CRAFT AND FLOATING DEBRIS

by

Nathan K. Bales

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

August 1963

Report 1723

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON 7, D.C. 20007

IN REPLY REFER TO
5605
3900/RESEARCH
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Ser 7-426
8 October 1963

From: Commanding Officer and Director, David Taylor Model Basin
To: Chief, Bureau of Ships (442) (in duplicate)

Subj: Hydrofoil Craft Structural Design Criteria, Task 1705, forwarding of report on

Ref: (a) BUSHIPS ltr F013-02-01 Ser 442-113 of 20 July 1961

Encl: (1) DTMB Report 1723 entitled "A Method for Predicting the Probable Number and Severity of Collisions between Foil-Borne Craft and Floating Debris"

1. The objective of the hydrofoil research program now being conducted is the provision of design load criteria for large, high speed, hydrofoil craft planned by the Bureau of Ships. Reference (a) authorized studies, under Task 1705, leading to the determination of criteria which would provide for various loadings to which hydrofoil craft are subject. The loading due to collisions with items of floating debris was among those cited as required areas of study. The first phase of such a study has been completed. This phase involved the derivation of a method for the analysis of collisions with items of floating debris. The probable number of occurrences and most critical structural effect of such collisions are discussed.

2. It is planned to study and report further on detailed procedures for calculating the magnitudes of the structural effects of the collisions and on the validity of the assumed debris distributions.

3. Enclosure (1) is forwarded herewith for the first phase of the debris problem work completed under Task 1705.

E. F. Noonan

E. F. Noonan
By direction

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A METHOD FOR PREDICTING THE PROBABLE NUMBER AND SEVERITY OF COLLISIONS BETWEEN FOILBORNE CRAFT AND FLOATING DEBRIS

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ABSTRACT

One type of loading which an operational hydrofoil craft will experience is that resulting from collisions with items of floating debris. This investigation derives a method for predicting the approximate number of collisions producing a structural response of given severity to be anticipated over a long operating period. The derivation is based on certain assumed debris item frequency distributions. Numerical values for these distributions are needed to give practical value to the proposed method.

INTRODUCTION

Collisions between foilborne craft and items of floating debris are of continuing concern to designers of hydrofoil craft. However, little information is available to the designer for predicting the occurrence or the effects of these collisions. The debris problem was among those posed by the Bureau of Ships in a hydrofoil craft research program to be undertaken by the David Taylor Model Basin.*

This report outlines an approach that determines the approximate number and the probable severity of significant collisions to be expected for any given design-target craft over a long operating period. Assumptions are made as to debris item frequency distributions, and a reasonably complete knowledge of the design-target craft is assumed.

It must be emphasized that only a method is presented here. No numerical values are available at the present time, but it is hoped that this report will stimulate interest in obtaining the necessary parameters to give practical value to the study.

Efforts will be made to obtain the required numerical parameters for a specific design-target craft. The results of this investigation will be published at a later date.

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*BuShips letter F013-02-01 Ser. 442-113 of 20 July 1961.

SELECTION OF DEBRIS PARAMETERS AND GENERAL APPROACH

Any selected debris item might be characterized by any of a large number of parameters. Weight, specific weight, mass density, and volume are a few of the possibilities. In selecting debris parameters for the present study, two criteria must be kept in mind. Since, by necessity, the approach to the subject must be probabilistic, parameters which have frequency distributions that may be expected to approximate the form of mathematically defined probability densities must be chosen. Also, the parameters chosen must lend themselves readily to an analysis of the effect of collisions that may occur.

In light of these two criteria, the parameters of mass density and mass have been chosen for this study. Justification for these selections will be given later in this report.

As to approach, the frequency distributions of mass density and mass will be considered separately. The two-dimensional distribution concept will be avoided as the parameters of mass density and mass cannot be considered independent, and the form of such a two-dimensional distribution cannot be rationalized.

THE PROBABLE NUMBER AND SEVERITY OF COLLISIONS

Determination of the number of debris collisions that a foilborne craft is likely to sustain and their probable severity will be undertaken through the creation of an analytical model which is amenable to theoretical analysis. As an initial step, a simplified model for which all parameters are known will be considered. This case will then be generalized to produce a model which more closely approximates the actual situation under investigation.

A SIMPLIFIED MODEL

Assume a body of water having a total surface area A. Consider a specified number of debris items, each spherical in shape and of known mass density and mass, to be uniformly distributed

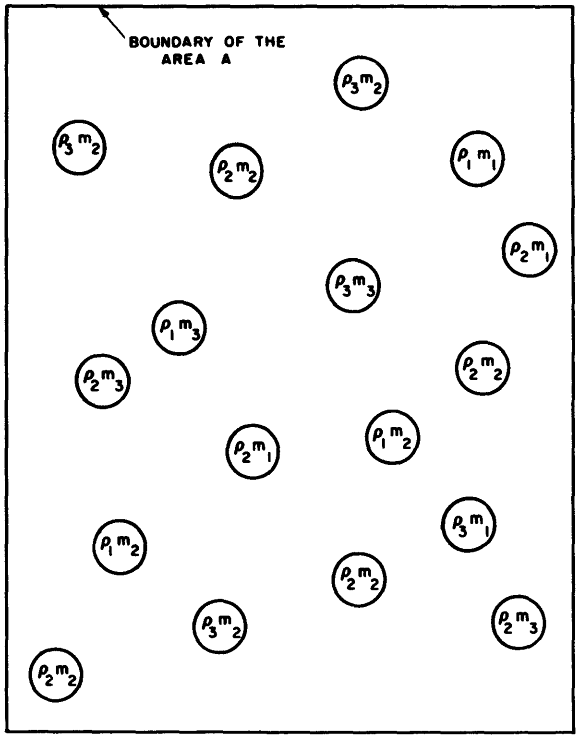

Figure 1 - Illustration of the Simplified Model

over the surface. Such a situation is illustrated by Figure 1 where each circle is a debris item, ρ is mass density, and m is mass. The subscripts associated with ρ and m denote specific values of these parameters. The magnitude of a parameter increases with its subscript.

