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THE EFFECT OF SURFACE WAVES ON SOME DESIGN PARAMETERS OF A HYDROFOIL BOAT

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TABLE OF CONTENTS

NOMENCLATURE

c	wave celerity in deep water
c_s	wave celerity in shallow water
$\sqrt{E}$	root mean square of wave amplitude, ft.
g	acceleration of gravity ft./sec.^{2}
h	instantaneous height of free surface measured from equilibrium position, ft.
$\overline{h_{1/3}}$	average amplitude of 1/3 highest waves
$H^2(\omega)$	power spectrum of wave heights measured from the equilibrium position, ft.^{2}-sec.
K	an empirical constant = 51.5 ft.^{2}/sec.^{5}
$Q^2(\omega)$	power spectrum of orbital velocity
$\sqrt{S}$	root mean square of wave orbital velocity, ft./sec.
t	time, sec.
u	longitudinal component of instantaneous orbital velocity, ft./sec.
U	boat speed, ft./sec.
v	transverse component of instantaneous orbital velocity, ft./sec.
V	wind speed, ft./sec.
V_k	wind speed, knots
w	vertical component of instantaneous orbital velocity, ft./sec.
x	longitudinal coordinate in plane of free surface in wind direction
y	transverse coordinate in plane of free surface
z	vertical coordinate, positive down

LIST OF FIGURES

THE EFFECT OF SURFACE WAVES ON SOME DESIGN PARAMETERS OF A HYDROFOIL BOAT

INTRODUCTION

In order to determine the motions of hydrofoil boats, keel clearances and the demands to be made on the controls, it is necessary to inquire into the effect of the various sea states on the flow over the hydrofoils. Based on some of the results of Neumann (3), (5), which describes the velocity potential of the sea as a function of wind speed, and of M. S. Longuet-Higgins (4) which determines the significant wave heights in terms of the cumulative energy density of the sea, charts have been prepared giving expected significant hydrofoil angles of attack and encounter frequencies for various sea states and boat speeds. Also curves of expected significant mean wave heights and wave lengths as a function of sea state are given for both fully developed and duration and fetch limited seas. In addition the principal properties of swells and the principal effects of shallow water on the sea state are discussed.

WAVE HEIGHT OF THE SHORT CRESTED SEA

Following Pierson (1) the amplitude of the seaway is represented by the sum of individual s.h.m. gravity waves of all frequencies and directions

$$h(x,y,t) = \int_{-\pi}^{\pi} \int_{0}^{\infty} \exp i \left[\frac{\omega^2}{g}(x \cos\beta + y \sin\beta) + \epsilon - \omega t \right] \sqrt{H^2(\omega,\beta)\,d\beta\,d\omega} \qquad [1]$$

where

h = height of the free surface measured from the equilibrium position, ft.

β = angle between wave component direction and x-axis.

g = acceleration of gravity, ft./sec.2

t = time, sec.

x, y = rectangular coordinate axes of arbitrary origin and orientation (in the equilibrium plane of the free surface)

H^2 = power spectrum of the wave heights measured from the equilibrium position, ft.^{2}-sec.

ϵ = random phase angle, rad

ω = frequency of each wave, rad/sec.

Equation [1] gives h as a stationary Gaussian process in three dimensions.

Neumann and Pierson (2) have shown, by a comparison of several formulations of the function $H^2(\omega,\beta)$ proposed by a number of investigators, with spectra determined from observations that the one derived by Neumann (3) agreed best with existing data. It correctly predicts the significant height, and it is consistent with average period considerations, with sea surface slope considerations, and with the properties that the sea should have when photographed. This is given, for any point on the surface, for a fully developed sea state by

$$H^2(\omega,\beta) = \begin{cases} \dfrac{2K}{\pi\omega^6} \cos^2\beta e^{-2g^2/V^2\omega^2}, & -\pi/2 \leq \beta \leq \pi/2 \\ 0 & \text{otherwise} \end{cases} \qquad [2]$$

where

x is now considered parallel to the dominant spectral component of the waves.

V = the speed of the wind, ft./sec.

K = 51.5 ft.^{2}/sec.^{5}, an empirical constant.

The root mean square of the wave amplitudes is given by

$$\sqrt{\overline{h^2}} = \left[\int_{-\pi}^{\pi} \int_{0}^{\infty} H^2 \ (\omega, \beta) d\beta d\omega \right]^{\frac{1}{2}} = \sqrt{E} = \left[\frac{3\sqrt{\pi}K}{2^{\frac{11}{2}}} \left(\frac{V}{g}\right)^5 \right]^{\frac{1}{2}} \qquad [3]$$

In addition a number of other wave amplitude parameters are of use in describing the sea state. These result from the reasonable assumption of a Gaussian distribution and are given by Longuet-Higgins (4) as follows:

The average wave amplitude is

$$\bar{h} = .885 \sqrt{E} \qquad [4]$$

The average amplitude of the one-third highest waves is given by

$$\bar{h}_{\frac{1}{3}} = 1.42 \sqrt{E} \qquad [5]$$

$2\bar{h}_{\frac{1}{3}}$ is commonly called the significant wave height (crest to trough) against which Equation [2] was checked. The average amplitude of the one-tenth and one-hundredth highest waves are given respectively by

$$\bar{h}_{\frac{1}{10}} = 1.80 \sqrt{E} \quad \text{and} \quad \bar{h}_{\frac{1}{100}} = 2.36 \sqrt{E} \qquad [6]$$

The highest wave expected over a very long period of time is

$$\bar{h}_{max} \approx 3.4 \sqrt{E} \qquad [7]$$

A plot of the root mean square wave amplitude against wind speed (Equation [3]) is given in Figure 1. The sea state ranges are also indicated thereon. Other height parameters may readily be obtained by multiplication by the appropriate constant determined from equations [4] - [7]. It should be emphasized that the amplitude parameters given in these equations are for one-half of the wave height. The wave height is defined as the vertical distance between the crest and trough.

A qualitative description of the various sea states and swells, prepared by the Hydrographic Office, has been reproduced and inserted at the end of this report in Table I.

FREQUENCY OF ENCOUNTER WITH DOMINANT WAVES

Figure 2(a) gives a plot of the spectral distribution of

$$H^2(\omega)\left(=\int_{-\pi/2}^{\pi/2} H^2(\omega,\beta)d\beta\right)$$ for wind speeds of 15 and 23.5 knots.

It is clear that the curves have well defined peaks and that most of the spectral energy is confined to a fairly small frequency band. It therefore makes sense to talk about the frequency of encounter of the boat with the dominant spectral component of the wave heights. The value of ω for which H^2 is a maximum is obtained from Equation [2] as

$$\omega_m = \sqrt{\frac{2}{3}}\ \frac{g}{V} \qquad [8a]$$

and for the corresponding wave length

$$\lambda_m = \frac{2\pi g}{\omega_m^2} \qquad [8b]$$

This represents the frequency and wavelength of the dominant spectral component of the wave heights. Since the amplitude falls off as $\cos^2\beta$ the rather crude but useful assumption may be made that the dominant waves are travelling in the direction of the wind with celerity, $c\left(=\frac{g}{\omega_m}\right)$. Thus for a boat moving with velocity U at an angle θ with the wind direction the frequency of encounter,

ω_e, is readily shown to be

$$\omega_e = \omega_m \left| 1 - \frac{\omega_m}{g} U \cos\theta \right| \quad [9]$$

It is clear that cos θ is always negative for the case of waves approaching from the bow so that $\omega_e \geq \omega_m$. For waves approaching from the stern ω_e approaches zero as the component of the boat speed in the wind direction U cos θ, approaches the wave speed and then increases again as the boat overtakes the waves. Figure 3 is a plot of Equation [9] for the case of head and following seas ($\theta = \pi$ and 0). Each curve is for the upper bound of the indicated sea state. The corresponding dominant frequency ω_m and wave length λ_m are also indicated thereon.

