STEVENS INSTITUTE OF TECHNOLOGY

CASTLE POINT STATION
HOBOKEN, NEW JERSEY

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DAVIDSON LABORATORY
REPORT 982

October 1963

HYDROFOIL LIFT IN HEAD SEAS

by

Charles J. Henry
and
M. Raihan Ali

Prepared for
Bureau of Ships
Contract Nonr 263(45)
(DL Project MP 2480/046)

Approved

Stavros Tsakonas

Stavros Tsakonas, Chief
Fluid Dynamics Division

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ABSTRACT

The major advantage of hydrofoil craft is their ability to sustain high speeds in spite of severe sea conditions. To maximize this advantage, a reliable method is needed to predict lift forces on hydrofoils running under waves. The results of the present investigation show that the measured lift response of finite aspect ratio hydrofoils in regular head seas is linearly related to the measured wave input. Thus, spectral theory can be used with gust response operators as well as wave height spectra to predict the statistical character of the unsteady lift on finite aspect ratio hydrofoils in irregular head seas.

Using the measured gust response operators from regular head sea tests for two hydrofoils with aspect ratios 2 and 4, the computed lift spectra were found to be in good agreement with the measured lift spectra. Reliable theoretical predictions of the gust response operator would facilitate the application of spectral theory to hydrofoil design. Accordingly, measured and predicted values of the gust response operator are compared for the two models tested. Predictions of the gust response operators were theoretically determined using the results of two approximate, unsteady, finite aspect ratio, airfoil theories: those by Lawrence and Gerber and by Reissner and Stevens. The measured and predicted magnitudes of the gust response operator are in fairly good agreement, but the phase is not. Some of the discrepancy is shown to be due to the approximations involved in using oscillating airfoil theory to predict the lift in a traveling gust. It is anticipated that accurate theoretical predictions of the lift spectra for a finite aspect ratio hydrofoil in irregular head seas can be obtained using an exact lifting surface theory to compute the gust response operator.

NOMENCLATURE

a	wave amplitude (ft)
b	semi chord length of hydrofoil (ft)
c	wave celerity (ft/sec)
$c(k_e)$	coherency
C_L	lift coefficient (eq. 1)
$\left[C_L(k_e)\right]^2$	measured lift spectrum (eq.6)
$\left[C_L(k_e)\right]_p^2$	predicted lift spectrum (eq. 7)
$C(k_e)$	Theodorsen function
d	depth of submergence of hydrofoil in semi chords
f_e	frequency of encounter (cps)
g	acceleration due to gravity (ft/sec/sec)
$h(t)$	translatory displacement of foil (ft)
h_o	amplitude of h(t) in semi chords
i	$\sqrt{-1}$
k_e	reduced frequency of encounter (eq. 3)
L	lift amplitude (lb)
$L_{h_r}, L_{h_i}, L_{\alpha_r}, L_{\alpha_i}$	dimensionless unsteady aerodynamic derivatives
$P(k_e, K), Q(k_e, K)$	real and imaginary parts of the generalized Sears function
$r(t)$	free surface elevation at midchord axis of hydrofoil
$\left[r(k_e)\right]^2$	measured wave height spectrum (eq. 5)
$\bar{r}$	average wave height in an irregular sea (eq. 12)
R	average energy in an irregular sea (eq. 11)
$R(k_e)$	complex gust response operator
$R_G(k_e, K)$	two-dimensional gust response operator in a traveling gust
s	semi span length of hydrofoil

NOMENCLATURE (Continued)

t	time
t_o, t_f	initial and final values of time
T	period of oscillation (sec)
U	forward speed of model (ft/sec)
$v(x,y,t)$	vertical velocity (ft/sec)
$V(x,t)$	complex representation of the downwash (ft/sec)
W	complex amplitude of traveling gust (ft/sec)
W_r, W_i	real and imaginary parts of W (ft/sec)
x, y	orthogonal cartesian coordinate system
$\alpha(t)$	rotational displacement of foil (radians)
α_o	amplitude of $\alpha(t)$
ϵ	relative phase between $h(t)$ and $\alpha(t)$ (rad)
$\eta(x, t)$	free surface elevation (ft)
λ	surface wave length (ft)
ρ	water density (lb-sec^2/ft^4)
τ	dummy variable
ϕ	phase lead of $C_L(t)$ relative to $r(t)$
$\psi(k_e)$	cross-spectrum (eq. 9)
ω	circular wave frequency (rad/sec)
ω_e	circular frequency of encounter (rad/sec)

INTRODUCTION

The major advantage of hydrofoil craft is their ability to sustain high speeds in spite of severe sea conditions, whereas displacement craft of similar overall proportions and under the same sea conditions must operate at considerably reduced speeds. This speed advantage is achieved by reducing the hydrofoil craft's motions by controlling the lift forces on the hydrofoil system. In order to maximize this advantage a reliable method is needed to predict the lift forces on the hydrofoils under realistic conditions -- including, for example, the effects of finite aspect ratio and irregular seas.

The presently available analytical technique for predicting the statistical characteristics of ship motions in irregular seas is to sum the response of the craft to each of the harmonic components which compositely represent the irregular sea.[1] In using this approach, one presumes that the ship motion is linearly related to the wave input at each frequency. Then for such a linear system, the output motion spectrum can be computed from the wave input spectrum and the system response operator. This response operator can be obtained either from experiments using sinusoidal input over a range of frequencies or it can be predicted theoretically if a reliable theory for harmonic input to the system is available.

This spectral superposition procedure has been verified experimentally for the case of displacement vessels in head seas.[2] However, it has not yet been validated in the case of unsteady forces on hydrofoils. This investigation was undertaken to find whether or not the lift response of finite aspect ratio hydrofoils in head seas could be represented as a linear system and, thus, to validate the application of spectral theory. To this end, two hydrofoil models with aspect ratios 2 and 4 were tested in regular and irregular head seas.

Reliable theoretical predictions of the gust response operator, which is the lift response to a regular sea, would facilitate the application of spectral theory to hydrofoil design. Accordingly, predicted values of the gust response operators for the two hydrofoil models are compared with measured values. An approximate gust response theory is developed using two approximate oscillating airfoil theories.[3,4] Although more accurate unsteady airfoil theories have been developed recently, as well as arbitrary Froude number hydrofoil theories,[5] the computer programs needed for the application of these theories have not yet been developed for the UNIVAC 1105 at Stevens Institute of Technology.

This research was sponsored by the Office of Naval Research under Contract Nonr 263(45).

APPARATUS DESCRIPTION

Two series of tests were carried out: one with an aspect ratio 2 model and one with aspect ratio 4, so that the effect of aspect ratio on the unsteady lift could be evaluated experimentally. Both models were constructed of brass and had rectangular planforms with thickness distribution as given by the NACA 64_1-012 cross-section, i.e., 12% thick and zero camber. Each model had a chord length of 3 in. The models were held rigidly at zero angle of attack at a depth of 2 chords below the calm water surface by a 12 in. steel strut with the same cross section as the hydrofoils.

The strut extended vertically from the midspan of the hydrofoil to a lift balance above water. The balance output was calibrated and found to be linear over the range of interest ($\pm$20 lb). The balance was supported on a carriage in Davidson Laboratory Tank No. 3. The surface wave height was measured by a resistance wave wire at the midchord axis of the hydrofoil about 10 in. outboard of the strut.

A dynamic calibration, carried out with the aspect ratio 2 model mounted on the carriage in the tank, indicated that the magnification factor (apparent amplification rate of the actual input due to flexibility of the supporting structure) was less than 3% over the frequency range of 0 to 12 cps. In addition, a spectrum analysis of the output noise was carried out with the foil operating at test speed in calm water. Although the lowest significant frequency of the noise spectrum was 42 cps., the amplitude was sufficiently large that the desired output signals were obscured. Therefore, passive low-pass filters were added in the wave wire and lift circuits which effectively attenuated the noise level. The attenuation and phase shift of the desired signals due to the filters were indeed appreciable in the range of frequencies of encounter of the tests. However, in the data analysis, only the relative magnitude and phase of the lift compared with the wave were needed, so that the effect of the filters was not accounted for in the data reduction. Calibrations were carried out to ensure that both filters had the same characteristics.

The speed of the apparatus was determined from an electrical timer which was started and stopped as the carriage passed two points in the tank at a known distance apart. The test speed was held constant for all tests at 15 ft per sec ($\pm$.05% variation) which corresponds to a Froude number of 5.28 based on full chord.

