NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Maryland 20034

DESIGN CRITERIA FOR HYDROFOIL HULL BOTTOM PLATING

(A PRACTICAL APPLICATION OF RESEARCH ON SLAMMING)

by

Sheng-Lun Chuang

STRUCTURES DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

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NOTATION

A	Hydrodynamic aspect ratio $(= \lambda_p^2/S)$
b	Beam
C_N	Normal-load coefficient (or average pressure) based on A
C_{N_p}	Normal-load coefficient (or average pressure) based on λ_p
c	Speed of sound in water
c_v	Viscous damping constant of fluid
D	Flexural rigidity of isotropic plate; see Reference 7
D_x, H, D_y	Flexural rigidity of orthotropic plate; see Reference 7
d_f	Foilborne draft
d_h	Hullborne draft
F	Impact force in general
F_N	Hydrodynamic force normal to keel (normal to surface for a flat plate)
f	Frequency in cycles per second (Hertz)
f	Water pressure coefficient; see Table 3
$\dot{f}$	Velocity in the planing direction
g	Gravitational acceleration
H	Maximum wave height measured from crest to trough (= 2h), where crest defined as the top of wave and trough as bottom of wave
h	Shell thickness
h	Maximum wave amplitude measured from calm water surface

i_y	Transverse radius of gyration of airplane
K	Water-rise ratio
K_1, K_2, K_3	Coefficients used in Table 3 and Figure 15 of Appendix A
k	Wave number = $2\pi/L_w$
k_f	Spring constant of fluid
L	Ship length
L	Half wetted breadth (measured horizontally)
L_w	Wave length
$\tilde{L}$	Average wave length
m_s	Mass of structure
m_{zz}	Added mass of fluid
p	Pressure in general
p_{ave}	Average impact pressure
p_c	Impact pressure at chine
p_c	Impact pressure at longitudinal centerline
p_i	Impact pressure
p_{i_1}	Interacting pressure
p_k, p_{keel}	Impact pressure at keel
p_{max}	Maximum impact pressure
p_n	Total normal pressure ($\equiv p_r$)
p_p	Planing pressure
p_r	Rigid body pressure ($\equiv p_n$)

p_t	$= p_r + p_{i_1}$
p_z, p_M	See MIL-A-8629(Aer) Formulas, Appendix A
r	Shell radius
S	Projection of wetted area normal to keel
s	Hull clearance from foilborne water surface to point of impact on hull bottom in feet
T_w	Wave period $= 2\pi/\omega = 1/f$
$\tilde{T}$	Average wave period
t	Time in general
t_o	Time at instant of impact
t_m	See MIL-A-8629(Aer) Formulas, Appendix A
u	Horizontal water velocity
u	A function relating normal component of velocity V_a to speed of propagation of wetted half-width dL/dt
V	Velocity in general
V	Instantaneous resultant velocity of falling body
V_a	Two-dimensional impact velocity
V_h	Longitudinal horizontal component of impact velocity
V_n	Normal component of impact velocity of falling body to wave surface
V_n'	Normal component of wave velocity on wave surface
V_o	Impact velocity at time t_o
V_s	Transverse horizontal component of impact velocity

V_{s_L}	Landing design stalling speed of airplane
V_t	Tangential component of impact velocity of falling body to wave surface
V'_t	Tangential component of wave velocity on wave surface
V_v	Vertical component of impact velocity
V_w	Wave velocity (wave celerity)
V_{w_o}	Water orbital velocity of wave
V_{wi}	Wind velocity
v	Vertical water velocity
v	Tangential displacement of shell
W	Total weight of falling body
w	Deflection in general, such as transverse displacement of plate, radial displacement of shell, etc.
x	Horizontal coordinate in transverse direction
y	Horizontal coordinate in longitudinal direction
z	Vertical coordinate
$\dot{z}$	Vertical velocity ($\equiv dz/dt$)
$\ddot{z}$	Vertical acceleration ($\equiv d^2z/dt^2$)
α	Buttock angle
β	Deadrise angle
β_e	Effective deadrise angle
β_{eh}	Angle on wave surface measured from forward longitudinal direction to the plane normal to wave surface and impact surface on hull bottom at a point of concern; see Figures 3 and 4