It is seen that three mass densities and three masses are represented among the debris items shown in Figure 1. The number of debris items in the figure which are characterized by each of the nine possible combinations of mass density and mass thus realized are listed in Table 1. A particular combination of mass density and mass defines a debris class. Thus, from Table 1, the debris class 3, 2 (corresponding to mass density ρ_3 and mass m_2) has three members.

The information contained in Table 1 will be used to plot the discrete frequency distribution of mass density for the area under investigation. It will also provide means for plotting the discrete frequency distributions

TABLE 1

Characterization of All Debris Items
in the Simplified Model

Mass Density	Mass		
	m_1	m_2	m_3
ρ_1	1	2	1
ρ_2	2	4	2
ρ_3	1	3	1

of mass in the given area for specific mass density values. The aforementioned plots are shown in Figure 2. Magnitudes of mass density and mass are assumed to be equally spaced along their respective axes in the subfigures of Figure 2.

If a foilborne craft travels at a given speed through the body of water represented in the simplified model, it will effectively "sweep out" a fraction of the total area A. The area swept out will be designated as a sweeping function δ. The magnitude of δ will, of course, vary with craft geometry and distance traveled.

Given that the craft makes no attempt to avoid collisions (and recalling that the debris items are uniformly distributed over the surface area A), it is seen that the number of encounters to be anticipated is the fraction of the total area A swept out times the total number of debris items in the area. This may be expressed mathematically as

$$F = \delta \frac{N}{A} \qquad [1]$$

where F is the anticipated number of encounters (encounter frequency),

δ is the sweeping function,

N is the total number of debris items in the body of water, and

A is the surface area of the body of water.

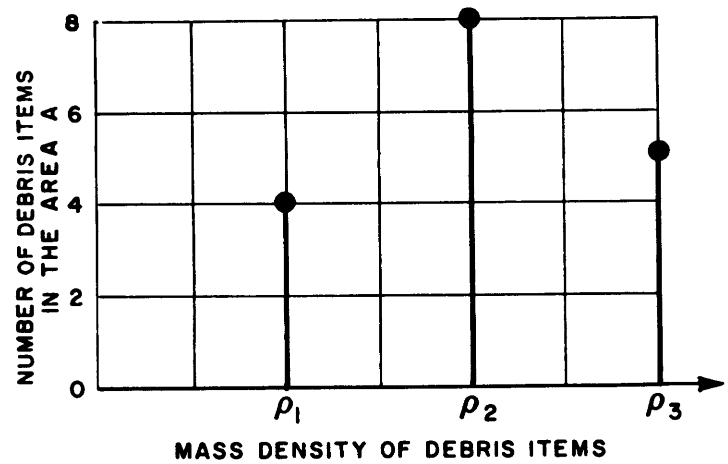

Figure 2a - Frequency Distribution of Density

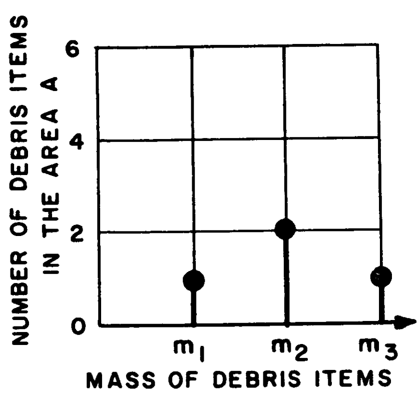

Figure 2b - Frequency Distribution of Mass for Mass Density ρ_1

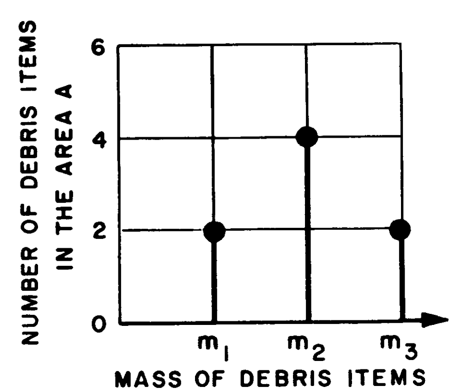

Figure 2c - Frequency Distribution of Mass for Mass Density ρ_2

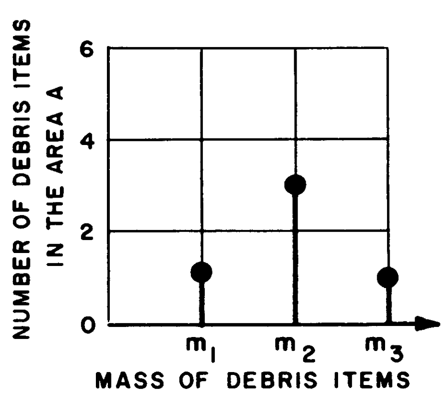

Figure 2d - Frequency Distribution of Mass for Mass Density ρ_3

Figure 2 - Discrete Frequency Distributions for the Simplified Model

Equation [1] is very limited in that it contains no information as to the characteristics of the debris items encountered and therefore provides no means of determining the severity of a given collision. However, if it is further assumed that each class of debris is uniformly distributed over the area of concern, it becomes possible to form an expression that is analogous to Equation [1] and surmounts the aforementioned limitations. Using the subscript p,q to denote a general class of debris items having mass density p and mass q, the expression is

$$F_{p,q} = \delta \frac{N_{p,q}}{A} \qquad [2]$$

where the notation is the same as that for Equation [1] except for the specifying subscripts.