The filtered outputs of the lift balance and wave wire were recorded on paper tape during the regular sea tests. During the irregular sea tests, the same outputs were recorded on both paper and magnetic tape to facilitate data reduction. The continuous magnetic tape records were converted to digital records on IBM cards by means of an analog to digital converting system at Davidson Laboratory.[6]

Between each regular sea test, a waiting period of from five to twelve minutes was allowed for the water to calm down. The range of wave lengths in the regular sea tests gave reduced frequencies of encounter from 0.05 to 0.5. This range covered the range of frequencies of significant energy in the irregular wave spectra. Both irregular sea tests were divided into several runs, each of which was obtained in a different part of the irregular sea pattern.

DATA ANALYSIS

Regular Seas

During the regular sea tests with each model, the lift amplitude L, phase ϕ, surface wave amplitude a, and frequency of encounter f_e, were obtained from the recorded outputs of the lift balance and wave wire. The phase was determined as the phase lead of the lift time history with respect to the wave time history at the midchord axis. The lift coefficient C_L, dimensionless wave amplitude r, at the free surface, and the reduced frequency of encounter k_e, were calculated from the defining relations

$$C_L = \frac{L}{2\rho U^2 bs} \tag{1}$$

$$r = \frac{a}{b} \tag{2}$$

$$k_e = 2\pi \frac{f_e b}{U} \tag{3}$$

where ρ = density of water
b = semi chord length
s = semi span length
U = model speed

The ratio of the lift coefficient to the dimensionless wave amplitude was obtained from these test results at each frequency. This ratio and the corresponding phase defines the gust response operator $R(k_e)$, as

$$R(k_e)\cos \omega_e t = \frac{C_L}{r} \cos (\omega_e t + \phi) \tag{4}$$

where $\omega_e = 2\pi f_e$ is the circular frequency of encounter. The measured magnitude and phase of $R(k_e)$ are plotted in Figs. 1 through 4 for the aspect ratio 2 and 4 models.

During the aspect ratio 4 tests, a series of runs were made at approximately the same frequency of encounter but with different wave amplitudes. The magnitude and phase of $R(k_e)$ were computed as before and these results are presented in Table I. This series of runs provided additional evidence concerning the linearity of the lift response.

Irregular Seas

The sea surface and lift response in an irregular head sea are each assumed to be composed of a linear superposition of a large number of sine waves with random phase distribution. However, the magnitude and phase of each component of the lift response are assumed to have a definite relationship to the corresponding wave component. In fact, if the former assumption is valid, then the relation between the lift and wave height components at each frequency in an irregular sea must be identical to that in a regular sea. The relation between the lift and wave height at various frequencies in a regular sea is called the gust response operator. Using spectral theory techniques, the statistical character of the irregular lift can be computed from the gust response operator as well as the statistical character of the irregular sea. To verify the applicability of this statistical method of superposition to the case of unsteady lift on hydrofoils, the computed lift spectra for the two hydrofoil models were compared with the measured lift spectra.

The measured spectra were calculated by the method outlined in Ref. 2. In this method, the wave height spectrum $\left[r(k_e)\right]^2$ is computed from the time history of the wave r(t), by

$$\left[r(k_e)\right]^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left[\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} r(t)r(t-\tau)dt\right] e^{-ik_e\tau}\, d\tau \qquad (5)$$

the Fourier Transform of the auto-correlation function (in square brackets). Similarly, the measured lift spectrum $C_L(k_e)_m^2$ was computed from the time history of the lift $C_L(t)$ by

$$\left[C_L(k_e)\right]_m^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left[\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} C_L(t)C_L(t-\tau)dt\right] e^{-ik_e\tau}\, d\tau \qquad (6)$$

The results obtained from eqs. 5 and 6 for several runs were then averaged arithmetically at each frequency. Two runs were used for the Aspect Ratio 2 model and five runs for Aspect Ratio 4. These average spectra are presented in Figs. 5, 6 and 7.

Under the assumptions outlined above, a computed lift spectrum $\left[C_L(k_e)\right]_c^2$ can be obtained from the wave height spectrum and the measured gust response operator by the relation

$$\left[C_L(k_e)\right]_c^2 = \left|R(k_e)\right|^2 \left[r(k_e)\right]^2 \tag{7}$$

Figures 6 and 7 show the comparison between the measured lift spectra obtained from eq. 6 with that computed by means of eq. 7 for the two models.

A measure of the linearity of the system as well as the quality of the experiment is provided by the coherency, $c(k_e)$. This quantity is computed from the relation

$$c(k_e) = \frac{\Psi(k_e)}{\left[C_L(k_e)\right]^2 \left[r(k_e)\right]^2} \tag{8}$$

where $\Psi(k_e)$ is the cross-spectrum defined by

$$\Psi(k_e) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left[\lim_{T \to \infty} \frac{1}{T}\int_{-T/2}^{T/2} r(t)C_L(t-\tau)dt\right] e^{-ik_e\tau}\, d\tau \tag{9}$$

which is the Fourier Transform of the cross-correlation function. The coherencies obtained from eq. 8 are presented in Figs. 6 and 7 for the two sets of experiments. The measured phase relation between lift and wave in the irregular sea can be calculated by the relation

$$\phi(k_e) = \tan^{-1}\left[\frac{\mathrm{Im}\ \Psi(k_e)}{\mathrm{Re}\ \Psi(k_e)}\right] . \tag{10}$$

The measured irregular sea phase angles are shown in Figs. 2 and 4.

Since the energy of a wave system is proportional to the square of the wave amplitude, the area under the wave height spectrum can be used to describe the average properties of the sea. That is, if R is defined as

$$R = \int_0^{\infty} \left[r(k_e)\right]^2 dk_e \tag{11}$$

then the average wave height is given by[1]

$$\bar{r} = 0.885 \sqrt{R} \tag{12}$$

and this value is reported in Fig. 5.

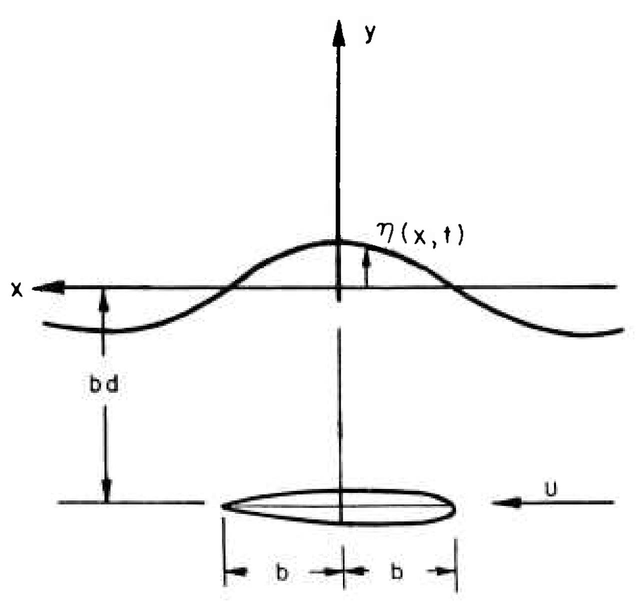
THEORETICAL ANALYSIS -- REGULAR SEAS

The hydrofoil lift spectrum in an irregular sea can be obtained from eq. 7 by means of the gust response operator. The theoretical approach for predicting the gust response operator for hydrofoils traveling at arbitrary Froude number has been derived[5] but the necessary computer programs for the UNIVAC 1105 are being developed. However, several approximate unsteady lifting surface theories are already available for the case of an oscillating airfoil. Although these theories are derived for the case of infinite fluid, the results can be used in the present study since the hydrofoils were two chord lengths below the free surface. At this depth, the effects on the free surface should be small.

Two approximate unsteady airfoil theories were used: those by Reissner and Stevens[3] and by Lawrence and Gerber.[4] Each of these theories treats the problem of an oscillating wing in uniform flow. However, the approximate gust response operator can be obtained from oscillating airfoil theory in the following manner.