β_{ev}	Angle on transverse plane normal to wave surface and measured from impact surface on hull bottom to wave surface; see Figures 3 and 4
γ	Instantaneous flight-path angle of falling body
ϵ	Pitch angle
ϵ	Strain
η	Wave amplitude at any point of wave
θ	Angular coordinate of cylinder
θ	Angle of wave slope
θ_{max}	Maximum wave slope
λ	Distance forward of step parallel to longitudinal centerline of craft
λ_p	Wetted length based on peak-pressure location (longitudinal distance from step to location of peak pressure at keel)
ν	Poisson's ratio
ξ	Effective impact angle on plane normal to wave surface and impact surface on hull bottom measured from wave surface to impact surface of hull bottom; see Figures 3 and 4
ρ	Mass density of fluid
σ	Stress
τ	Trim angle
τ_o	Initial trim angle
ϕ	Velocity potential
$\phi(A)$	Aspect ratio correction
ω	Circular frequency, rad/sec
∇^4	Operator, e.g., $\left(\frac{\partial^4}{\partial x^4} + 2\frac{\partial^4}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4}\right)$ in rectangular coordinate system

Subscripts:

ave	Average
c	Chine or longitudinal centerline
k, keel	Keel
max	Maximum
o	At instant when falling body first contracts water surface, or initial condition
r	Angle measured in radians
w	Wave
wi	Wind

ABSTRACT

This report introduces a method for calculating pressure distributions on the hull bottom of a craft that is subjected to slamming loads at high cruising speed in waves. Design procedure and criteria for hydrofoil hull bottom plating and structure are included and examples given of their utilization in applications of the method. Various existing theories and methods on slamming are included in summary form for purposes of review and comparison.

ADMINISTRATIVE INFORMATION

This investigation was carried out as part of the slamming study and design application funded by Subproject S 46-06X, Task 1707 (Hydrofoil Hull).

INTRODUCTION

Determination of the ability of high performance craft scantlings to resist bottom slamming is generally not covered in the rules established by various classification societies. In most cases, the development and selection of suitable methods for the hull bottom design of such craft are based on or influenced by the impact theories developed for seaplane landings on water surfaces. At present then, the structural design in the slamming area of the hull bottom of a high performance craft is based mostly on past experience or on individual preference.

The classic sources for predicting bottom pressure are the theoretical studies of von Kármán[1] and Wagner.[2] A later publication, Military Specification MIL-A-8629 (Aer)[3] gives design criteria for the hull pressures of seaplanes. On the basis of experimental results for prismatic wedges, Smiley[4-6] developed several empirical formulas for use in computing the bottom pressures of seaplane hulls. The trapped air phenomenon discovered recently during experiments on flat bottom impact and impact of wedges with small deadrise angles conducted at this Center has led to better estimations of impact pressures of wedges with any deadrise angle.[7]

However there is a gap between scientific work and design applications in this area because theoretical and experimental results on slamming can be put into practical use only when a design method is provided. The purpose of this report is therefore to formulate a design method to determine the hull bottom impact loads of the craft encountered at sea. When these loads are used with appropriate design criteria, the hull bottom plating can be properly designed.

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[1] References are listed on page 83.

Although this report is written for the design of hydrofoil craft hull bottoms, a similar design method and procedure can be developed for other types of craft and surface ships such as air cushion vehicles, conventional surface ships, catamarans, trimarans, drill platforms, etc.

Various existing theories and methods on slamming are summarized in Appendix A for review purposes. To illustrate the method proposed in this report, two examples, one for the FHE-400 and one for the AG(EH)-1 hydrofoil craft, are presented in Appendix B.

This report is a continuation of the slamming study reported in Reference 8. Therefore, that reference is needed as a pocket companion when the design method of this report is used.

BOTTOM SLAMMING LOAD ON WAVES

The NSRDC formulas given in Appendix A are used to determine the slamming load acting on the hull bottom, and they are applicable only for impact on smooth water. Some modifications are needed for rough water impact. These modifications are given and discussed below.