Using Equation [2] in conjunction with Table 1, it is seen that the numbers of anticipated encounters for the nine debris classes of the simplified models are

$$\begin{aligned} F_{1,1} = F_{1,3} = F_{3,1} = F_{3,3} &= \frac{\delta}{A} \\ F_{1,2} = F_{2,1} = F_{2,3} &= \frac{2\delta}{A} \\ F_{3,2} &= \frac{3\delta}{A} \\ F_{2,2} &= \frac{4\delta}{A} \end{aligned} \qquad [3]$$

where the subscripts 1, 2, and 3 are those associated with mass density and mass magnitudes considered in the simplified model. The area A is, of course, constant; and for a given craft, the sweeping function δ varies only with the distance which the foilborne craft logs in the area under study.

It is thus possible to plot the number of anticipated encounters with debris of a given class as a function of distance traveled in the foilborne attitude. If a linear relationship is assumed between distance and number of encounters, such a plot would have the appearance of Figure 3.

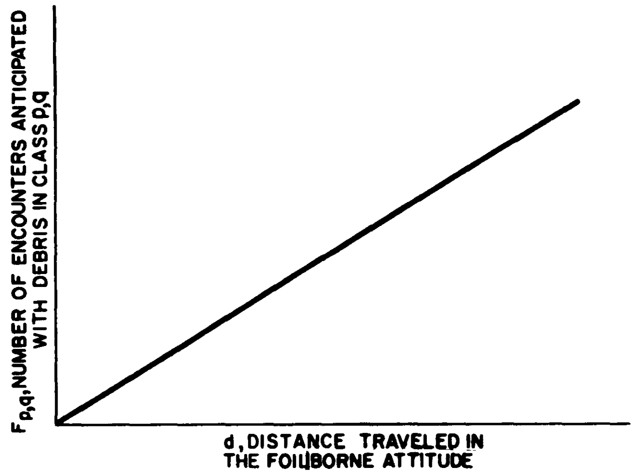

Figure 3 – Typical Encounter Curve for the Simplified Model

TABLE 2

Debris Class – Encounter Curve Array for the Simplified Model

$\rho_1 m_1$	$\rho_1 m_2$	$\rho_1 m_3$
$\rho_2 m_1$	$\rho_2 m_2$	$\rho_2 m_3$
$\rho_3 m_1$	$\rho_3 m_2$	$\rho_3 m_3$

Further, it is convenient to visualize these "encounter frequency curves" as belonging to an array such as that given by Table 2, each member of which is generated for a particular debris class belonging to the simplified model. This arrangement will facilitate work with the structural response of the craft to collisions with debris items.

Mass is selected as the parameter governing the character of the response of the craft to a collision. It is assumed that all collisions are direct center of mass rather than "glancing" eccentric impacts. The simplified model will thus exhibit three magnitudes of response - R_1, R_2, and R_3 associated, respectively, with the mass values m_1, m_2, and m_3. The number of encounters with debris items of given mass (and thus of given responses) may be easily obtained from the encounter frequency curves represented by the array in Table 2.

Each column of the array gives the anticipated number of encounters with debris items of a given mass as a function of distance. It is thus possible to determine the number of responses of a given magnitude to be expected in traveling a given distance (say $\bar{d}$) by a summation of the ordinate values of the encounter curves represented by a column of the array at the distance $\bar{d}$. For response R_1 the summation is

$$F(R_1)]_{\bar{d}} = [F_{1,1} + F_{2,1} + F_{3,1}]_{\bar{d}} \qquad [4]$$

where $F(R_1)]_{\bar{d}}$ is the total number of anticipated encounters which produce response R_1 in traveling the distance $\bar{d}$ and the right-hand member shows the previously mentioned summation.

The values of $F(R_2)]_{\bar{d}}$ and $F(R_3)]_{\bar{d}}$ may be determined in a like manner. Since each of the three $F(R)]_{\bar{d}}$ values results from a summation over a column of the array and mass density is constant in the rows of the array, the frequency distribution of the response values will have the general form of the frequency distributions associated with mass at constant mass density, e.g., Figures 2b - 2d. The response frequency distribution for the simplified model is shown in Figure 4.

This frequency distribution may be converted to a discrete probability (relative frequency) distribution as

$$F'(R_q) = \frac{F(R_q)]_{\bar{d}}}{\sum_{u=1}^{3} F(R_u)]_{\bar{d}}} \qquad [5]$$

where $F'(R_q)$ indicates the probability of occurrence of the general response R_q and the symbol Σ calls for a summation over all values of R.

Note that unlike $F(R)]_{\bar{d}}$, $F'(R)$ is independent of distance. The response probability distribution for the simplified model is shown in Figure 5.

The total number of encounters anticipated with all debris classes may be found by a summation of all the encounter curves represented by the Table 2 array. Summations of the ordinate values of each of the nine curves are made at two arbitrary values of distance, and the two points which result suffice to determine the cumulative encounter frequency curve. This result is given by Figure 6 where the symbol F_c is used to represent the cumulative number of anticipated encounters.

It is seen that Figures 6 and 5 provide, respectively, the total number of encounters anticipated by a foilborne craft operating under the conditions specified for the simplified model, and the probability that a collision will produce a response of given magnitude. Thus the necessary solution of the problem in a simplified model is complete.

GENERALIZATION TO A MORE REALISTIC MODEL

A number of changes must be made in the simplified model before it will provide a reasonable working estimate of an actual situation. Obviously, the mass density and mass parameters must be regarded as continuous rather than discrete variables. The form of the frequency distributions of these parameters must be estimated, and the possibility of physical limits on these distributions must be considered. Consideration must be given to the facts that an operational craft will attempt to avoid collisions and that many collisions will result in eccentric impacts. The most pertinent structural effect of debris collisions must be determined, and the long-term probability of occurrence of a given magnitude of the effect must be estimated.