The surface elevation $\eta(x,t)$ due to a regular long crested wave of frequency ω traveling in the positive x-direction (where x,y denotes an orthogonal Cartesian coordinate system with the y-axis vertically upward) is given by

$$\eta(x,t) = br \cos \frac{2\pi}{\lambda}\left[x-(U+c)t \right] \quad (13)$$



where

r = wave amplitude in semi chords

$c = g/\omega$ = wave celerity

$\lambda = 2\pi g/\omega^2$ = wave length

U = uniform stream velocity in positive x-direction

g = acceleration due to gravity

The reduced frequency of encounter, k_e, is then given by

$$k_e = \frac{\omega b}{U}\left(1 + \frac{\omega U}{g}\right)$$

In eq. 13, a crest is located at x = 0 (midchord) when t = 0, which gives the same phase reference as was used in the experiments. With the surface elevation given by eq. 13, the vertical velocity distribution v(x,y,t) for small values of r will then be

$$v(x,y,t) = br\omega e^{\frac{2\pi}{\lambda}y} \sin\frac{2\pi}{\lambda}\left[x - (U+c)t\right] \tag{14}$$

In the region $-b \leq x \leq b$, $y = -bd$, when $b << \lambda$, $v(x,-bd,t)$ can be approximated by

$$v(x,-bd,t) = br\omega e^{\frac{-2\pi}{\lambda}bd}\left[\frac{2\pi x}{\lambda}\cos\omega_e t - \sin\omega_e t\right] \tag{15}$$

where the relation $\omega_e = 2\pi(U+c)/\lambda$ has been introduced.

For a thin airfoil with zero camber oscillating in heave h(t), positive down, and pitch $\alpha(t)$ about its midchord, positive for leading edge up, such that

$$h(t) = h_o b \cos\omega_e t \tag{16}$$

$$\alpha(t) = \alpha_o \cos(\omega_e t + \epsilon)$$

the vertical velocity distribution over the foil is given by

$$v(x,-bd,t) = \left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\left[h(t) + x\alpha(t)\right]$$

$$= (-bh_o 2\pi f_e - U\alpha_o \sin\epsilon - x\alpha_o 2\pi f_e \cos\epsilon)\sin\omega_e t$$

$$+ (U\alpha_o \cos\epsilon - x\alpha_o 2\pi f_e \sin\epsilon)\cos\omega_e t \tag{17}$$

Comparing the corresponding coefficients of the sine and cosine terms in eq. 15 and 17, it is seen that the vertical velocity distribution on a stationary airfoil in a sinusoidal gust can be made nearly the same as that on an oscillating airfoil in uniform flow if

$$\epsilon = \pi/2$$

$$\frac{\alpha_o}{r} = -\frac{\omega b}{f_e \lambda} e^{-\frac{2\pi}{\lambda} bd} \tag{18}$$

$$\frac{h_o}{r} = \frac{\omega}{2\pi f_e} e^{-\frac{2\pi}{\lambda} bd} - \frac{U}{2\pi f_e b} \frac{\alpha_o}{r}$$

The lift response[4] to harmonic heaving h(t) and pitching about midchord $\alpha(t)$ can be found from

$$\bar{L} e^{i\omega_e t} = -\pi\rho b^3 \omega_e^2 \, 2s \left[L_h \frac{h(t)}{b} + L'_\alpha \alpha(t) \right]$$

where $\bar{L}$ is the complex lift amplitude, s is the semispan length and L_h, L'_α are the complex unsteady aerodynamic derivatives for heaving and pitching oscillations, respectively, with respect to midchord. The quantities L_h and h(t) are divided into real and imaginary parts in the form

$$h(t) = b(h_r + ih_i)(\cos \omega_e t + i \sin \omega_e t)$$

$$L_h = L_{hr} + iL_{hi}$$

Treating $\alpha(t)$ and L'_α in a similar fashion, then expanding all terms in the expression for $\bar{L} e^{i\omega_e t}$ and taking the real part of both sides yields

$$\mathrm{Re}\left\{\bar{L}e^{i\omega_e t}\right\} = -\pi\rho b^3\omega_e^2 \, 2s\left\{\left[L_{hr}h_r - L_{hi} + L'_{\alpha r} - L'_{\alpha i}\alpha_r - L'_{\alpha i}\alpha_i\right] \cos\omega_e t - \left[L_{hr}h_i + L_{hi}h_r + L'_{\alpha r}\alpha_i + L_{\alpha i}\alpha_r\right] \sin \omega_e t\right\} \tag{19}$$

The heaving motion is then represented by

$$\mathrm{Re}\left\{(h_r + ih_i)(\cos\omega_e t + i \sin \omega_e t)\right\} = h_r \cos \omega_e t - h_i \sin \omega_e t$$

Comparing this result with eq. 16, it is seen that

$$h_r = h_o$$

$$h_i = 0$$

Similarly, for the pitching motion in eq. 16 with ϵ given by eq. 18,

$$\alpha_r = 0$$

$$\alpha_i = \alpha_o$$

The lift response operator due to harmonic heaving and pitching can then be obtained from the expression for $\mathrm{Re}\left\{\bar{L}e^{i\omega_e t}\right\}$ giving

$$\frac{C_L}{r}\cos(\omega_e t + \varphi) = \frac{\mathrm{Re}\left\{\bar{L}e^{i\omega_e t}\right\}}{2\rho U^2 bsr}$$

$$= -\pi k_e^2\left[\left(\frac{h_o}{r}L_{hr} - \frac{\alpha_o}{r}L'_{\alpha i}\right)\cos\omega_e t - \left(\frac{h_o}{r}L_{hi} + \frac{\alpha_o}{r}L'_{\alpha r}\right)\sin\omega_e t\right]$$

The dimensionless wave number K, and the reduced wave frequency k, are defined as

$$K = \frac{2\pi b}{\lambda} \quad \text{and} \quad k = \frac{\omega b}{U}$$

The approximate gust response operator is that obtained from the lift response operator for the oscillating airfoil. The amplitudes of motion are replaced by the corresponding wave characteristics of eq. 18 and the approximate gust response operator is then

$$R(k_e)\cos\omega_e t = -\pi k k_e e^{-Kd}\left\{\left[L_{hr}\left(1 + \frac{K}{k_e}\right) + KL'_{\alpha_i}\right]\cos\omega_e t + \left[KL'_{\alpha r} - \left(1 + \frac{K}{k_e}\right)L_{hr}\right]\sin\omega_e t\right\} \qquad (20)$$

The magnitude and phase of $R(k_e)$ was calculated by the methods of ref. 3 and 4 and the results are presented in Figs. 1 and 3 for $|R(k_e)|$ and in Figs. 2 and 4 for the phase of $R(k_e)$ for aspect ratio 2 and 4, respectively.

Using the values of $|R(k_e)|$ predicted by eq. 20, theoretical predictions of the lift spectra, $\left[C_L(k_e)\right]_T^2$ were obtained from the relation

$$\left[C_L(k_e)\right]_T^2 = |R(k_e)|^2 \left[r(k_e)\right]^2 \tag{21}$$

The theoretically predicted lift spectra are compared with the measured and computed lift spectra in Figs. 6 and 7.

DISCUSSION OF RESULTS

Regular Seas

The measured and predicted values of the magnitude of the gust response operator C_L/r are compared in Fig. 1 and 3 for aspect ratio 2 and 4, respectively. It is seen that the value of C_L/r predicted by eq. 20 using the Lawrence and Gerber results is lower than that predicted by Reissner and Stevens. At aspect ratio 2 the discrepancy is about 12% whereas at aspect ratio 4, it is only about 7%.

In the case of aspect ratio 2, the value of C_L/r predicted by Reissner and Stevens is in good agreement with the measured values at all frequencies, while the Lawrence and Gerber prediction falls below the measured values, particularly at reduced frequencies of encounter k_e, above 0.15. At aspect ratio 4, the predicted value of C_L/r using the Reissner and Stevens results falls above the measured values when $0.05 < k_e < 0.3$, whereas for $0.3 < k_e < 0.5$ the predicted value becomes increasingly smaller than the measured one. The Lawrence and Gerber result at aspect ratio 4, however, is in agreement with the measured values of C_L/r for $0.05 < k_e < 0.25$ but again it falls below them when $k_e > 0.25$.

The measured and predicted values of the phase φ of the gust response operator are compared in Figs. 2 and 4 for aspect ratio 2 and 4, respectively. It is seen that the predicted values of φ by the two theories are in agreement but that both predictions are less than the measured values for both aspect ratios. This discrepancy is found to be worse at the high frequencies in both cases and increases with increasing aspect ratio.

At least part of these discrepancies results from the approximations used in deriving eq. 20. An indication of the magnitude of error introduced is seen by comparing the approximate gust response operator in two-dimensional flow with the exact value as derived by Kemp.[7] The values of L_h and L'_α in two-dimensional flow are given in Ref. 8.