When a craft rides in rough water, a bottom impact occurs where the surface of the sea is not necessarily horizontal.

Assume that the surface of the sea can be described mathematically as a harmonic deep-water wave of finite height and the following properties (see Figure 1):*

$$
\left.
\begin{aligned}
&\text{Wave number:} && k = 2\pi/L_w \\
&\text{Surface profile:} && \eta = h \sin k(y - V_w t) \\
&\text{Velocity potential:} && \phi = h V_w e^{kz} \cos k(y - V_w t) \\
&\text{Orbiting water velocity:} && V_{w_o} = k h V_w e^{kz} = H e^{kz} \sqrt{\frac{\pi}{2} \frac{g}{L_w}} \\
&\text{Horizontal water velocity:} && u = - \partial\phi/\partial y \\
& && = k h V_w e^{kz} \sin k(y - V_w t) \\
&\text{Vertical water velocity:} && v = - \partial\phi/\partial z \\
& && = - k h V_w e^{kz} \cos k(y - V_w t)
\end{aligned}
\right\} \quad (1)
$$

---

* This assumption is reasonable compared to other assumptions made later.

$$
\left.
\begin{aligned}
&\text{Wave celerity:} && V_w = \sqrt{\frac{g}{k}} = \sqrt{\frac{g\,L_w}{2\pi}} = 2.26\sqrt{L_w},\ \text{fps} \\
& && = \frac{L_w}{T_w} \\
& && = \frac{g\,T_w}{2\pi} \\
&\text{Wave slope:} && \theta = \partial\eta/\partial y \\
& && = k\,h\cos k(y - V_w\,t) \\
&\text{Maximum wave slope:} && \theta_{max} = k\,h = \frac{2\pi}{L_w}\,h \\
&\text{Wave length:} && L_w = \frac{2\pi}{g}\,V_w^2 = 0.196\,V_w^2,\ \text{ft} \\
& && = \frac{g}{2\pi}\,T_w^2 = 5.12\,T_w^2,\ \text{ft} \\
&\text{Wave period:} && T_w = \sqrt{\frac{2\pi}{g}\,L_w} = 0.442\sqrt{L_w},\ \text{sec}
\end{aligned}
\right\}
\quad (1)
$$

Now assume that a craft impacts on the surface wave, indicated as point A in Figure 2, with its horizontal and vertical velocities V_h and V_v, respectively. The resultant velocity V can then be separated into V_n, which is normal to the wave surface at point A, and V_t, which is tangent to the