Debris Distributions

Two factors are of primary importance in rationalizing the form of the frequency distribution of debris item mass density. First, it is obvious that the distribution will be limited to the right at the density of the water in the area of concern. If the average mass density of some item introduced into a body of water is greater than the mass density of

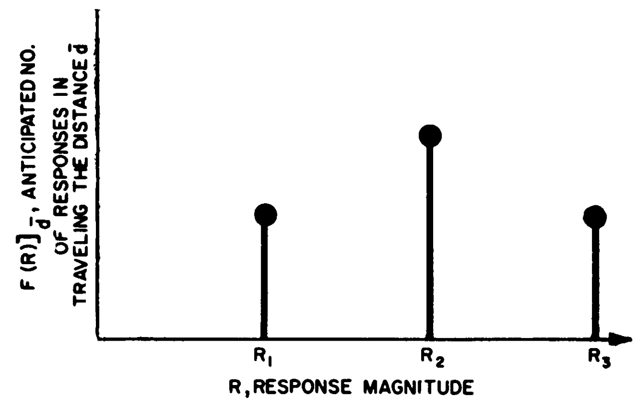

Figure 4 - Response Frequency Distribution for the Simplified Model

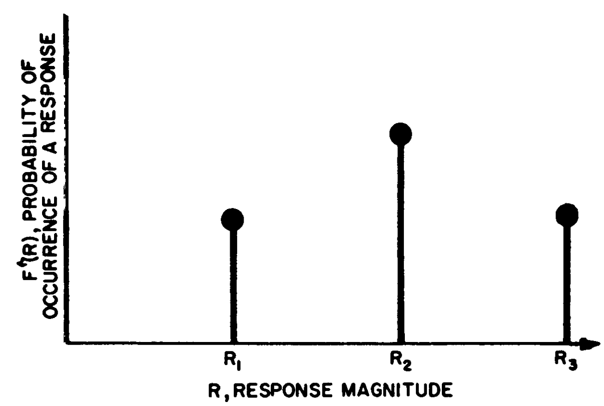

Figure 5 - Probability Distribution for the Simplified Model

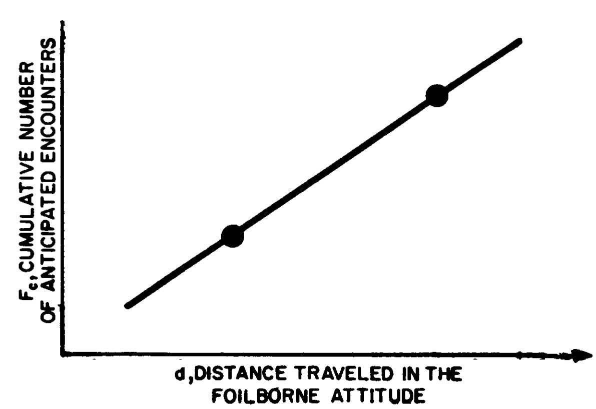

Figure 6 - Cumulative Encounter Curve for the Simplified Model

the water, the item sinks and is no longer a problem. Second, it may be expected that the average mass density of wood will be the modal value of this frequency distribution. Wooden items, natural and manmade, are likely to predominate in any body of water.

A check of the mass densities of common woods in any good handbook will indicate an average value on the order of 0.60 gm/cm^3 (37 lb/ft^3). Allowing for some increase as a result of "waterlogging," an average value of 0.70 gm/cm^3 (44 lb/ft^3) would probably be a safe estimate. The density of salt water is about 1.02 gm/cm^3 (64 lb/ft^3). Thus the continuous frequency distribution of the mass density of debris items is assumed to be negatively skewed with a modal value equal to the average mass density of waterlogged wood and to terminate at the density of the water in the area of concern. Such a distribution is sketched in Figure 7.

Now consider some arbitrarily selected, small zone of debris item mass densities such as $\Delta\rho_p$ in Figure 7 (ρ_p is the midpoint of the zone identified as $\Delta\rho_p$). The mass values associated with the debris items falling in this mass density zone are affected by a variety of unrelated events (e.g., which pilings fall into the water, which ships break up and lose their cargos, what is thrown overboard, etc.), none of which is likely

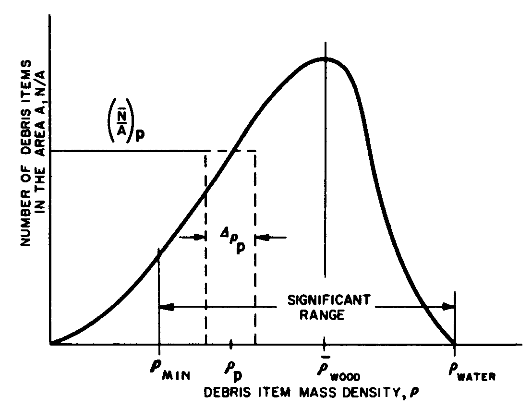

Figure 7 – Debris Item Mass Density Frequency Distribution

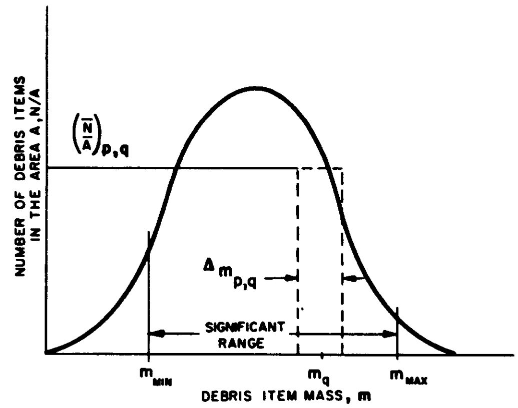

Figure 8 – Debris Item Mass Frequency Distribution for the Mass Density Range $\Delta\rho_p$ in Figure 7

to predominate. Thus it may be hypothesized that the frequency distribution of mass for debris items in any selected small mass density zone has the form of the probability density curve associated with a normal distribution.