The exact form of the downwash due to the regular waves is given by Eq. 14. However, to obtain the complex representation of this downwash, consider

$$V(x,t) = We^{i(\frac{2\pi}{\lambda} x - \omega_e t)} \qquad (22)$$

where W is the complex amplitude of the traveling gust. Separating each factor into its real and imaginary parts, then expanding and taking only the real part of both sides leads to

$$\mathrm{Re}\left\{V(x,t)\right\} = W_r \cos(\frac{2\pi}{\lambda} x - \omega_e t) - W_i \sin(\frac{2\pi}{\lambda} x - \omega_e t)$$

Comparing this result with eq. 14, it is seen that

$$W_r = 0$$

$$W_i = -b\omega r e^{\frac{2\pi}{\lambda} y}$$

The exact gust response has been derived by Kemp[7] in the form

$$\bar{L} e^{i\omega_e t} = 2\pi\rho U b W e^{i\omega_e t}\left\{\left[J_o(K) - iJ_1(K)\right] C(k_e) + i \frac{k_e}{K} J_1(K)\right\} \qquad (23)$$

where $J_o(K)$ and $J_1(K)$ are Bessel functions and $C(k_e)$ is the Theodorsen function. If the quantity in brackets, which is the generalized Sears function, is separated into its real and imaginary parts, $P(k_e,K)$ and $Q(k_e,K)$, respectively, then $R_G(k_e,K)$ is obtained as follows:

$$R_G(k_e,K)\cos \omega_e t = \frac{\mathrm{Re}\left\{\bar{L} e^{i\omega_e t}\right\}}{2\rho U^2 \, b \, s \, r}$$

$$= 2\pi k e^{-kd}\left[Q(k_e,K)\cos \omega_e t + P(k_e,K)\sin \omega_e t\right] \qquad (24)$$

The exact gust response operator obtained from eq. 24 and the approximate gust response operator obtained from eq. 20, are compared in Fig. 8 for two-dimensional flow. There the two results are shown to be in good agreement. The error is found to increase with k_e to about 10% at $k_e = 0.5$. However, the phases predicted by eqs. 20 and 24 do not agree. The discrepancy again increases with k_e to about 22^o at $k_e = 0.5$. Thus, it is concluded that the magnitude of the approximate gust response operator predicted by eq. 20 is reliable in the reduced frequency range $0 < k_e < 0.5$ but the phase is not.

However, these results are for two-dimensional flow. Since the three-dimensional effect on the gust response operator has not as yet been calculated, no quantitative conclusions can be drawn regarding the accuracy of eq. 20 in three-dimensional flow. However, in the predicted three-dimensional phase presented in Figs. 2 and 4, there is a possible source of error due to the approximations leading to eq. 20.

In order to show the importance of finite aspect ratio in determining unsteady hydrodynamic lift, the value of C_L/r predicted by eq. 20 for two-dimensional flow is compared in Figs. 1 and 3 with three-dimensional flow results for aspect ratios 2 and 4, respectively. In both cases, there is a large discrepancy near the peak of the gust response operator. At Aspect Ratio two, the two-dimensional value is about 100% higher than the three-dimensional value, while at aspect ratio four, the difference is reduced to 40%. In addition, the discrepancy between two- and three-dimensional predictions is found to decrease for each aspect ratio as the reduced frequency of encounter increases. These observations are in agreement with the conclusions presented by Reissner and Stevens[3] and are further substantiated by the graphs of L_h, L_α, etc. given by Lawrence and Gerber.[4] In addition, the same conclusions have been reached by Shiori and Tsakonas[9] in their study of unsteady lifting surface theory applied to the Marine propeller.

Due to the phase error shown in Fig. 8, no comparison is made here between two- and three-dimensional results. However, Shiori and Tsakonas have shown that the discrepancy in phase has the same behavior as that for the magnitude of the unsteady load on a propeller blade, i.e., the phase of the three-dimensional loading approaches that of the predicted one in two-dimensional flow as the reduced frequency increases for a given aspect ratio, or as the aspect ratio increases at constant reduced frequency. It is concluded, therefore, that a two-dimensional representation of the unsteady forces is not adequate to predict the magnitude or phase of the lift on a finite aspect ratio hydrofoil in head seas in the reduced frequency range tested ($0<k_e<0.5$).

Irregular Seas

The averaged wave height spectra for the two series of tests are shown in Fig. 5, together with the average wave height obtained from eq. 12. The large values of $\left[r(k_e)\right]^2$ shown at low k_e may be attributed to variations in the spray sheet on the wave wire. The loss of coherency at low k_e as well as the low measured values of $\left[C_L(k_e)\right]^2$ in this range of k_e shown in Figs. 6 and 7 give supporting evidence for this presumption.

A computed lift spectrum $\left[C_L(k_e)\right]_C^2$ was obtained for each aspect ratio from eq. 7. The values of $|R(k_e)|$ used there were obtained from lines faired through the measured values of C_L/r in regular seas, which are shown in Figs. 1 and 3. In Figs. 6 and 7, the measured and computed values of $\left[C_L(k_e)\right]^2$ are in good agreement. In addition, the values of coherency also shown in Figs. 6 and 7 are between .85 and 1.00 in the range of $0.08 < k_e < 0.37$. Finally, the measured values of C_L/r shown in Table I obtained at the same k_e over a range of r are nearly constant. From these three observations, it is concluded that the lift response is linearly related to the wave height and thus the linear superposition theory using spectral techniques is applicable to this system.

The linear behavior of the system indicates that nonlinear effects are not important. Thus, all approximations of linearized lifting surface theory are valid. One such approximation is that the shed vorticity is a plane sheet extending downstream from the trailing edge. In reality, this vortex sheet is distorted by the wave motion plus the self-induced velocity distribution. Despite this, the present results indicate that the effect of the distortion of the vortex sheet is small.

Therefore, using linearized lifting surface theory, a theoretical prediction of the lift spectrum in an irregular sea can be obtained by using eq. 21. This prediction was carried out using both the Lawrence and Gerber and the Reissner and Stevens Theories in evaluating the approximate gust response operator. The results are shown in Figs. 6 and 7 for aspect ratio 2 and 4, respectively. As can be anticipated from the regular sea results at aspect ratio 2, the predicted lift spectrum using the Lawrence and Gerber results is lower than the measured lift spectrum, particularly at the higher frequencies--whereas, the Reissner and Stevens prediction is in fairly good agreement with the measured spectrum. The irregular sea results at aspect ratio 4 also lead to the same conclusions as the regular sea tests. That is, the Reissner and Stevens prediction of the lift spectrum is too high at low values of k_e and low at high values of k_e whereas the Lawrence and Gerber result is in agreement with the measured lift spectrum at low k_e but too low at high k_e. However, in the derivation of the unsteady lift presented in refs. 3 and 4, approximate forms of the integral equation relating the downwash to the unknown load distribution were introduced in order to simplify the numerical solution. Now, by means of high speed computers, the numerical solution of the integral equation is possible using the exact form of the kernel function, including the free surface effect.

The measured phase of the lift in the irregular sea with the aspect ratio 2 model exceeds that obtained from the regular sea by an amount which increases with k_e to about 15^o at $k_e = 0.35$, whereas at aspect ratio 4, the regular sea and irregular sea results are in agreement. This may be a result of the smaller amount of data used in the irregular sea analysis at aspect ratio 2.

In this investigation, the hydrofoil was considered to be restrained against free motions. In dealing with the dynamic behavior of a rigid hydrofoil craft in a seaway, all restraints must be released and the craft must be treated as a free body. Then, the motions of the craft can be related to the irregular sea spectrum as was done previously for the lift. Since the same lift-producing mechanism would be involved (response of a lifting surface to a downwash distribution) in the case of an unrestrained vehicle as in the case of the restrained foil in a traveling gust, it is anticipated that the same conclusions would result. In particular, it is expected that the motions of a hydrofoil craft in irregular head seas will be a linear superposition of the response to the harmonic components of the irregular sea.

CONCLUSIONS

1. The lift response of a finite aspect ratio hydrofoil in head seas is linearly related to the wave height as indicated by the good agreement observed between measured and computed lift spectra in irregular head seas. Therefore, linear superposition theory can be used to predict hydrofoil lift spectra.