EFFECT OF SEA ON HYDROFOIL ANGLE OF ATTACK

In what follows it may be assumed, for the present purpose, that the vertical component of the orbital velocity is uniform over the hydrofoil and that the effect of the horizontal component may be neglected in computing angle of attack on the hydrofoil, i.e., U >> w. Thus the instantaneous angle of attack is given by

$$\alpha = \tan^{-1} \frac{w}{U} \quad [10]$$

where w is the vertical component of the orbital velocity at the hydrofoil. The orbital velocity is determined from the velocity potential.

$$\phi = \int_{-\pi}^{\pi} \int_{0}^{\infty} \exp\left\{ i \left[\frac{\omega^2}{g} (x \cos\beta + y \sin\beta) + \epsilon - \omega_t\right] - \frac{\omega^2 z}{g} \right\} \frac{ig}{\omega} \sqrt{H^2 d\beta d\omega} \quad [11]$$

where z is the depth. Equation [11], constructed by Neumann (5), satisfies Laplace's equation, the free surface boundary condition and Equation [1]. From Equation [11] the three components of the orbital velocity, $\frac{-\partial\phi}{\partial x}$, $\frac{-\partial\phi}{\partial y}$ and $\frac{-\partial\phi}{\partial z}$ are found to be respectively

$$u = \int_{-\pi}^{\pi} \int_{0}^{\infty} \exp i \left[\frac{\omega^2}{g}(x \cos\beta + y \sin\beta) + \epsilon - \omega t \right] \sqrt{Q^2(\omega,\beta,z)\cos^2\beta d\beta d\omega} \quad [12a]$$

$$v = \int_{-\pi}^{\pi} \int_{0}^{\infty} \exp i \left[\frac{\omega^2}{g}(x \cos\beta + y \sin\beta) + \epsilon - \omega t \right] \sqrt{Q^2(\omega,\beta,z)\sin^2\beta d\beta d\omega} \quad [12b]$$

$$w = \int_{-\pi}^{\pi} \int_{0}^{\infty} \exp i \left[\frac{\omega^2}{g}(x \cos\beta + y \sin\beta) + \epsilon - \omega t \right] \sqrt{Q^2(\omega,\beta,z) d\beta d\omega} \quad [12c]$$

where

$$Q^2(\omega,\beta,z) = e^{-\frac{2\omega^2 z}{g}} \omega^2 H^2(\omega,\beta) \quad [13]$$

is the energy spectrum of the orbital velocity at depth z associated with the free surface waves. The root mean squares of the amplitude of these components are, with the aid of Equation [2], readily determined to be

$$\sqrt{\overline{u^2}} = \sqrt{\frac{3}{2}} \sqrt{\overline{w^2}}$$

$$\sqrt{\overline{v^2}} = \frac{1}{2} \sqrt{\overline{w^2}} \quad [14]$$

$$\sqrt{\overline{w^2}} = \left[\int_{-\pi}^{\pi} \int_{0}^{\infty} Q^2(\omega,\beta,z) d\beta d\omega \right]^{\frac{1}{2}} = \sqrt{S(z)}$$

$$= \left[\frac{\sqrt{\pi K}}{2^{7/2}} \left(\frac{V}{g}\right)^3 \left[1 + \frac{4\sqrt{gz}}{V} \right] e^{-\frac{4\sqrt{gz}}{V}} \right]^{\frac{1}{2}}$$

Since the distribution of the orbital velocity is also Gaussian orbital velocity parameters similar to the wave height parameters of Equations [4] - [7] may be written. Thus for the mean amplitude of the vertical component of the orbital velocity one has

$$\bar{w} = .885 \sqrt{S} \qquad [15]$$

The average vertical velocity component amplitude for the one-third highest values is

$$\bar{w}_{\frac{1}{3}} = 1.42 \sqrt{S} \qquad [16]$$

and the averages for the one-tenth and one-hundredth highest values are respectively

$$\bar{w}_{\frac{1}{10}} = 1.80 \sqrt{S} \quad \text{and} \quad \bar{w}_{\frac{1}{100}} = 2.36 \sqrt{S} \qquad [17]$$

The maximum expected value is given by

$$\bar{w}_{max} \approx 3.4 \sqrt{S} \qquad [18]$$

Equations [14] - [18], together with Equation [10], lead to various angle of attack parameters. A plot of α_{rms} $\left(= \sqrt{\frac{\overline{w^2}}{U^2}} \right)$, $\alpha_{1/3}$ $\left(= \frac{\bar{\omega}_{1/3}}{U} \right)$ and $\alpha_{1/10}$ $\left(= \frac{\bar{w}_{1/10}}{U} \right)$ as a function of boat speed for the upper bound of a state 5 sea (V = 23.5 K) and depth z = 5 ft. is given in Figure 4. Values of $\alpha_{r_{m_s}}$ for other sea states at depth z = 3 ft. are given in Figure 5.

The important effect of depth on the attenuation of the orbital velocity indicated by Equations [14] is shown plotted on Figures 6a and 6b for various wind speeds.

FREQUENCY OF ENCOUNTER WITH DOMINANT ANGLE OF ATTACK

Another important parameter is the frequency of encounter with the dominant angles of attack at the hydrofoil. The energy spectrum of the orbital velocity, given by

$$Q^2(\omega,z) = \int_{-\pi}^{\pi} Q^2(\omega,\beta,z)\, d\beta = \frac{K}{\omega^4}\, e^{-2\left(\frac{g^2}{V^2\omega^2} + \frac{\omega^2 z}{g}\right)} \qquad [19]$$

is shown plotted in Figure 2b with z = C and for the upper bound of a state 5 sea. This gives a good indication of the spectral distribution of a quantity related to the square of the angle of attack for any particular boat speed. It is seen that the curve is rather sharply peaked and that the frequency range is not especially broad. Most of the spectral energy is contained in a rather narrow band about the frequency of the peak, ω_n. The value of ω_n is readily obtained from Equation [19] and is given by

$$\omega_n = \left\{\frac{g}{2z}\left[\sqrt{1 + \frac{4gz}{V^2}} - 1\right]\right\}^{\frac{1}{2}} \rightarrow \frac{g}{V} \text{ as } z \rightarrow 0 \qquad [20]$$

The effect of z on ω_n is not very large for depths and speeds of interest. If one makes the same assumptions as in the derivation of Equation [9], there results for the frequency of encounter of the dominant spectral component of the angle of attack

$$\omega_E = \frac{g}{V}\left|1 - \frac{U}{V}\cos\theta\right| \qquad [21]$$

Figure 7 is a plot of Equation [21] for the case of head and following seas ($\theta = \pi$ and 0). Each curve is for the upper bound of the indicated sea state. Comparison with Figure 3 shows that the encounter frequencies are about 50 percent higher at the high boat speeds. It should be kept in mind however that the spectral distribution of orbital velocity amplitudes as shown in Figure 2b, indicates a definite band of important frequency components and must be taken into account in the determination of the boat motions (see Reference 6).

EFFECT OF FETCH AND DURATION

Theoretically a fully developed sea would contain all frequencies from $\omega = 0$ to $\omega = \infty$ and would be generated only by a storm of infinite fetch and duration. However, in practice such a sea will be developed by a much more limited storm. The minimum fetch and minimum duration required for a fully developed sea depends on the wind speed. Table II, taken from Reference 7, gives these values for various wind speeds.

According to Reference 7, the spectrum of a non-fully-developed sea may be obtained by cutting off the spectrum of the fully developed sea at some frequency depending on the duration and fetch and disregarding that portion of the spectrum which contains wave components of smaller frequencies. If the fetch of a wind is long enough to produce a fully developed sea but the duration is insufficient, then the sea is duration limited. The cut-off frequencies, ω_c, for some duration limited storms are indicated on Figure 2a. If the duration of the storm is sufficiently long to produce a fully developed sea but the fetch is insufficient then the sea is fetch limited. Cut-off frequencies for this case are indicated in Figure 2a. The cut-off is not always sharp insofar as occasional waves of frequencies down to $0.85\ \omega_c$ are present when $\omega_c > \omega_m$.