The number of debris items in mass density zone $\Delta\rho_p$ of Figure 7 is taken to be the average of the frequency values associated with its upper and lower limits and is symbolized as $(\bar{N}/A)_p$. The integral over the mass frequency distribution curve for this mass density zone must, of course, equal $(\bar{N}/A)_p$. A mass frequency distribution curve for the mass density zone $\Delta\rho_p$ of Figure 7 is illustrated by Figure 8.

An arbitrary mass zone $\Delta m_{p,q}$ (where the subscript p refers to the mass density zone $\Delta\rho_p$ and the subscript q is the midpoint of and designates the arbitrarily selected mass zone) is shown in Figure 8. In a manner analogous to that used in determining $(\bar{N}/A)_p$, a value $(\bar{N}/A)_{p,q}$ may be found for the frequency of occurrence of debris items having a mass density in the zone $\Delta\rho_p$ and a mass in the zone Δm_q. Thus it is seen that mass density and mass zones have taken the place of the discrete values of these parameters used in the simplified model. Further, a debris class is now defined by a mass density zone and a mass zone. Thus the debris class for the case just discussed is p,q. As in the simplified model, each debris class will be considered to be uniformly distributed over the area of interest.

Parameter Limits

The existence of an upper limit on mass density has already been mentioned. A minimum mass density capable of producing structural response should also be obtainable. Mass densities below this minimum value will be of no concern, and a total significant mass density range extending from this ρ_{min} to ρ_{water} is thus indicated in Figure 7.

Limiting values of mass may also be determined. A collision will not produce a significant structural response at very low ratios of debris item mass to craft mass. The minimum debris mass which will cause a significant response in a given design target craft may thus be determined and values below it eliminated from consideration.

At the other extreme, collisions may occur which are outright crashes. Collision with an iceberg, while unlikely to the extreme, could hardly be regarded as a "debris collision." A debris item mass to craft mass ratio which will produce such a "crash" can be established, and a maximum value of debris item mass of concern thus obtained for the given craft. In light of these considerations, a significant mass range is indicated in Figure 8. Any debris item falling in the ranges thus defined will be designated as a "significant debris item" and a collision with such an item as a "significant collision."

In the simplified model, all mass and mass density values were tacitly assumed to be significant. Thus there is no direct analogy with the determination of parameter limits as described here.

Encounters and Collisions

Consider first the mechanistic encounter frequency which makes no allowance for human or instrument corrections to avoid collisions. As pointed out in the simplified model, the encounter frequency with debris in class p,q is given by the product of the sweeping function of the craft (δ) and the number of debris items of the class in the area of concern. In present notation this is

$$F_{p,q} = \delta\,(\bar{N}/A)_{p,q} \qquad [6]$$

which is analogous to Equation [2] of the simplified model.

As previously noted, the sweeping function will vary with craft geometry and foilborne distance traveled in the area of concern. Since high densities cannot occur among debris items (the limit being the density of water) and since items of small mass have been eliminated from this study on the grounds that collisions with such items would not produce a significant structural response, it is seen that all debris items of concern here must be of moderately large size. With due consideration to this factor, the strut spacing at the foilborne waterline of the design-target craft (s in Figure 9) may be chosen as the necessary geometric parameter. Thus we have

$$\delta = sd \qquad [7]$$

where d is the foilborne distance traveled. It is thus seen that the encounter frequency, Equation [6], varies linearily with distance traveled in the foilborne attitude as indicated by Figure 3 of the simplified model.

Since the encounter frequency relationship is based on statistical considerations, its validity depends on sufficient sample size. Thus it should be used only when the total area of concern A and the distance traveled d are large.

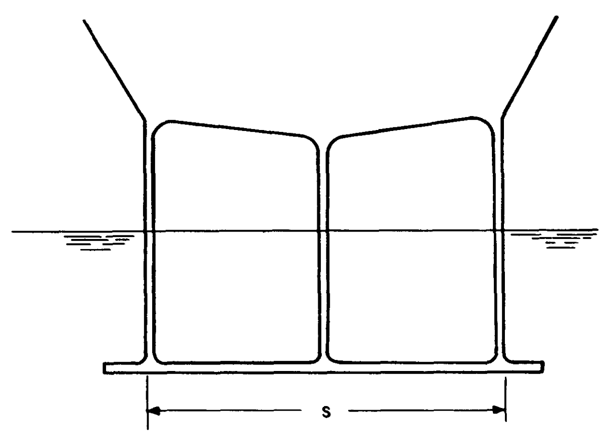

Figure 9 - Section of Typical Hydrofoil Craft Showing Geometric Sweeping Function Parameter

The encounter frequency concept may be extended to include all significant debris items in the area under study. First, divide the significant range of the debris item mass density frequency distribution (ρ_{min} to ρ_{water} in Figure 7) into n zones. Next, generate debris item mass frequency distributions (such as Figure 8) for each of these n ranges; then divide the significant range (m_{min} to m_{max} in Figure 8) of each of the n distributions thus obtained into n' mass zones. The manner in which the significant mass zone is divided should be the same for each of the n debris item mass frequency distributions considered.

Each of the n mass density zones obtained by this scheme corresponds to a value of p in Equation [6], and each of the n' mass zones corresponds to a value of q in the same equation. Thus it is possible to construct encounter frequency curves for all debris classes by considering all values of p from 1 to n and all values of q from 1 to n' in Equation [6]. The encounter frequency curve array used in the simplified model may be used to advantage here. The array for the present general case is given by Table 3.