2. Measured and predicted values of the magnitude of the gust response operator in three-dimensional flow are in fairly good agreement. However, a discrepancy was found in the phase.

3. The predicted magnitudes of the exact and approximate gust response operators in two-dimensional flow show good agreement but the phases do not. Thus, the error introduced by the approximate gust response operator in predicting the phase for three-dimensional flow may account for the discrepancy with measured values.

4. In the ranges of reduced frequency of encounter and aspect ratio which are typical for hydrofoil craft, two-dimensional theory is not adequate to predict the gust response operator in head seas.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the guidance and assistance of Dr. Stavros Tsakonas, head of the Fluid Dynamics Division of Davidson Laboratory. Also, helpful discussions with Mr. John Dalzell during the initial stages of this study is gratefully acknowledged.

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TABLE I

VARIATION OF GUST RESPONSE OPERATOR
WITH WAVE AMPLITUDE
ASPECT RATIO 4

U ft/sec	2L lb	2a in	f_e cps	C_L	r	k_e	C_L/r	deg
14.98	14.1	4.25	3.63	.133	1.44	.190	.0928	267.8
14.98	4.59	1.32	3.73	.0433	.44	.195	.0984	240.7
14.98	8.70	2.58	3.75	.0820	.86	.196	.0955	256.7
14.98	12.6	3.64	3.61	.119	1.21	.189	.0983	272.5