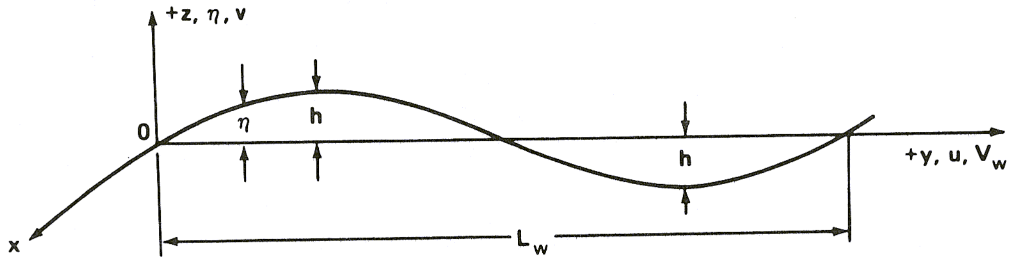


Figure 1 - Harmonic Deep-Water Wave

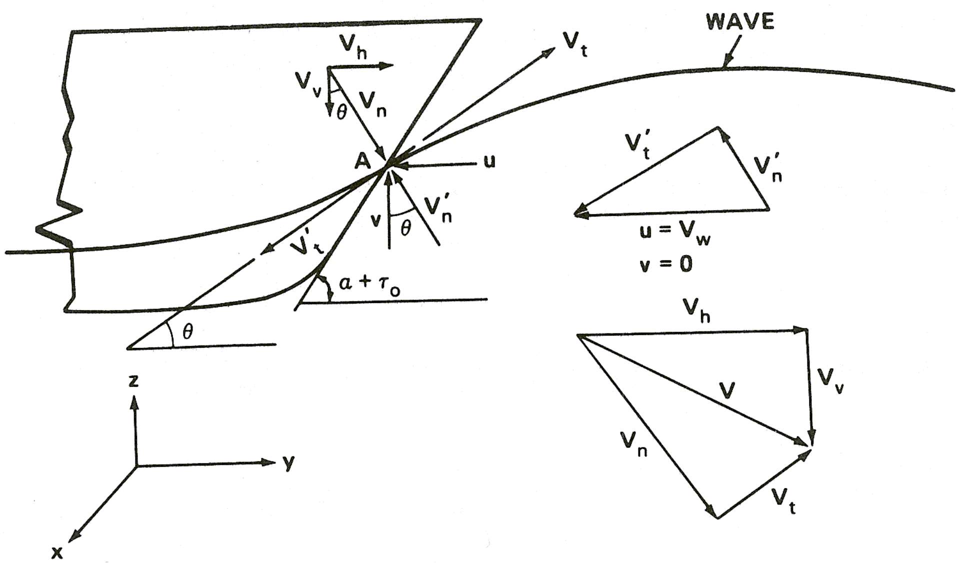


Figure 2 - Impact of Craft on Wave

wave surface at point A also. If the craft hits the wave at a point which has a wave slope of θ, then the normal velocity is

$$V_n = V_v \cos \theta + V_h \sin \theta$$

and the tangential velocity is

$$V_t = - V_v \sin \theta + V_h \cos \theta$$

Even though the water particle is oscillating within an orbiting circle, the apparent movement of the surface wave looks as if the wave is moving with the wave celerity V_w. V_w can also be separated into V_n', which is also normal to the wave surface at point A, and V_t', which is also tangent to the wave surface at point A. Therefore,

$$V_n' = V_w \sin \theta$$

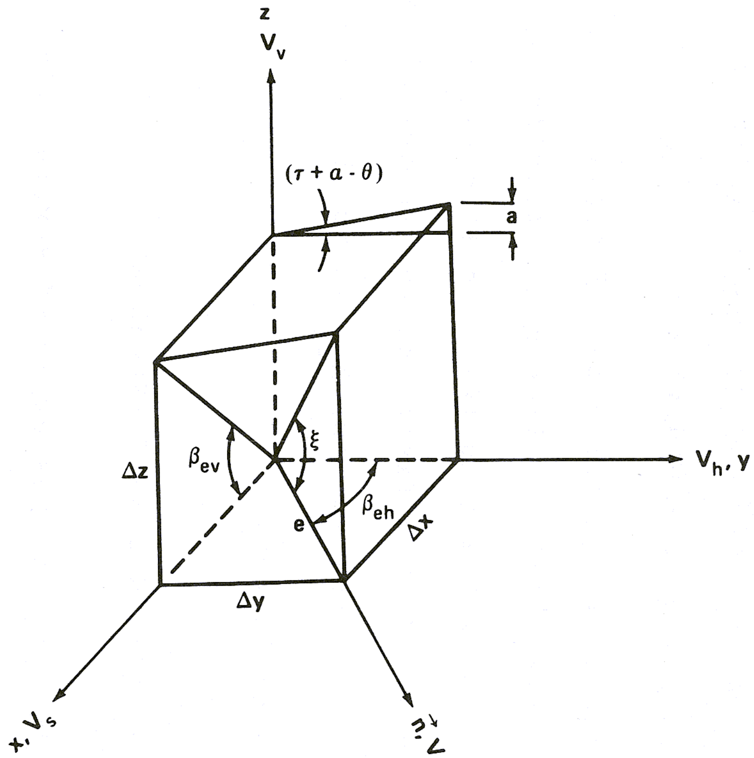
$$V_t' = V_w \cos \theta$$

Let the reference point be fixed at point A of the surface wave. This is then similar to the case where the surface of the sea is stationary and the craft is moving toward it with a velocity equal to the sum of the velocities of the craft and the wave. Therefore, the velocities used for the impact are:

$$\left.\begin{aligned} V_n &= V_v \cos\theta + (V_h + V_w)\sin\theta \\ V_t &= -V_v \sin\theta + (V_h + V_w)\cos\theta \end{aligned}\right\} \quad (2)$$