The encounter frequency curves represented by the Table 3 array were derived from purely mechanistic considerations. In a realistic situation, pilot and instrument corrections would prevent many collisions, particularly those with the larger debris items. It is thus necessary to weight the encounter frequency curves in such a manner as to correct them to reflect true collision frequencies.

TABLE 3

Debris Class – Encounter Curve Array for the General Model

$\rho_1 m_1$	$\rho_1 m_2$	. . . .	$\rho_1 m_{n'-1}$	$\rho_1 m_{n'}$
$\rho_2 m_1$	$\rho_2 m_2$	. . . .	$\rho_2 m_{n'-1}$	$\rho_2 m_{n'}$
. . . .	. . . .	. . . .	. . . .	. . . .
. . . .	. . . .	$\rho_p m_q$	. . . .	. . . .
. . . .	. . . .	. . . .	. . . .	. . . .
$\rho_{n-1} m_1$	$\rho_{n-1} m_2$	. . . .	$\rho_{n-1} m_{n'-1}$	$\rho_{n-1} m_{n'}$
$\rho_n \; m_1$	$\rho_n \; m_2$	. . . .	$\rho_n \; m_{n'-1}$	$\rho_n \; m_{n'}$

In general, initially nonhomogeneous debris items which have been in the water for an appreciable length of time will have become so waterlogged that their densities will be fairly uniform. Thus, assuming that all debris items are reasonably homogeneous, the weighting may be accomplished by a simple reduction of the ordinate values of each encounter frequency curve. The amount of reduction will be separately determined for each curve. The ordinates of curves for debris classes having mass and mass density values indicating a large volume above water would be reduced more than those applicable to debris items with only a small volume above water.

After this weighting process, the Table 3 array will properly represent collision frequency curves. It will be considered in this sense for all future references. The symbol C will replace F when referring to true collision frequencies, e.g., the number of anticipated collisions with debris items in class p,q is $C_{p,q}$.

Critical Effect and Probability of Collisions

Collisions which occur will produce varied responses. In order to formulate an approach for this study, it will be necessary to consider the nature of hydrofoil craft with the view of finding a suitable, critical criterion.

Hydrofoil craft are extremely weight-critical vehicles. This fact requires that they be designed in accordance with rational criteria which minimize the weights of all structural components. For instance, the struts, strut-hull junctions, and the hull must contribute a minimum of weight as restricted by their structural integrity requirements.

One type of loading which will be imposed upon the three elements just mentioned is that due to debris collisions. Should a severe collision of this type occur, it would be imperative for the strut-hull junction rather than the hull to fail. The critical structural response to a debris collision is thus seen to be the reaction produced at the strut-hull junction.

In this paper the reaction will be described in terms of the stress produced at the junction. The magnitude of the stress produced by a given collision is a function of craft speed, the mass of the debris item impacted, the eccentricity of the impact, and the coefficient of restitution applicable to the impact. Craft speed, eccentricity, and coefficient of restitution will be elaborated upon in this paper, but the actual development of an expression for stress produced by a given collision will be deferred to a later paper.

Since the frequency distribution of the debris item mass density has been truncated to omit extreme values, an intermediate coefficient of restitution may be used for all impacts without great loss of accuracy. Initially all impacts will be considered to be center of mass and the craft will be considered to operate at only one foilborne speed. Thus the response to a collision is reduced to a function of debris item mass only and may be handled in the manner of the simplified model.

In the present model, we must consider n' values of mass (each the central value of one of the selected mass zones) and their n' associated responses which will now be designated by σ's for stress magnitudes rather than the generalized R of the simplified model. The range of stress magnitudes of interest extends from some value σ_{min} associated with m_{min} to a value σ_{max} associated with m_{max}. The number of responses of a given magnitude within this range to be expected in traveling an arbitrary large distance $\bar{d}$ may now be found by summing the ordinates of collision frequency curves represented by a column of the Table 3 array. Analogous to Equation [4] of the simplified model, the number of collisions which produce a stress σ_q at the strut-hull junction in traveling a foilborne distance $\bar{d}$ is given by

$$C(\sigma_q)]_{\bar{d}} = \sum_{p=1}^{n} C_{p,q}]_{\bar{d}} \qquad [8]$$

Again, this calculation may be repeated for all required mass values (q = 1, 2, 3, ... n') to obtain a frequency distribution of stress response magnitude. Following the reasoning of the simplified model, this distribution should exhibit the form of the distribution associated with debris item mass, i.e., a normal distribution. Due to the weighting process which converts the original encounter frequency curves to collision frequency curves, this will not be strictly true for the general model. However, the discrepancies should not be great; thus for the sake of mathematical preciseness, a suitably fitted, normal-type frequency distribution of stress response magnitudes will be used.

The stress response frequency distribution thus obtained may now be altered to compensate for the center of mass assumption which was required in its derivation. Very generally, the effect of non-center of mass collisions is the introduction of a measure of positive skewness into the total distribution. The extent of the skewness is a function of the degrees of reduction of the response magnitudes associated with the non-center of mass collisions. The greater the mean reduction, the more pronounced the skewness will be.

It is not feasible to compensate for the infinite variety of degrees of reductions that will actually be encountered. It will, therefore, be assumed that for all collisions, the center of mass assumption is either valid or invalid. The response produced by the invalid cases will be considered to be insignificant.

Any collision with an elongated debris item may result in an invalid case. However, highly eccentric impacts are equally likely whether the elongated debris item impacted is of large or small mass, and elongated items are equally likely to have large or small mass values. Thus the correction can be made by a simple reduction of the ordinate scale of the stress response frequency distribution. Since this correction affects all values equally, the distribution retains its normal form (see Figure 10).