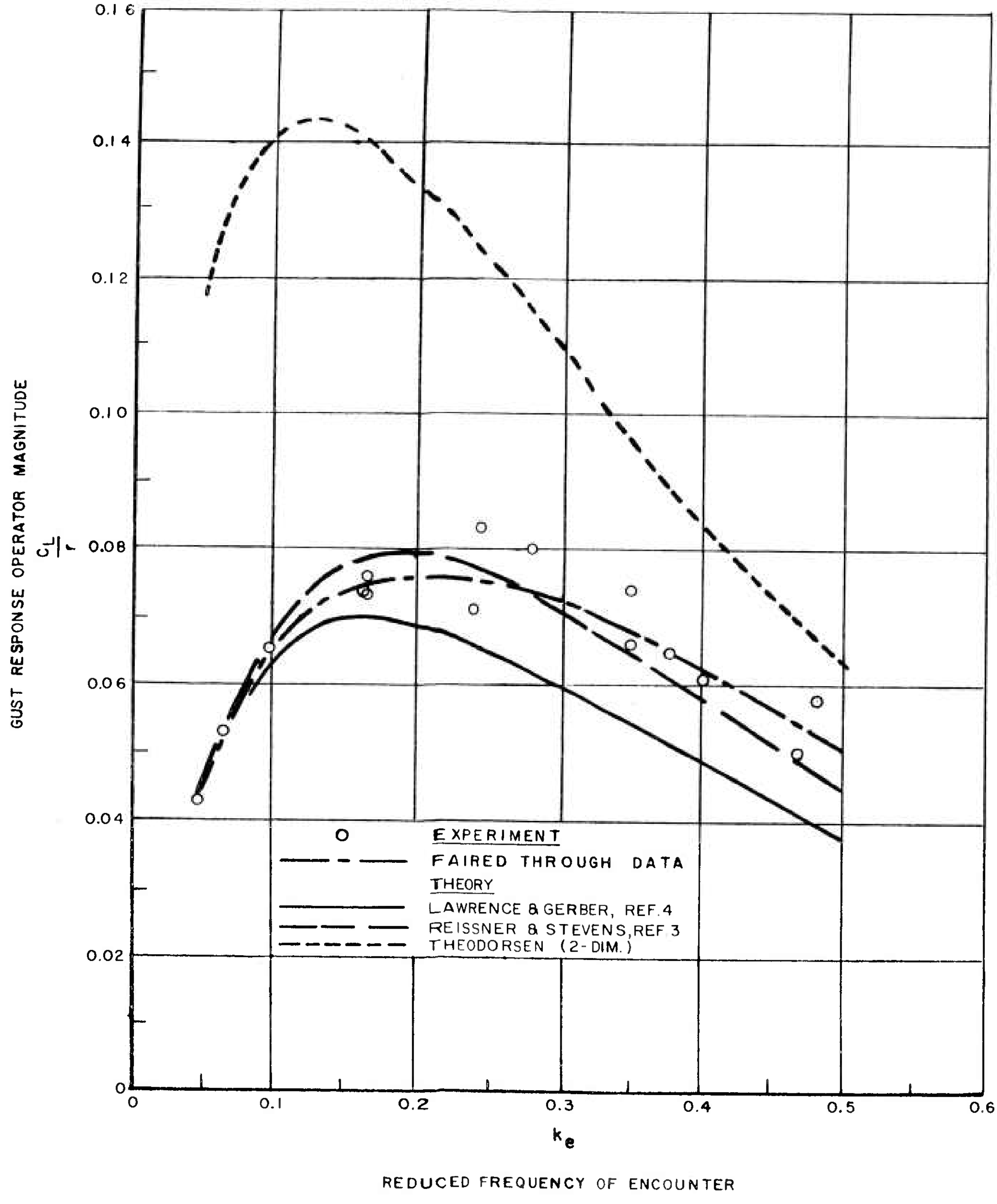

FIGURE 1. GUST RESPONSE OPERATOR MAGNITUDE ASPECT-RATIO 2, REGULAR SEAS

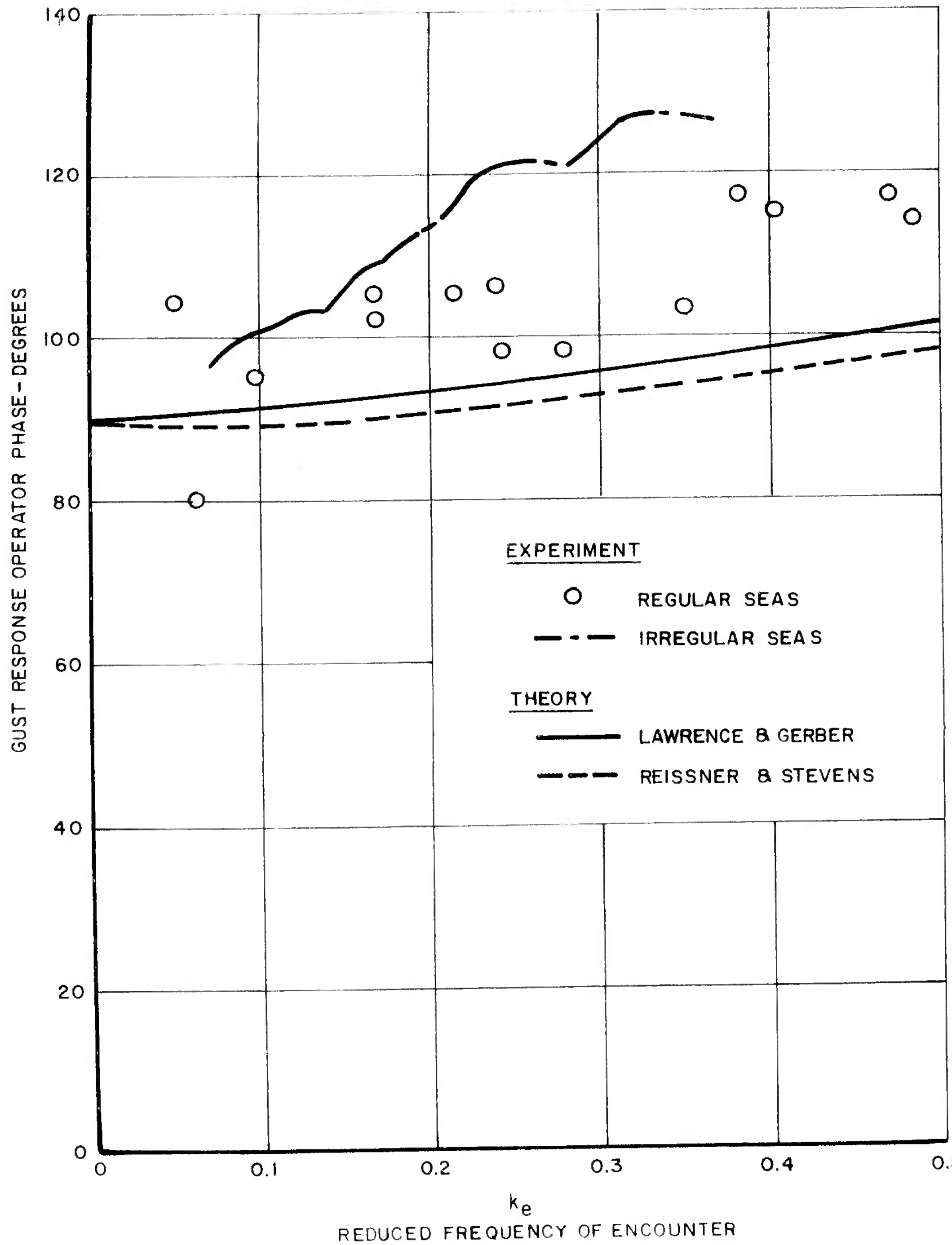

FIGURE 2. GUST RESPONSE OPERATOR PHASE.
ASPECT RATIO 2
REGULAR AND IRREGULAR SEAS

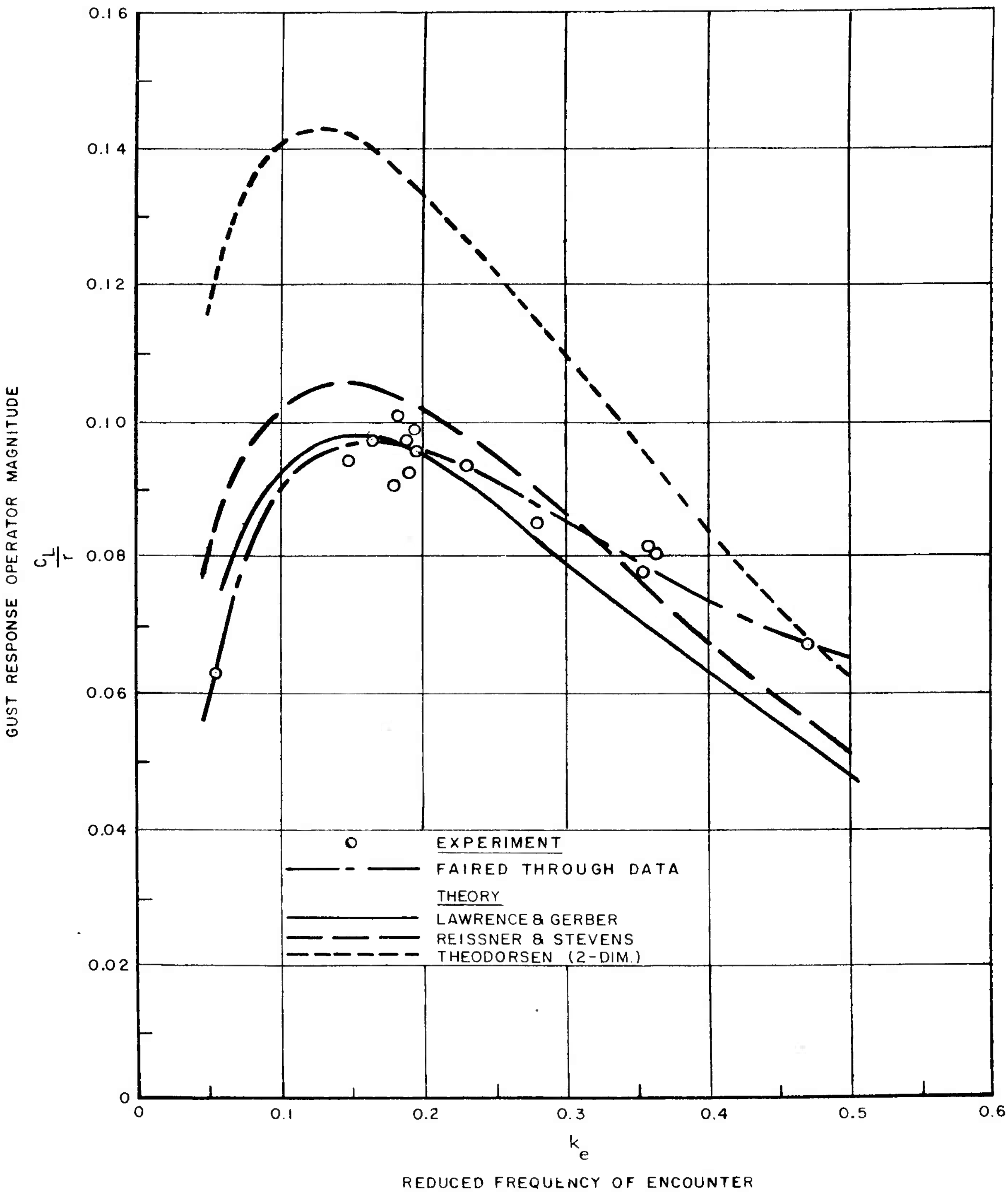