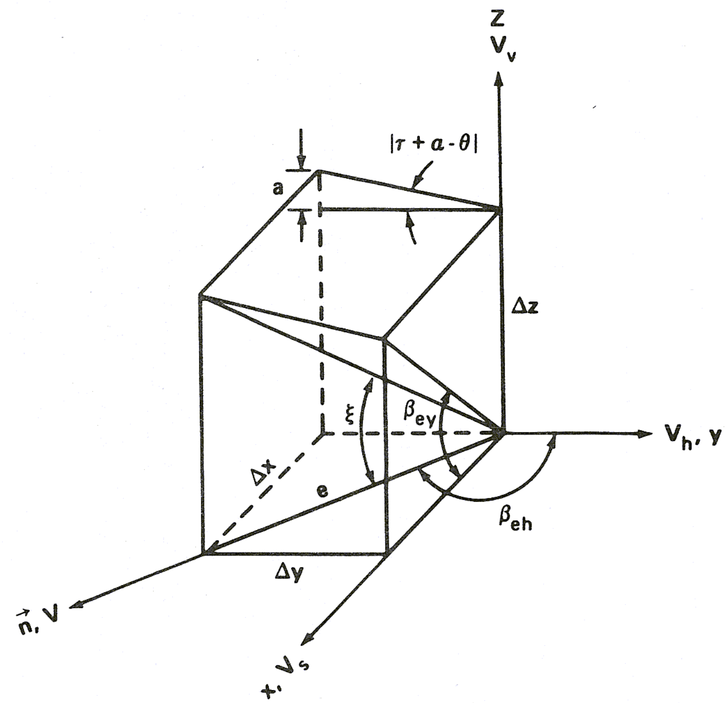
As indicated in Reference 8, V_n is used to determine the normal impact pressure and V_t to determine tangential planing pressure. Thus V_n is called the impact velocity and V_t the planing velocity.

Consider now a prismatic wedge-shaped body dropped vertically upon a calm water surface. If there is no trim (i.e., $\tau = o$), the deadrise angle β is the impact angle used for the NSRDC formulas given in Appendix A to determine the impact pressure. When the prismatic wedge-shaped body drops trimmed upon the water surface, the impact angle should be the angle β_{ev} which is measured from the horizontal plane to the line intersected by the impact surface of the wedge and the vertical normal plane to the impact surface of the wedge (which is the X-Z plane in Figure 3 of Reference 8). Obviously, the angle β_{ev} becomes the deadrise angle β when there is no trim.



$$a = \Delta y \tan(\tau + a - \theta)$$
$$\Delta z = \Delta x \tan \beta_{ev}$$
$$\Delta y = e \cos \beta_{eh}$$
$$\Delta x = e \sin \beta_{eh}$$
$$a + \Delta z = e\,[\cos \beta_{eh} \tan(\tau + a - \theta) + \sin \beta_{eh} \tan \beta_{ev}]$$

Figure 3 - Nonprismatic Wedge in a Trimmed-Forward Position



$$a = \Delta y \tan|\tau + a - \theta| = \Delta y\,|\tan(\tau + a - \theta)|$$
$$\Delta z = \Delta x \tan \beta_{ev} = \Delta x\,|\tan \beta_{ev}|$$
$$\Delta y = e\,|\cos \beta_{eh}|$$
$$\Delta x = e \sin \beta_{eh} = e\,|\sin \beta_{eh}|$$
$$a + \Delta z = e\,[\,|\cos \beta_{eh}|\,|\tan(\tau + a - \theta)| + |\sin \beta_{eh}|\,|\tan \beta_{ev}|\,]$$
$$= e\,[\cos \beta_{eh} \tan(\tau + a - \theta) + \sin \beta_{eh} \tan \beta_{ev}]$$