Since the wave height distribution is still considered to be Gaussian, the root mean square wave amplitude, $\sqrt{E}$, is determined from Equation [3] with good approximation by changing the lower limit of the integration with respect to wave frequency ω from zero to ω_c. Likewise the other wave amplitude equations [4], [5], [6] and [7] also apply. Where the sea is both duration limited and fetch limited, the E value for the fetch will in general be different from that for the duration. Reference 7 recommends that the lower value be used. An extensive set of curves, giving values of E and cut-off frequencies for various wind speeds, durations and fetch, are given in Reference 7 in a convenient form for ready use. Some significant wave properties have been computed from these curves and plotted on Figure 8. The curve labeled peak of spectrum for fully developed sea is simply a plot of Equation [8]. The curve labeled longest significant wave length is determined by the condition that only 5% of the total wave energy of the fully developed sea resides in waves of greater length. The curve labeled shortest wave length is determined by the condition that only 3% of the wave energy resides in waves of shorter length. The average wave length is based on an empirical formula

$$\lambda_{av} = .277\ V_K^2 \qquad [22]$$

for a fully developed sea. V_K is the wind speed in knots.

Reference 6 states that conditions in nature will usually permit the waves of the sea to attain their fully developed state for winds up to about 32 knots, but for much greater velocities fully developed seas are rare. The significant wave height of a fully developed sea generated by a 32 knot wind is, from Figure 1, about 25 feet. This height could be achieved by stronger winds of shorter duration or fetch than that indicated in Table II for a 32 knot wind. However, the spectrum will be different and the period of the longest significant wave component will be shorter as discussed in the preceding paragraphs. Figure 9 gives the various storm conditions which can produce a sea of a given significant height under duration limited conditions.

SWELL

In contrast to a sea, described for example by the Neumann spectrum (Equation [2]), a swell is the disturbance created by the storm outside the sea generating area. Since the longest waves in a sea travel fastest they will reach a point outside of the generating area first with shorter, lower energy waves following. Thus a swell has a very narrow spectrum compared to that of a sea. The more distant a point of observation is from a given storm, the narrower is the band of frequencies present and the more regular is the swell. In addition the angular spreading is also much smaller. It is often less than 10° compared to 180° in the storm area. The highest swell passing a given point will have a period corresponding to the maximum value of H^2 in Equation [2]. Reference 7 describes methods of determining the properties of swells resulting from various types of storms.

EFFECTS OF SHALLOW WATER

The results described so far apply only to deep water where the depth is greater than one-half of the wave length associated with the highest spectral period present. Because the speed of the waves is reduced in shallow water (see Lamb[8]), refraction effects take place as the waves approach coast lines in much the same way as light rays traveling through air are refracted by a denser medium such as water or glass.

Each two-dimensional spectral wave component is refracted according to Snell's Law

$$\frac{c_s}{c} = \frac{\sin \alpha_s}{\sin \alpha} \qquad [23]$$

where c is the deep water speed of the wave (depends on wavelength).

c_s is the shallow water speed (depends on depth and wavelength).

α is the angle that the wave crest makes with the shore line in deep water.

α_s is the angle that the wave crest makes with the shore line in shallow water.

Thus, in principle, equation [23] applied to all the spectral components of the wave system, will give the effect of changing depth.

Refraction affects waves in several ways as they travel from deep water over the shoal waters off the coast and finally break up on the shore. The waves are bent so that their crests are more parallel to the shore than in deep water. The speed of the waves is reduced in shallow water and since the frequency is fixed for a given wave train the distance between crests is generally less than in deep water. The waves frequently appear more long crested near the coast than in deep water because the waves approaching the shore at large angles to the coast are bent more than those approaching at small angles. Since the spectral components of long period waves will be refracted in deeper water than the short period components, considerable dispersion may take place. Depending on the direction of the waves and the slope of the coast, the high long period waves can be focused into the coast at one point and deflected away from another point causing considerable increase in the significant wave height and periods at the first point and relatively small and short period waves to appear at the other point. Procedures for making approximate predictions of the effect of shoal waters on waves have been developed. These are described in Reference 7.

SUMMARY AND CONCLUSIONS

Computations have been made and presented in graphical form of

1. Important wave height parameters as a function of wind speed.

2. Neumann's energy spectrum for wave heights and orbital velocities for a state 5 sea.

3. Frequency of boat encounter with dominant waves and angles of attack in head and following seas for different sea conditions and boat speeds.

4. Important angle of attack parameters induced by the waves on the hydrofoils for a state 5 sea.

5. Effect of depth on the orbital velocity parameters, and

6. Effect of wind duration and fetch on the sea state.

The calculations are based on the reasonable assumption of a Gaussian distribution of the wave amplitudes and the use of Neumann's spectrum, which appears to be the most accurate existing formula that describes the energy spectrum of the short crested sea.

REFERENCES

1. Pierson, W. J., Wind Generated Gravity Waves. Advances in Geophysics, V. 2, Ed. by H. E. Landsberg, N. Y.; Academic, 1955, p. 93.

2. Neumann and Pierson, A Detailed Comparison of Theoretical Wave Spectra and Wave Forecasting Methods. Deutschen Hydrographischen Zeitschrift, Band 10, Heft 3, 1957.

3. Neumann, G., On Ocean Wave Spectra and a New Method for Forecasting Wind Generated Sea, Beach Erosion Board Tech. Memo, 43, 1953.

4. Longuet-Higgins, M. S., On the Statistical Distribution of the Heights of Sea Waves. Journal of Marine Research, Yale University, V. XI, n3 (1952).

5. Neumann, G., On Wind Generated Wave Motions at Subsurface Sea Levels. Trans. Am. Geophysical Union, V. 36, 1955, p. 985.

6. St. Denis, M., and Pierson, W. J. "On the Motion of Ships in Confused Seas", SNAME, November 1953.

7. Pierson, W. J., Jr., G. Neumann, and R. W. James, Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics, Hydrographic Office Publication No. 603, Navy Dept., Washington, D. C., 1958.

8. Lamb, Sir Horace, Hydrodynamics, Dover Publications, New York, p. 367.

TABLE I.

U. S. Navy Hydrographic Office Scale of Sea Conditions

Code Fig.	Approx. Height of Sea	Seaman's Description
0	0	Calm -- Sea like mirror
1	Less than 1 foot	Smooth -- Small wavelets or ripples with the appearance of scales, but without crests.
2	1-3 feet	Slight -- The waves or small rollers are short and more pronounced, when capping the foam is not white but more of a glassy appearance.
3	3-5 feet	Moderate -- The waves or large rollers become longer and begin to show whitecaps occasionally. The sea produces short rustling sounds.
4	5-8 feet	Rough -- Medium waves that take a more pronounced long form with extensive whitecapping and white foam crests. The noise of the sea is like a dull murmur.
5	8-12 feet	Very rough -- The medium waves become larger and begin to heap up, the whitecapping is continuous, and the seas break occasionally; the foam from the capping and breaking waves begins to be blown along in the direction of the wind. The breaking and capping seas produce a perpetual murmur.
6	12-20 feet	High -- Heavy, whitecapped waves that show a visible increase in height and are breaking extensively. The foam is blown in dense streaks along in the direction of the wind. The sea begins to roll and the noise of the breaking seas is like a dull roar, audible at greater distance.

TABLE I.

(Continued)

7	20-40 feet	Very high -- High, heavy waves developed with long overhanging crests that are breaking continuously, with a perpetual roaring noise. The whole surface of the sea takes on a white appearance from the great amount of foam being blown along with the wind. The rolling of the sea becomes heavy and shocklike.
8	40 feet and over	Mountainous -- The heavy waves become so high that ships within close distances drop so low in the wave troughs that for a time they are lost from view. The rolling of the sea becomes tumultuous. The wind beats the breaking edge of the seas into a froth, and the whole sea is covered with dense streaks of foam being carried along with the wind. Owing to the violence of the wind the air is so filled with foam and spray that relatively close objects are no longer visible.
9		Note -- Qualifying condition applicable to the previous conditions, e. g., (5-9). A very rough confused sea.

TABLE I.