For this general model, it is desirable to convert the corrected stress response frequency distribution into the mathematically defined normal probability density and thence to a cumulative probability. The normal stress response probability density is given by

$$p(\sigma) = \frac{1}{\beta\sqrt{2\pi}} \exp \frac{-(\sigma - \mu)^2}{2\beta^2} \qquad [9]$$

where β^2 is the variance and μ is the mean value of the stress response. As was the case with the simplified model, this probability is independent

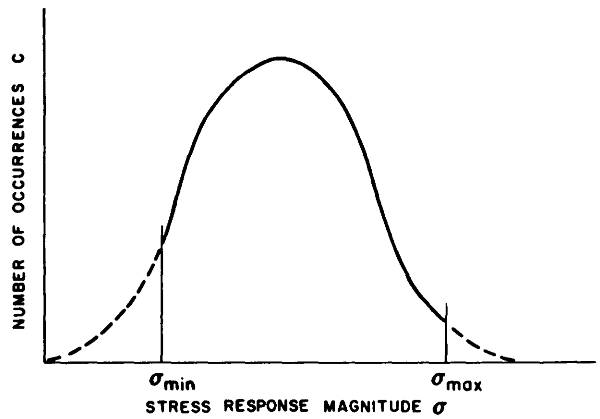

Figure 10 - Corrected Stress Response Magnitude Frequency Distribution

of distance. The variance and mean value may be estimated from the corrected stress response frequency distribution. Values in the extrapolated regions below σ_{min} and above σ_{max} (the dashed portions of Figure 10) should be considered in making these estimations since the "tails" of the frequency distribution are considered in Equation [9].

In general, the cumulative probability that some magnitude X of a variate x will not be exceeded is given by

$$P(X) = \int_{-\infty}^{X} p(x)\, dx \qquad [10]$$

where p(x) is the probability density of x. In this instance, however, the variate (stress response magnitude) is applicable only over a restricted range (σ_{min} to σ_{max}). Designating the cumulative nonoccurrence probability of a stress in this restricted range as $Q(\sigma)$, we may form the expression

$$Q(\sigma) = P(\sigma) - P(\sigma_{min}) \qquad [11]$$

where $P(\sigma)$ and $P(\sigma_{min})$ are the general cumulative nonoccurrence probabilities of the selected stress and the minimum stress to which the

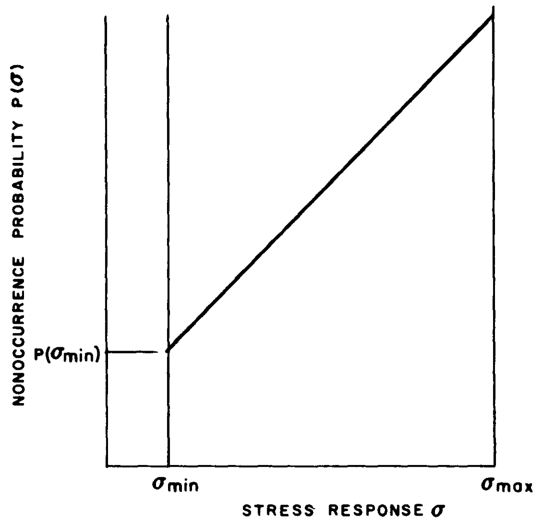

Figure 11 – Restricted Cumulative Probability Distribution of Stress Response Magnitudes

calculations here are applicable.

This result may be demonstrated on normal probability paper as a linear plot. Such a result is given by Figure 11. To obtain $Q(\sigma)$, the cumulative probability that the response to a significant collision will not exceed a stress magnitude σ taken from the restricted region between σ_{min} and σ_{max}, the value of $P(\sigma)$ is read from Figure 11, and $P(\sigma_{min})$ is subtracted from this value. It is seen that Figure 11 is comparable to Figure 5 for the simplified model.

Long-Term Loading

Extending the general model to a long-term basis will require that variations in craft foilborne speed be accounted for. It will also be convenient to obtain the total number of collisions anticipated with all debris classes.

The latter step may be taken in the fashion described for the simplified model. All collision frequency curves represented by the Table 3 array are summed to determine a cumulative collision frequency curve. The symbol C_c will be used to designate the cumulative number of anticipated collisions.

Recourse to the mission profile of the design-target craft will yield information as to the foilborne speeds at which the craft is expected to operate. As previously noted, collision response magnitude is a function of craft speed. Should a foilborne craft impact a given item of debris in a similar manner at two different speeds, the higher speed would produce a larger response magnitude.

It is thus seen that there is a stress response magnitude frequency distribution for each operating speed. However, due to the similar nature of these distributions, it will not be necessary to calculate their normal probability density parameters and cumulative probability distributions fully. Each of the distributions has an identical set of ordinate values since they are obtained from the same array. Each column of the array corresponds to a different response magnitude, however. The total effect is thus a "shift" in the abscissa scale of the distribution.

Having obtained a restricted cumulative probability distribution of stress response magnitudes for one speed by the method of the preceding section, it is very simple to obtain cumulative distributions for other speeds. The response magnitudes associated with the minimum significant debris item mass are calculated for all other speeds of concern, and their distributions are given by lines parallel to the one obtained for the initial speed. Only the abscissa coordinate of the origin of the distribution is altered.

The two long-term loading curves discussed in this section are exemplified by Figure 12. Three foilborne speeds are assumed for the figure. These curves provide the basic tools by which the method developed here may be applied to predicting the occurrence of given responses to significant debris collisions for a design-target craft. They represent a complete solution of the general model.