Figure 4 - Nonprismatic Wedge in a Trimmed-Aft Position

$\tan(\tau + \alpha - \theta)$, $\sin\beta_{eh}$, and $\tan\beta_{ev}$ are positive since all of them are in the first quadrant. If the impact is in the trimmed-aft position, then $\cos\beta_{eh}$ and $\tan(\tau + \alpha - \theta)$ are negative because $\cos\beta_{eh}$ is in the second quadrant and $\tan(\tau + \alpha - \theta)$ is in the fourth quadrant. The term $\cos\beta_{eh} \cdot \tan(\tau + \alpha - \theta)$ gives a positive value. The function $\sin\beta_{eh}$ is positive again since it is in the second quadrant, and the function $\tan\beta_{ev}$ is also positive since it is in the first quadrant. Therefore the third equation of Equation (6) applies for both cases and satisfies automatically.

The first equation of Equation (6) satisfies automatically where $\sin(\tau - \theta)$, $\cos(\tau - \theta)$, and $\tan\alpha$ are in the first and fourth quadrants (i.e., 0 to ±90 deg) and $\tan\beta_{eh}$ is in the first and second quadrants (i.e., 0 to 180 deg). The second equation of Equation (6) satisfies automatically also. As for the first equation of Equation (6), $\sin(\tau - \theta)$, $\cos(\tau - \theta)$, and $\tan\alpha$ are in the first and fourth quadrants (i.e., 0 to ±90 deg). The function $\tan\beta_{ev}$ is in the first quadrant only (i.e., 0 to 90 deg).

BOTTOM PLATING DESIGN PROCEDURE

Recent research in slamming has explored several unknowns, and to some extent slamming loads can now be predicted

The relation between the angles β_{ev} and β in terms of the trim angle γ is given in Reference 8 as

$$\tan \beta_{ev} = \tan \beta / \cos \tau$$

For the nonprismatic wedge with different deadrise angles along the longitudinal direction (i.e., y-direction), the relation between β_{ev} and β is affected not only by the trim angle τ but also by the buttock angle α. This relation is also given in Reference 8 as

$$\tan \beta_{ev} = \frac{\tan \beta}{\cos \tau - \tan \alpha \sin \tau} \tag{3}$$

Similarly, the horizontal effective deadrise angle β_{eh} should be used to determine pressure caused by the horizontal planing velocity V_h. For the nonprismatic wedge, the equation is

$$\tan \beta_{eh} = \frac{\tan \beta}{\sin \tau + \tan \alpha \cos \tau} \tag{4}$$

Since in the case of vertical impact of a nonprismatic wedge, the surrounding water is pushed away in the direction perpendicular to the impact surface of the wedge, the impact angle ξ should also be measured on a plane perpendicular to the impact surface. This angle ξ is neither the deadrise angle β nor the vertical effective deadrise angle β_{ev}, but it is related to these angles as

$$\tan \xi = \cos \beta_{eh} \tan (\tau + \alpha) + \sin \beta_{eh} \tan \beta_{ev} \qquad (5)$$

When the craft slams on the wave surface, it may be considered that the surface of the sea is flat by rotating the craft and the wave surface with an angle of wave slope θ. In other words, $\tau \rightarrow (\tau - \theta)$. Thus for the rough water impact,

$$\left.\begin{aligned} \tan \beta_{eh} &= \frac{\tan \beta}{\sin (\tau - \theta) + \tan \alpha \cos (\tau - \theta)} \\ \tan \beta_{ev} &= \frac{\tan \beta}{\cos (\tau - \theta) - \tan \alpha \sin (\tau - \theta)} \\ \tan \xi &= \cos \beta_{eh} \tan (\tau + \alpha - \theta) + \sin \beta_{eh} \tan \beta_{ev} \end{aligned}\right\} \qquad (6)$$

Using Equation (2) to determine impact velocity V_n and planing velocity V_t and Equation (6) to determine angles β_{eh}, β_{ev}, and ξ, the pressure distribution of the hull bottom to impact and planing loads can then be calculated by means of the NSRDC impact formulas given in Appendix A.

As shown in Figures 3 and 4, if the nonprismatic wedge impacts in a trimmed-forward position, $\cos \beta_{eh}$, with greater accuracy than was possible a few years ago. The method presented here is intended to guide the designer in putting these findings on slamming to practical use.