(Continued)

Swell Conditions

Code Fig.	Approx. Height in feet	Description		Approx. Length in feet
0	0	No swell		0
1	1-6	Low Swell	Short or average	0-600
2			Long	Above 600
3	6-12	Moderate	Short	0-300
4			Average	300-600
5			Long	Above 600
6	Greater than 12	High	Short	0-300
7			Average	300-600
8			Long	Above 600
9	--------	Confused		

The direction from which the sea and swells move to be recorded in numerical points from 1, N x E, to 32, N.

TABLE II.

MINIMUM FETCH AND MINIMUM DURATION NEEDED TO GENERATE A FULLY DEVELOPED SEA FOR VARIOUS WIND VELOCITIES

V knots	10	12	14	16	18	20	22	24	26	28
F_m NM............	10	18	28	40	55	75	100	130	180	230
t_m hr..........	2.4	3.8	5.2	6.6	8.3	10	12	14	17	20

V knots	30	32	34	36	38	40	42	44	46
F_m NM..........	280	340	420	500	600	710	830	960	1100
t_m hr..........	23	27	30	34	38	42	47	52	57

V knots	48	50	52	54	56
F_m..............	1250	1420	1610	1800	2100
t_m hr............	63	69	75	81	88

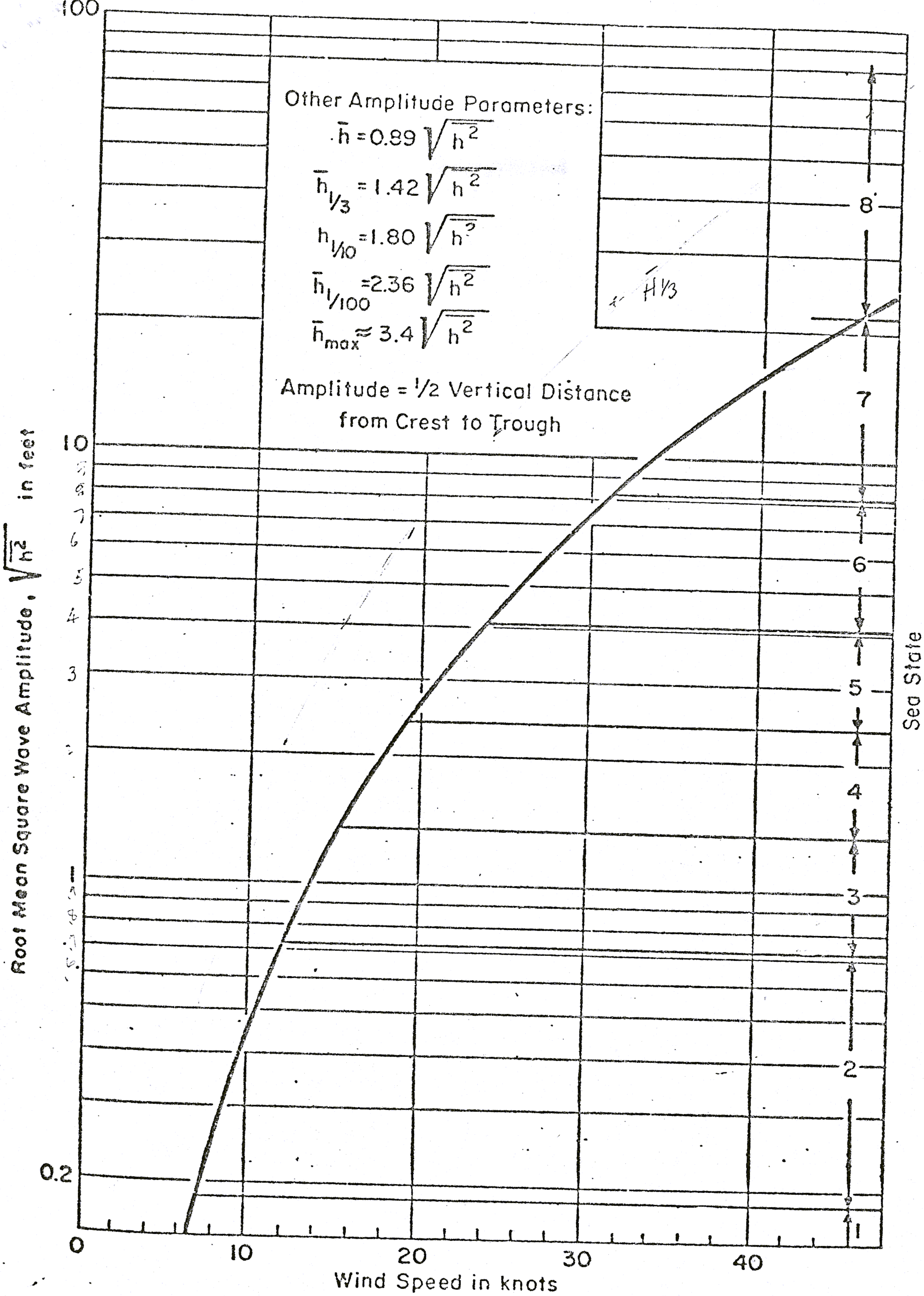

Figure I - Wave Amplitude Parameters versus Wind Speed

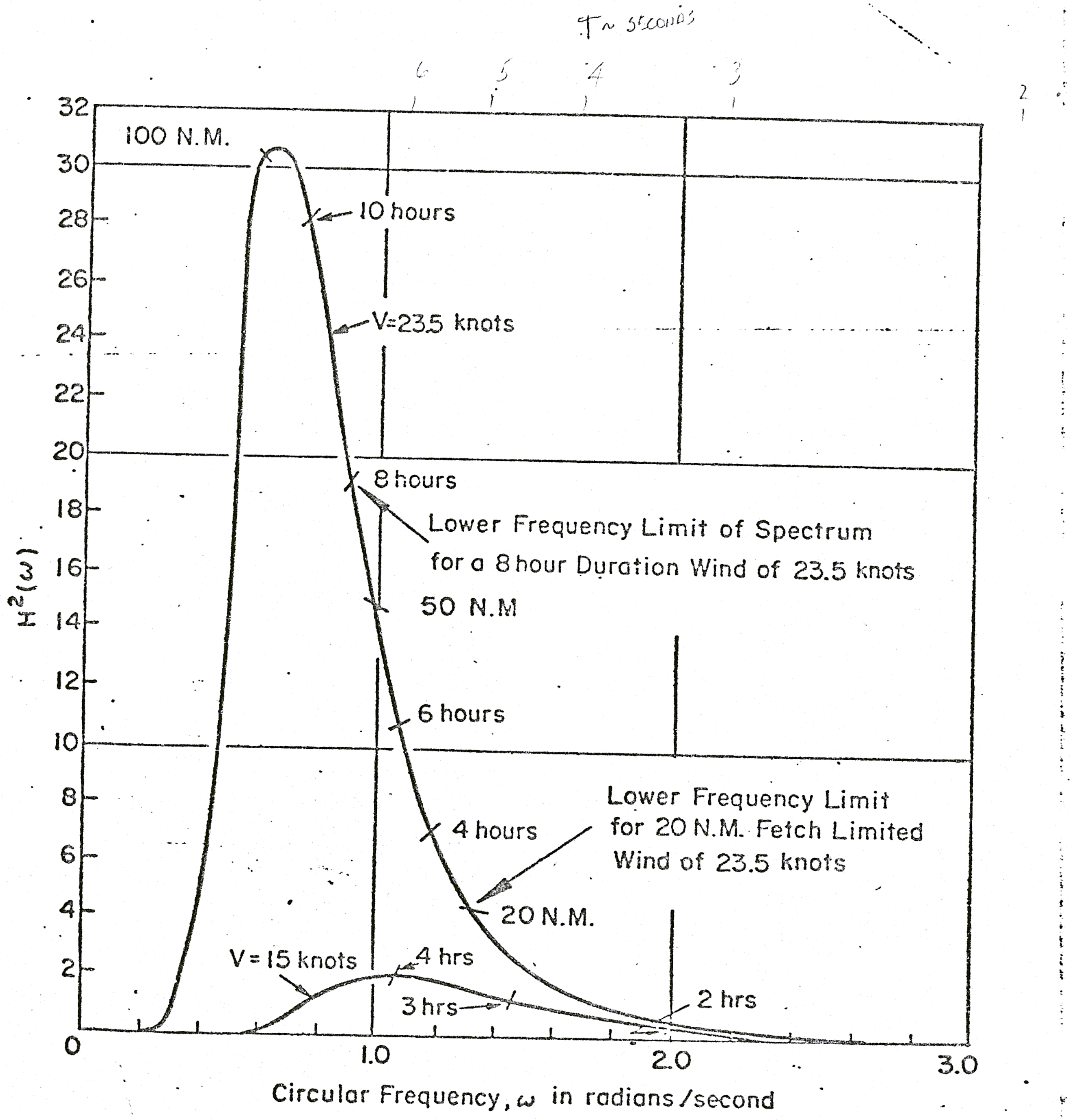

Figure 2a – Energy Spectrum of Wave Amplitudes at Free Surface

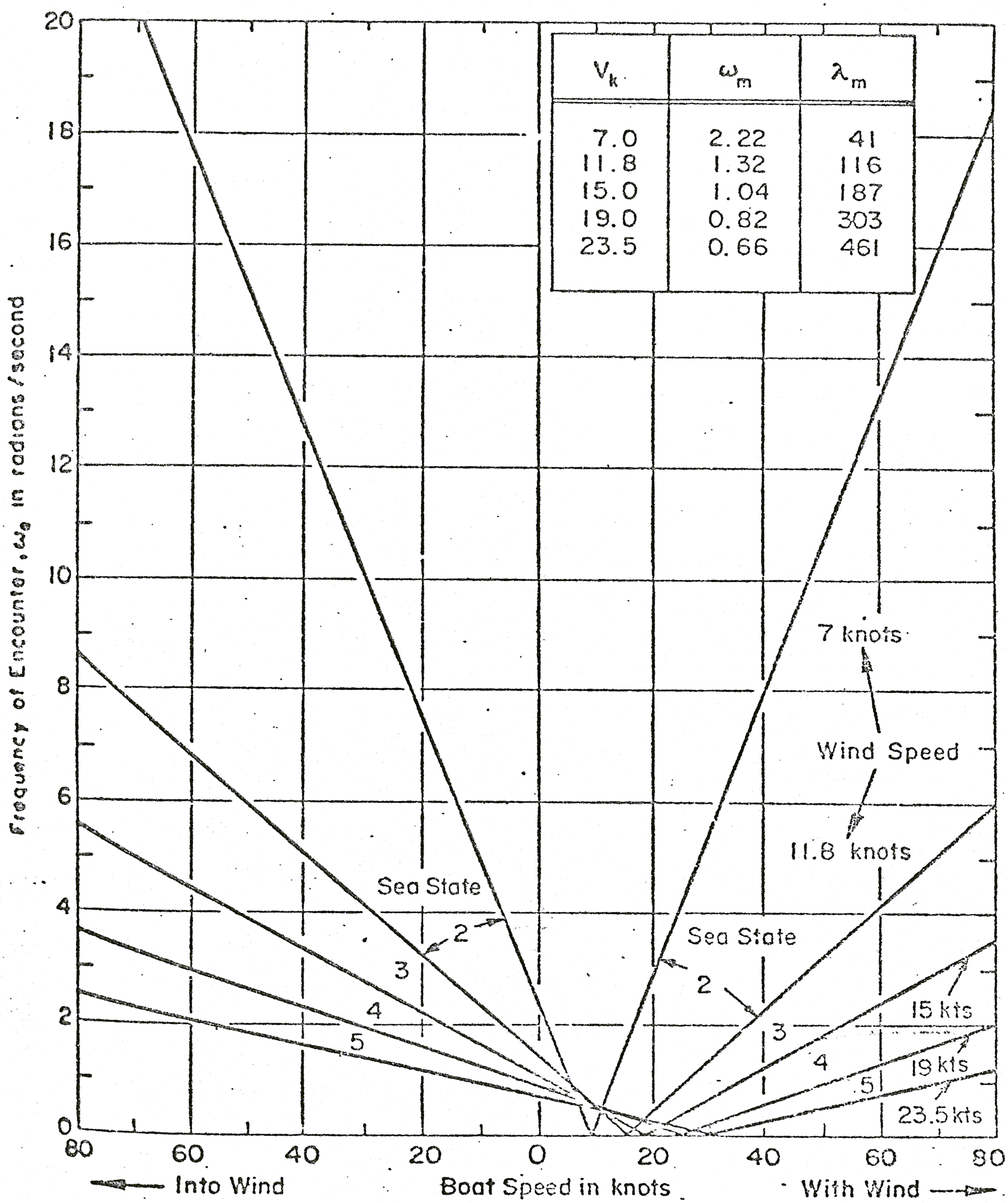

Figure 3- Frequency of Encounter with Dominant Waves

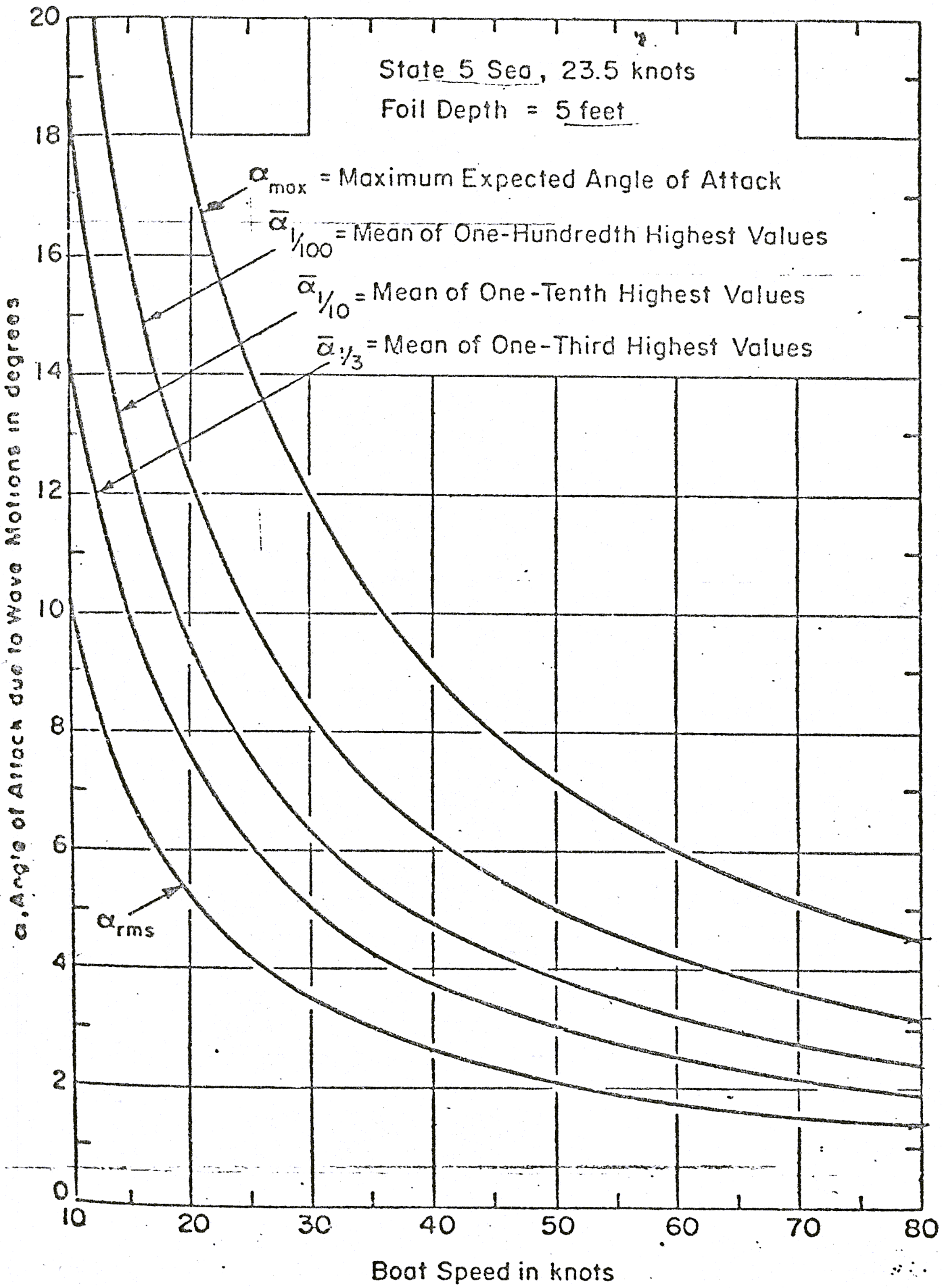

Figure 4– Wave Induced Angle of Attack

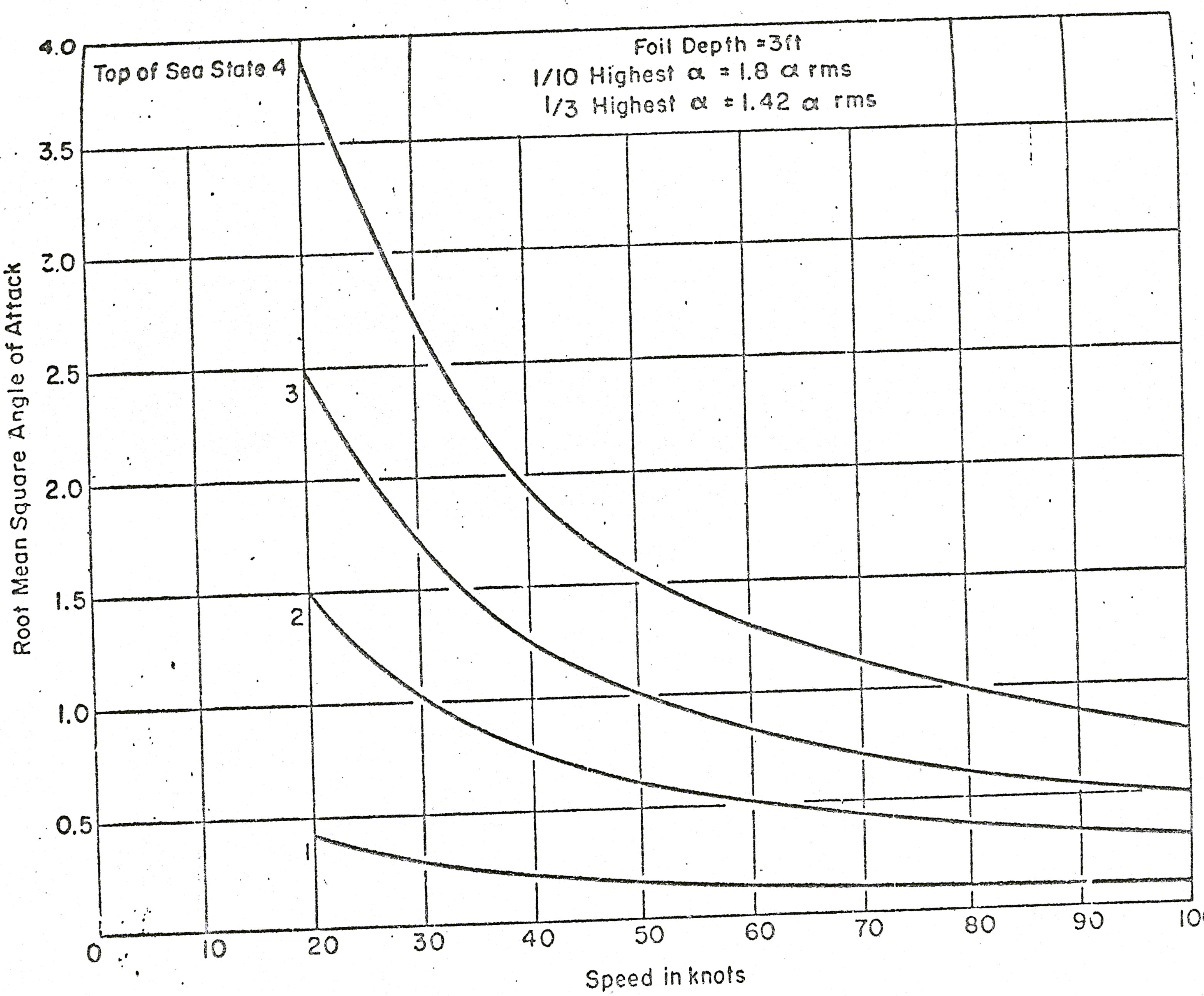