FIGURE 3. GUST RESPONSE OPERATOR MAGNITUDE ASPECT-RATIO 4, REGULAR SEAS

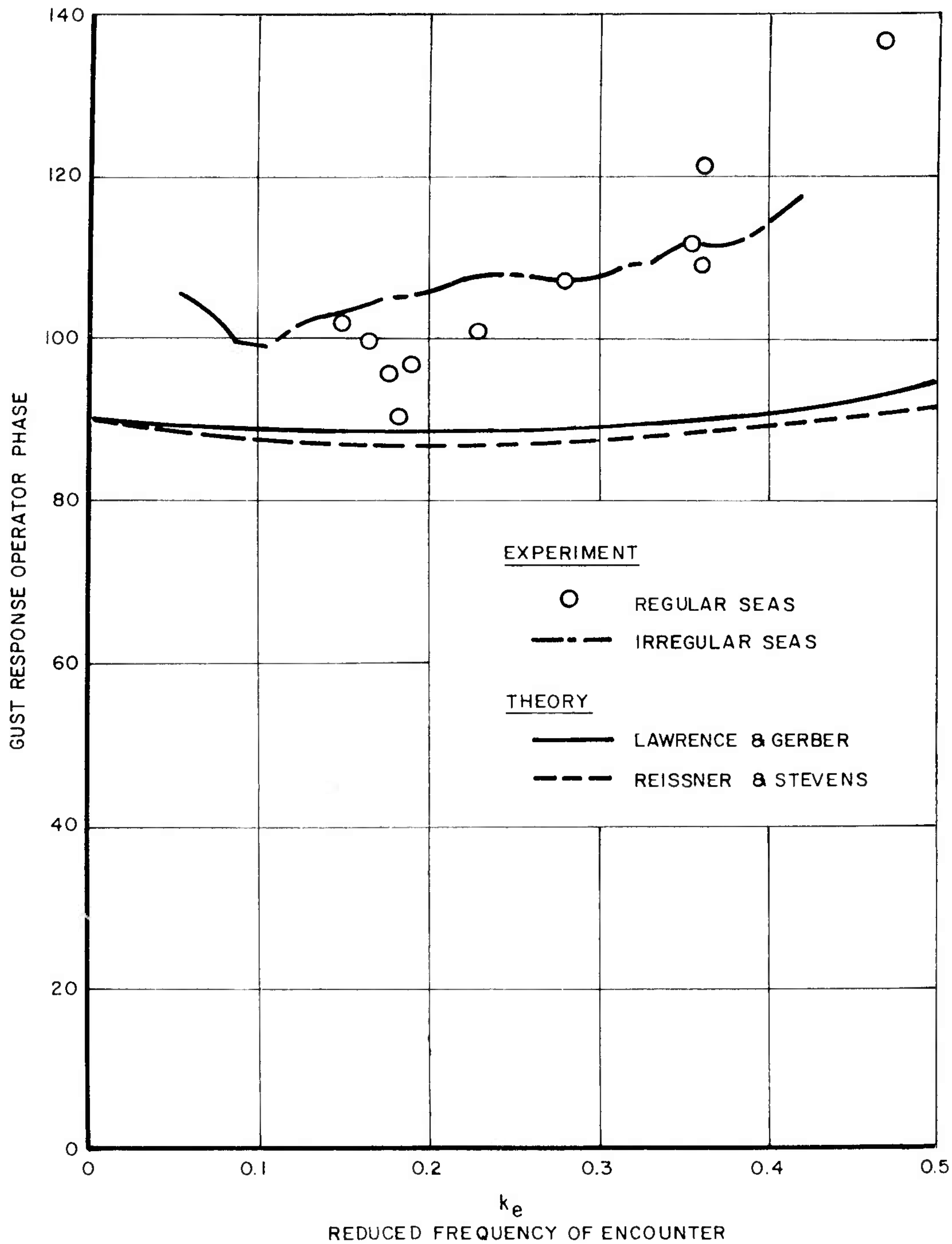

FIGURE 4. GUST RESPONSE OPERATOR PHASE.
ASPECT RATIO 4
REGULAR AND IRREGULAR SEAS

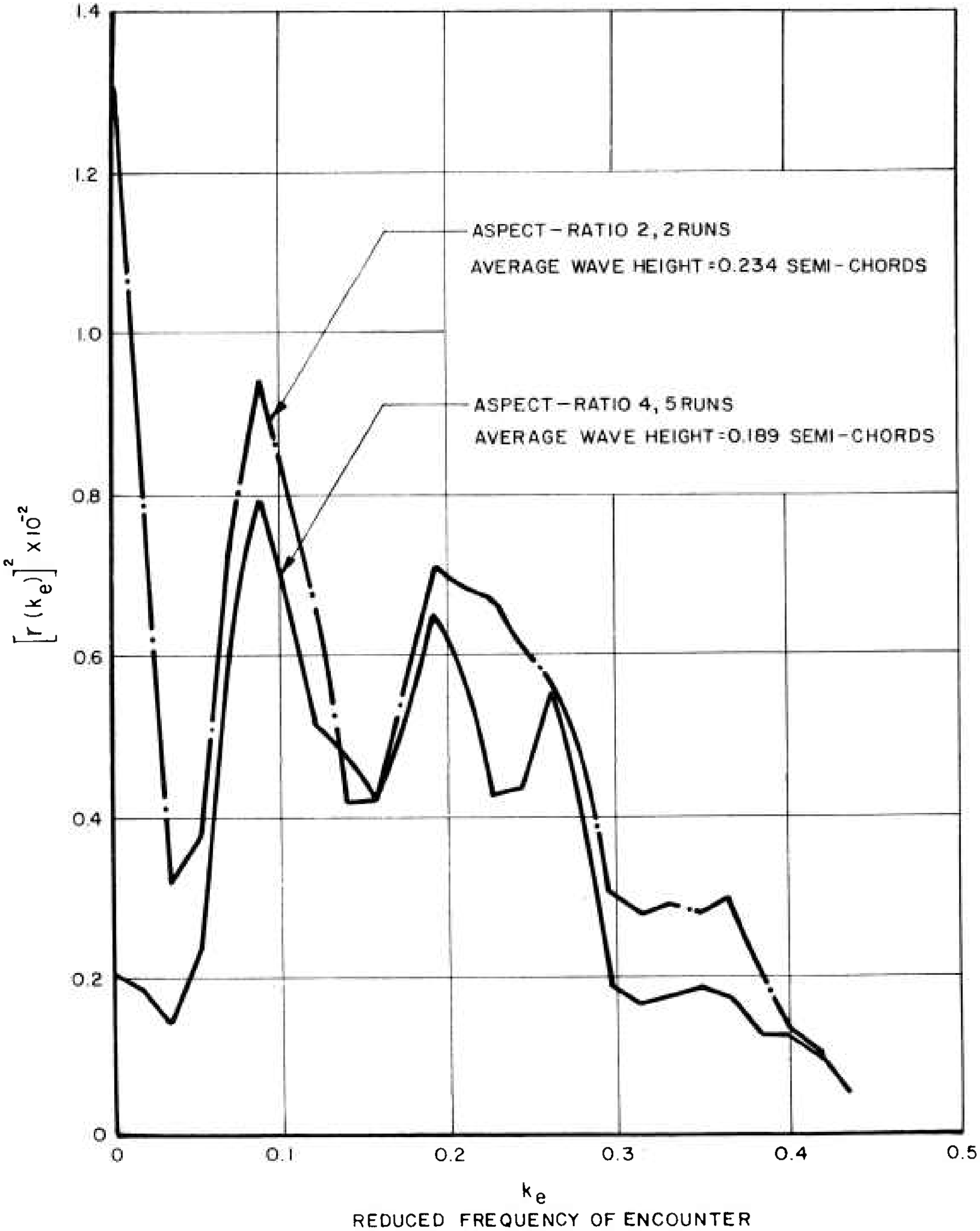

FIGURE 5. AVERAGED WAVE HEIGHT SPECTRA.