DISCUSSION OF POSSIBLE APPLICATION

Practical response prediction will require several derivations not considered here as well as the determination of a number of empirical and semi-empirical factors. It will be necessary to know those structural aspects of the design-target craft required to determine the stress

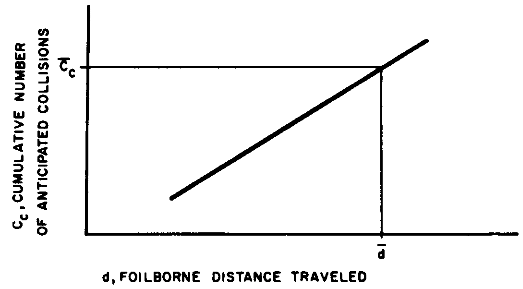

Figure 12a - Cumulative Collision Curve

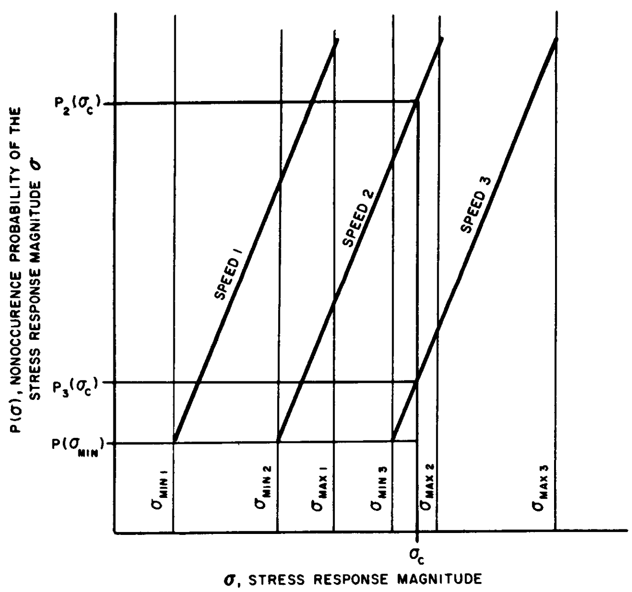

Figure 12b - Long-Term Stress Response Magnitude Distribution

Figure 12 - Long-Term Loading Curves

response produced by a given collision as well as the strut spacing and total craft mass. Also needed are estimates of the foilborne speeds at which the craft will operate and weighting factors to correct from encounter to collision frequency and to account for non-center of mass impacts. Finally, it is necessary that the debris item frequency distributions of mass density and mass be numerically defined for the area(s) of interest and that the limiting values for these distributions be determined.

Of these, the determination of numerical parameters for the debris item frequency distributions will doubtlessly prove the greatest impediment. Response magnitude calculations will require some analytical development, but they should not cause excessive trouble.

With these various factors in hand, it will be possible to generate a set of long-term loading curves having numerical values. This could readily permit predicting the number of collisions producing a given response magnitude which would be sustained by a design-target craft in traveling a given distance. Suppose, for instance, that it was desired to predict from Figure 12 the number of occurrences of a stress response magnitude equal to or greater than σ_c in traveling the distance $\bar{d}$. Using $C(\sigma_c, \bar{d})$ to designate the prediction, the result is

$$C(\sigma_c, \bar{d}) = \bar{C}_c \left[1 - P_2(\sigma_c) - P_3(\sigma_c) + 2P(\sigma_{min})\right] \qquad [12]$$

where the notation is as used in Figure 12 and the subtraction from unity enters as a result of the conversion from nonoccurrence to occurrence probability. Equation [12] may be simplified through the use of the restricted nonoccurrence probability $Q(\sigma)$ as

$$C(\sigma_c, \bar{d}) = \bar{C}_c \left[1 - Q_2(\sigma_c) - Q_3(\sigma_c)\right] \qquad [13]$$

If the selected σ_c is the maximum value which it is felt that the structure can sustain as a result of debris collisions and $\bar{d}$ is the total distance which the craft will travel during its operating life, $C(\sigma_c, \bar{d})$ should be very small (ideally less than one). If such is not the case, then the structure should be reinforced or a fail-safe mechanism incorporated.

The method as proposed is ordinarily applicable to tandem or conventional hydrofoil craft, but it will probably be necessary to apply it twice for canard-type craft. This results from the fact that the forward foil on such a craft is usually supported by a single strut in contrast to a two- or three-strut system for the larger aft foil. The sweeping function for the forward member is, therefore, small with respect to that for the aft member, and there is little "masking" effect between the sweeping functions.

CONCLUSIONS

If the debris item frequency distributions were numerically defined, it appears possible to determine the number of collisions producing a given stress response magnitude which would be sustained by a design-target craft in traveling a given distance. The likelihood of exceeding some critical value of stress response at the hull-strut junction could thus be obtained, and the structural adequacy of the design-target craft with respect to debris collisions could be evaluated accordingly.

RECOMMENDATIONS

It is necessary that numerical parameters be determined for the debris item frequency distributions, that collision effects be determined, and that weighting factors be developed to correct from encounter to collision frequency and to correct for non-center of mass collisions. It is suggested that information as to debris item frequency distributions may be obtained from surveys conducted in areas of interest or through a classification of debris according to source and a formulation of data available on the various sources.

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David Taylor Model Basin. Report 1723.

A METHOD FOR PREDICTING THE PROBABLE NUMBER AND SEVERITY OF COLLISIONS BETWEEN FOILBORNE CRAFT AND FLOATING DEBRIS, by Nathan K. Bales. Aug 1963. iii, 25p. illus., graphs, diagrs., tables. UNCLASSIFIED

One type of loading which an operational hydrofoil craft will experience is that resulting from collisions with items of floating debris. This investigation derives a method for predicting the approximate number of collisions producing a structural response of given severity to be anticipated over a long operating period. The derivation is based on certain assumed debris item frequency distributions. Numerical values for these distributions are needed to give practical value to the proposed method.

1. Hydrofoil boats--Collisions --Prediction
2. Floating debris--Frequency distribution

I. Bales, Nathan K.
II. S-F013 02 01, Task 1705