Figure 5 - Angle of Attack Induced by Waves for Various Speeds and Sea States

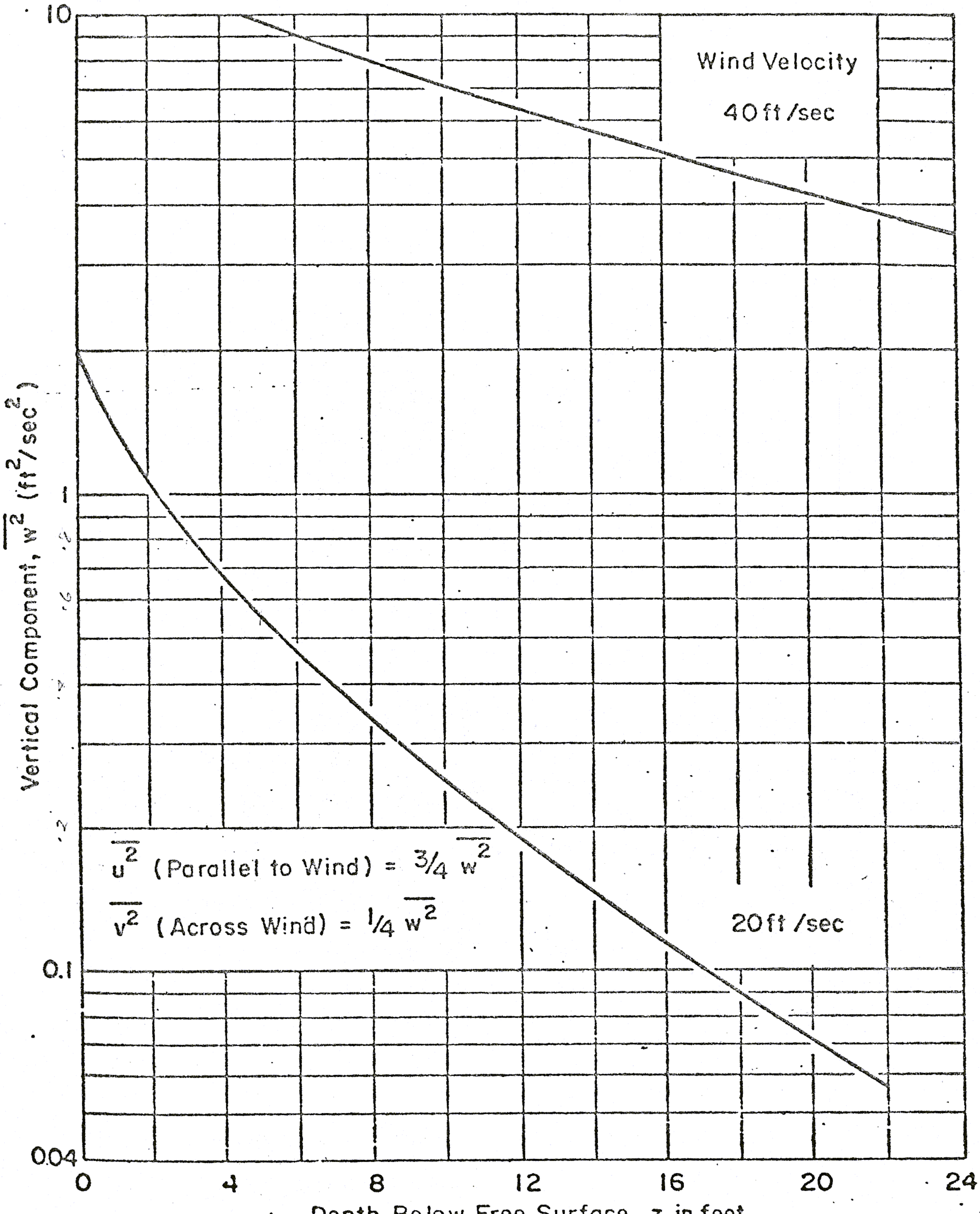

Figure 6a- Mean Square of Orbital Velocity Components at Various Depths

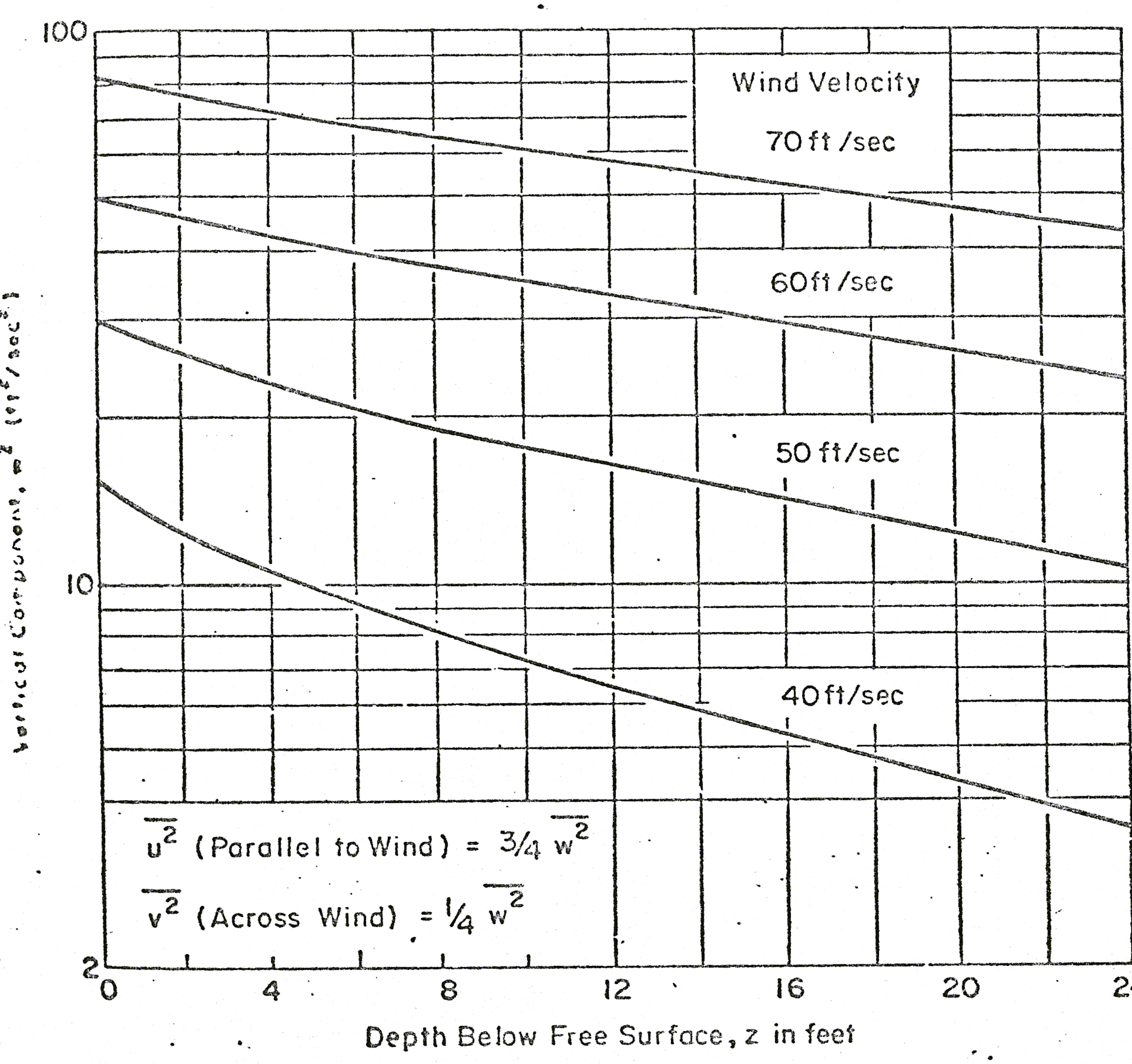

Figure 6 b — Mean Square of Orbital Velocity Components at Various Depths

V_k	ω_n	λ_n
7.0	2.72	27
11.8	1.62	77
15.0	1.27	126
19.0	1.00	202
23.5	0.81	309

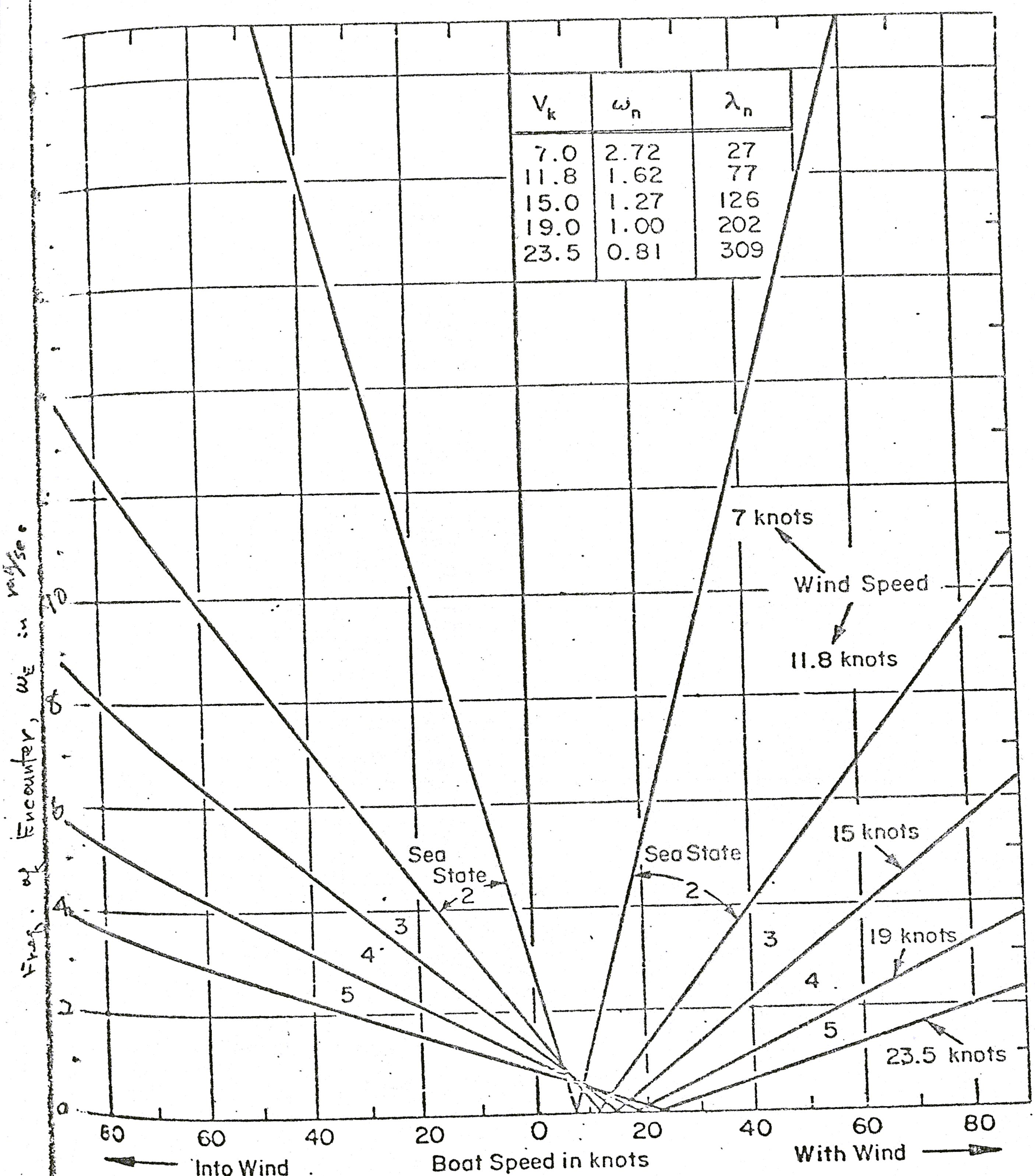

Figure 7- Frequency of Encounter with Dominant Angle of Attack (z=0)