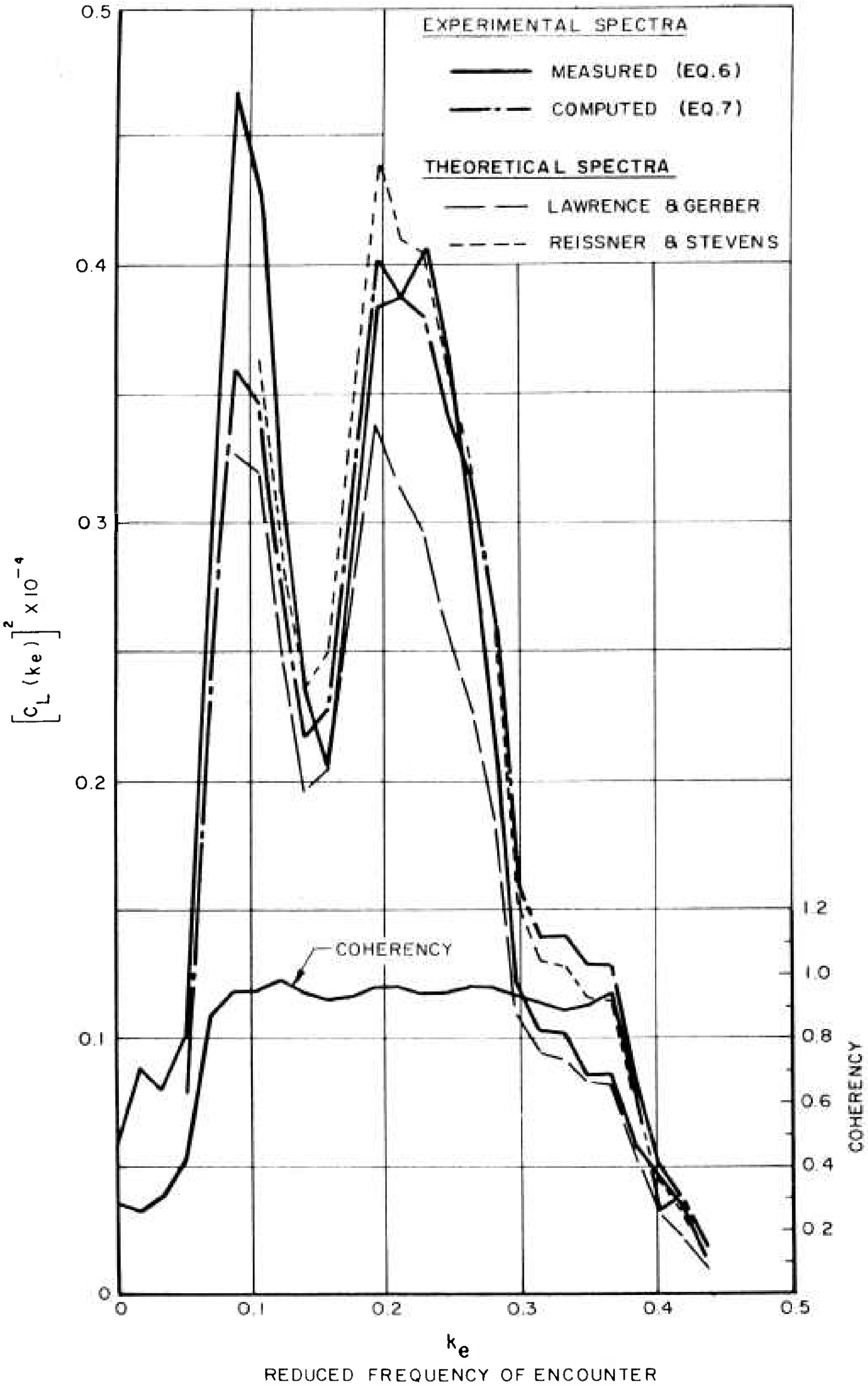

FIGURE 6. COMPARISON OF LIFT SPECTRA. ASPECT RATIO 2

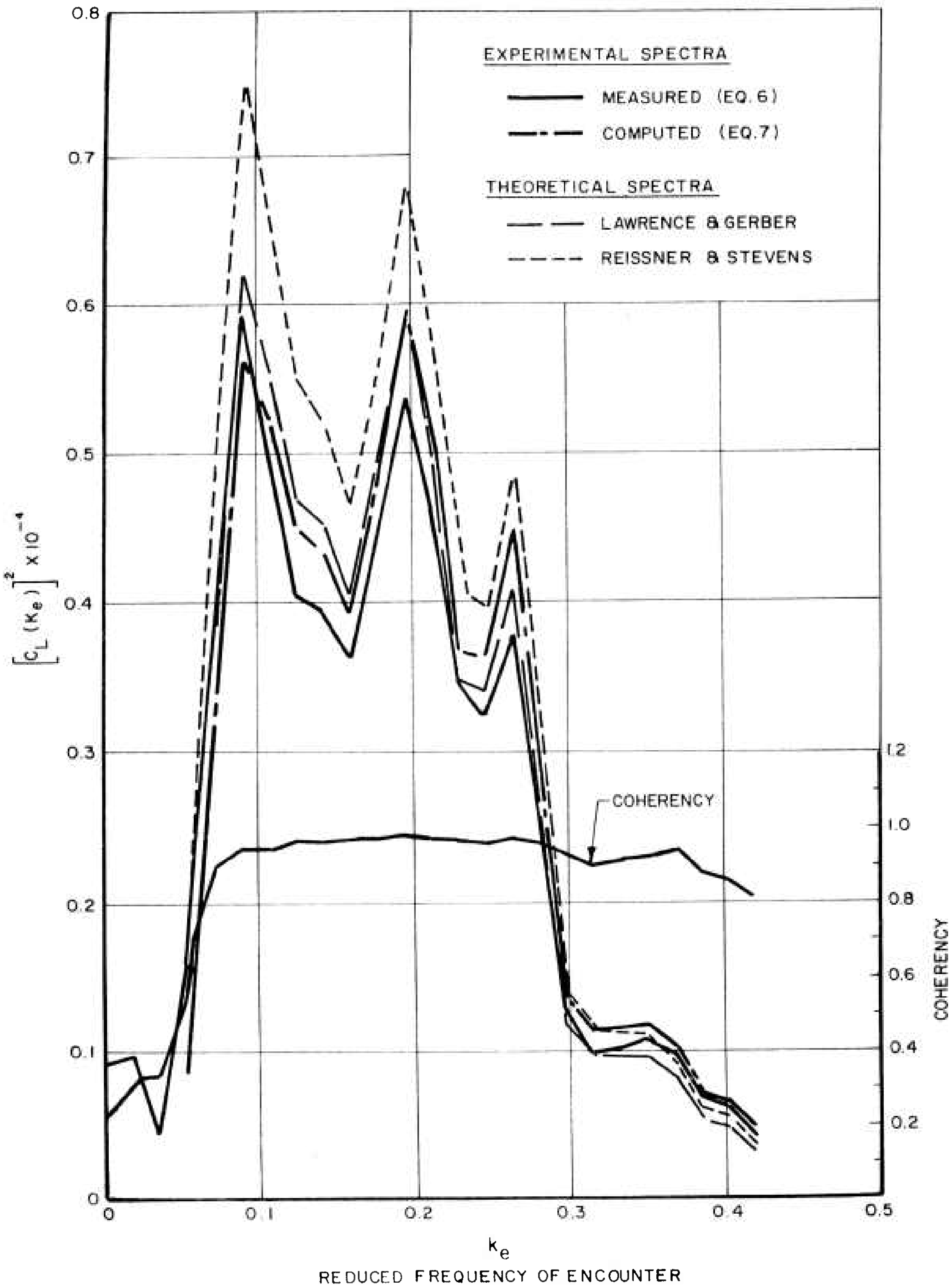

FIGURE 7. COMPARISON OF LIFT SPECTRA, ASPECT RATIO 4

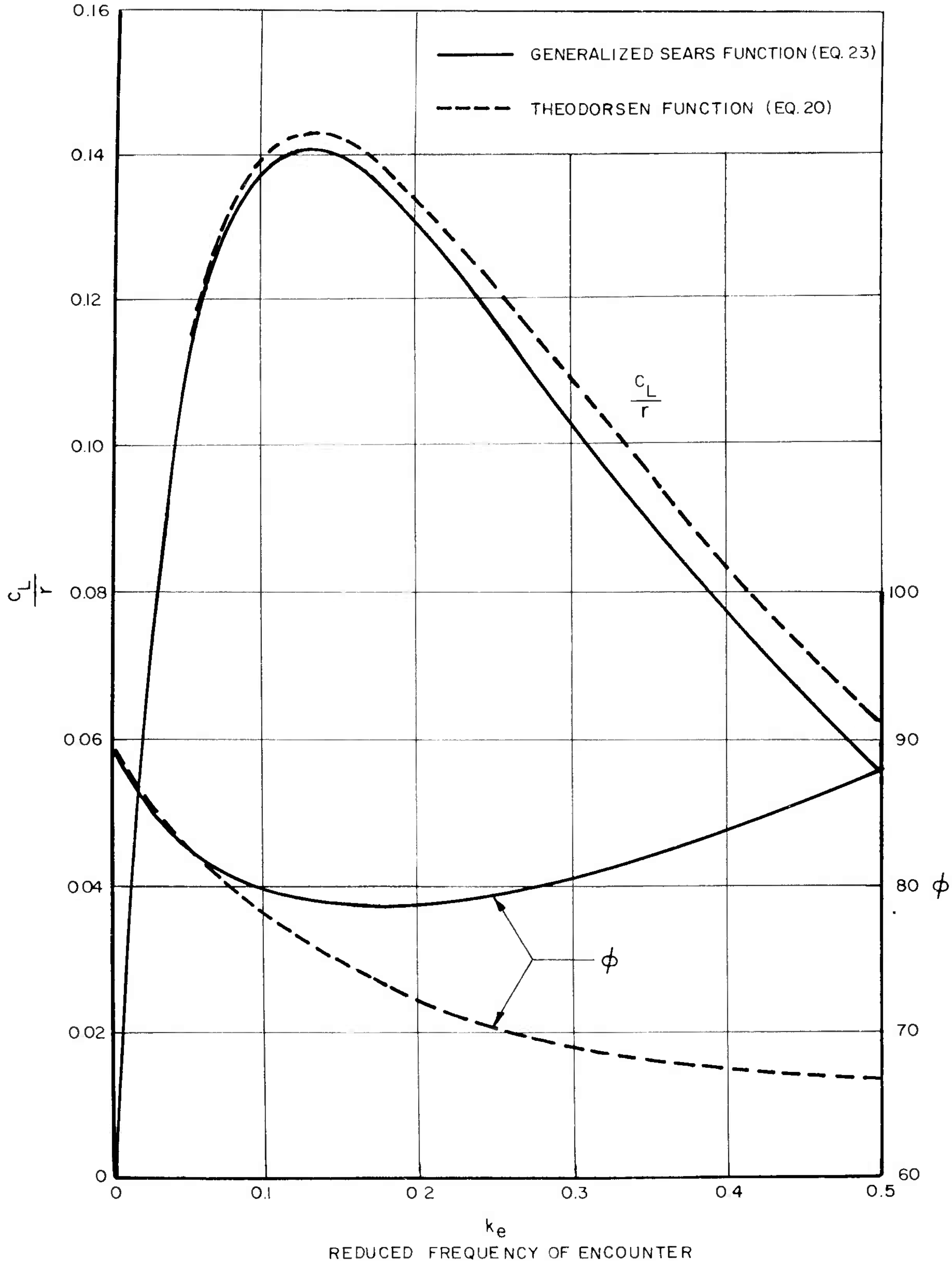

FIGURE 8. COMPARISON OF EXACT AND APPROXIMATE GUST RESPONSE OPERATORS IN TWO DIMENSIONAL FLOW.

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HYDROFOIL LIFT IN HEAD SEAS

The results of the present investigation show that the measured lift response of finite aspect ratio hydrofoils in regular head seas is linearly related to the measured wave input. Thus, spectral theory can be used with gust response operators as well as wave height spectra to predict the statistical character of the unsteady lift on finite aspect ratio hydrofoils in irregular head seas. It is anticipated that accurate theoretical predictions of the lift spectra for a finite aspect ratio hydrofoil in irregular head seas can be obtained using an exact lifting surface theory to compute the gust response operator.

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