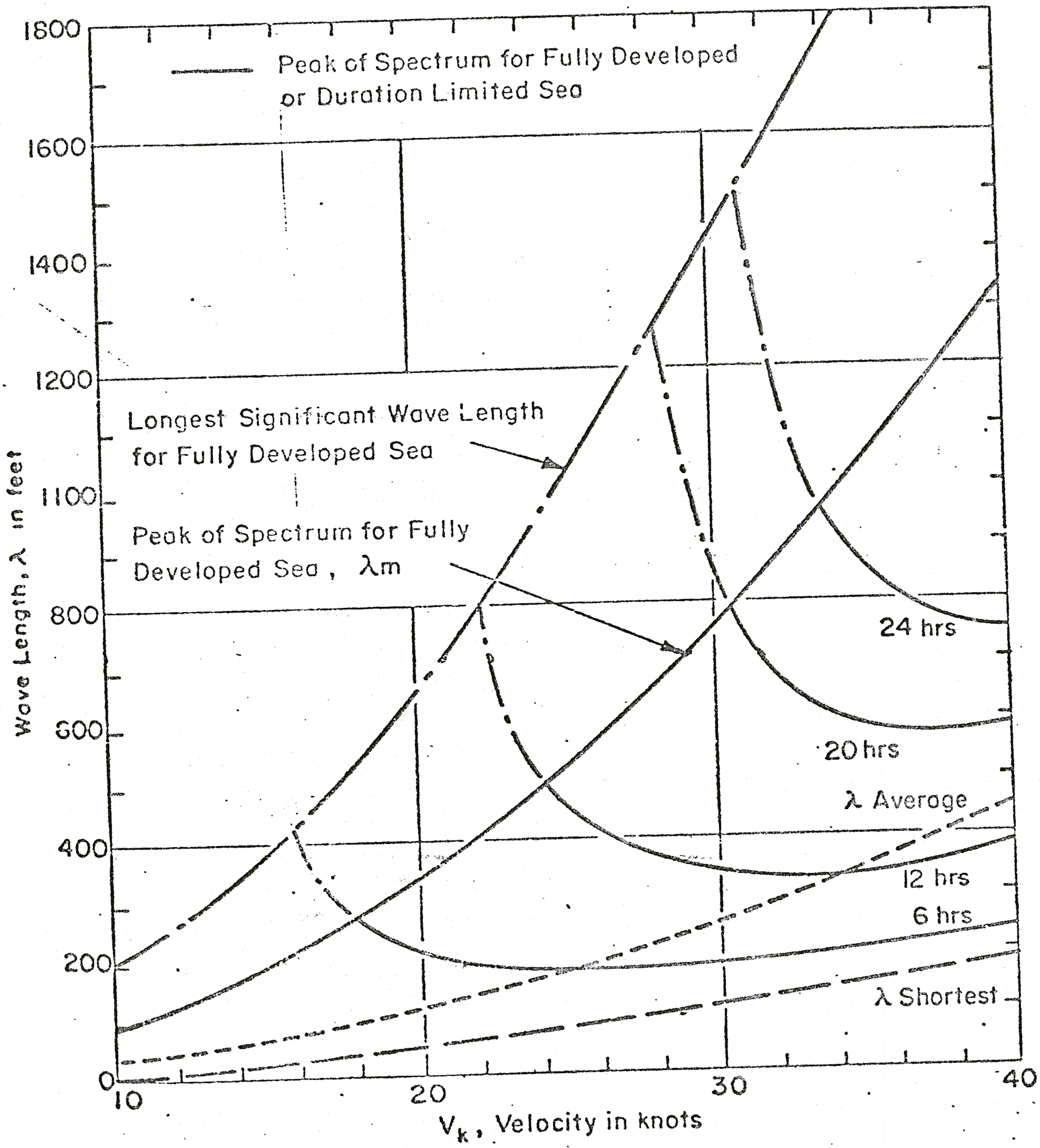

Figure 8 - Variation of Wave Length with Wind Speed and Duration

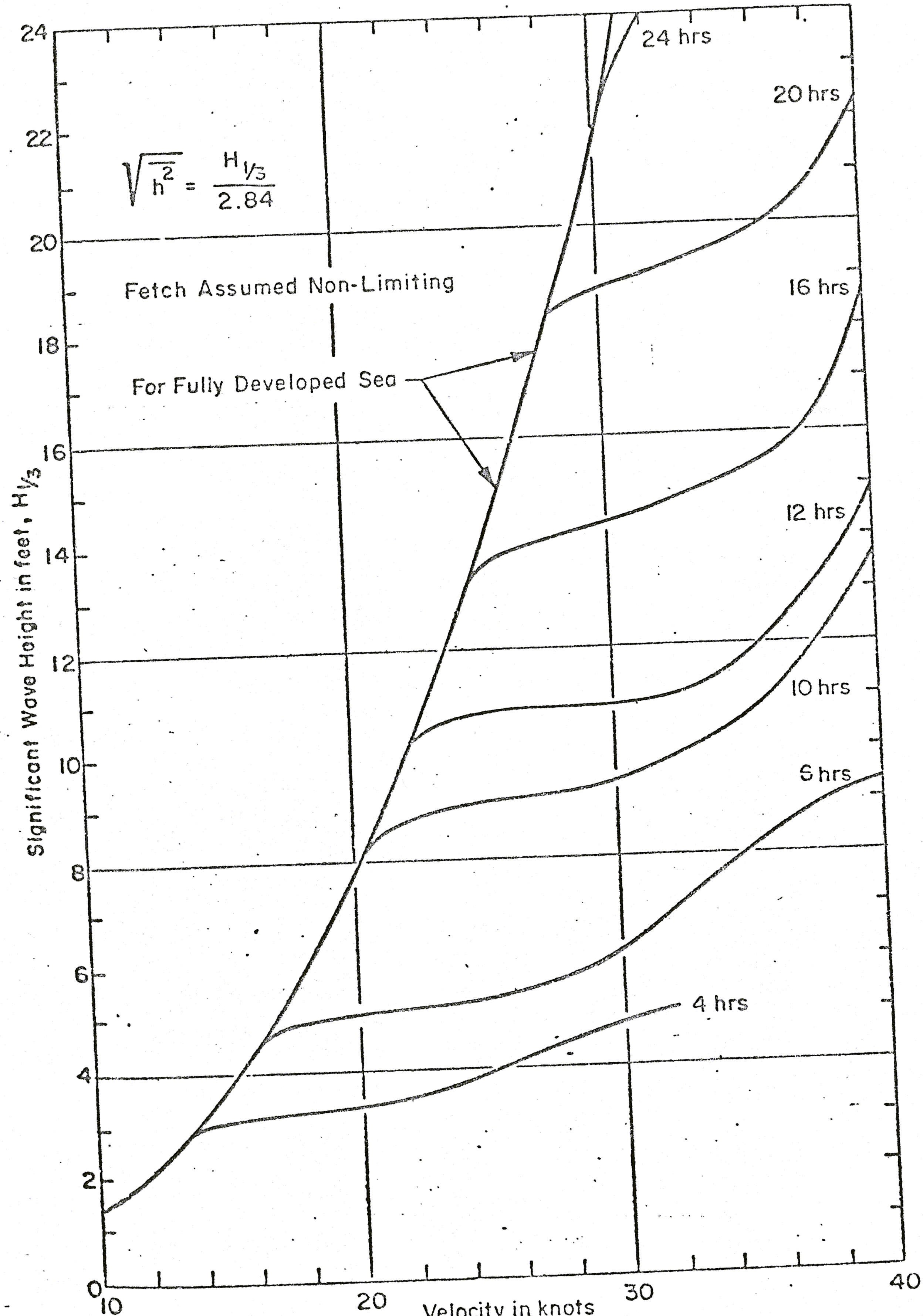

Figure 9 - Variation of Significant Wave Height with Wind Speed and Duration