Slamming is an unsteady hydrodynamic phenomenon and involves many unknowns. At present, theories and experiments have revealed only a few of them. As new findings are obtained from practical experience, experimental work, and theoretical studies, the present method can be improved further.

The procedure for the design of bottom plating of the hydrofoil craft subjected to slamming load is outlined below. It includes determinations of hull bottom form, sea state and wave, operating conditions, slamming loads, and bottom plating scantlings.

HULL BOTTOM FORM OF CRAFT

The hull form of a craft is affected by many factors: engineering economy, purpose of design, powering, stability, wave resistance, etc. So far as the bottom portion of the hull is concerned, the buttock angles, the deadrise angles, the deviation of the keel line from the baseline, and the configurations of bow and stern are all determining factors which influence slamming loads and thus affect the design of bottom plating.

The entrance angle ($\equiv \beta_{eh}$) at the bow of high-speed craft considerably affects the planing pressure in this region. The buttock angles α and the deadrise angles β are used to determine the effective impact angle ξ as well as the planing angle β_{eh}. Although it is theoretically advisable to use large deadrise angles to reduce the bottom impact pressure (or load), in actual practice it is necessary to use small deadrise angles to avoid losing space that would otherwise be available and undesirably increasing the depth of the hull. Because of the reasons stated above, it is therefore necessary to make a compromise on the hull form even though it is quite adequate from other aspects of the problem.

Design of the hull form is usually finalized before it is available for the investigation of bottom slamming. If from the point of view of slamming, the hull form is found inadequate however, then it has to be redesigned accordingly.

SEA STATE AND WAVES

The wind, sea state, and sea scale for a fully arisen sea are given in Table 1.[9] If the sea is random but narrow (i.e., if it has narrow sea spectra), then for the purpose of this report, the sea will be assumed to be regular and oscillating with the average 1/10 highest wave heights and the average wave length (both from Table 1). The wave velocity V_w and the maximum wave slope can both be calculated from Equation (1). These values are summarized in Table 2. In each sea state, the maximum values mentioned in Table 1

TABLE 1

Wind and Sea Scale for Fully Arisen Sea
(From Reference 9)

	WIND				SEA								
SEA STATE	DESCRIPTION	BEAUFORT	RANGE (KNOTS)	WIND VELOCITY (KNOTS)	WAVE HEIGHT FEET: AVERAGE	WAVE HEIGHT FEET: SIGNIFICANT	WAVE HEIGHT FEET: AVERAGE 1/10 HIGHEST	SIGNIFICANT RANGE OF PERIODS (SECONDS)	T_{max} (PERIOD OF MAXIMUM ENERGY OF SPECTRUM)	$\bar{T}$ (AVERAGE "PERIOD")	$\bar{L}$ (AVERAGE "WAVE LENGTH")	MINIMUM FETCH (NAUTICAL MILES)	MINIMUM DURATION (HOURS)
	CALM	0	0-1	[a]**0**	0	0	0	-	-	-	-	-	-
0	LIGHT AIR	1	1-3	**2**	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in	5	18 min
	LIGHT BREEZE	2	4-6	**5**	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
1	GENTLE BREEZE	3	7-10	**8.5**	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
				10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2	MODERATE BREEZE	4	11-16	12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
				13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3				14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
				16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	FRESH BREEZE	5	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
				19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
				20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	STRONG BREEZE	6	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
				24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
				24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6				26	9.6	15	20	4.0-14.5	10.5	7.4	188	180	17
	MODERATE GALE	7	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
				30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
				30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
				32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	FRESH GALE	8	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
				36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
				37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
				38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
				40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	STRONG GALE	9	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
				44	36	58	73	7-24.2	17.7	12.5	534	960	52
				46	40	64	81	7-25	18.6	13.1	590	1110	57
	WHOLE GALE *	10	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
				50	49	78	99	7.5-27	20.2	14.3	700	1420	69
				51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
				52	54	87	110	8-28.5	21.0	14.8	750	1610	75
9				54	59	95	121	8-29.5	21.8	15.4	810	1800	81
	STORM *	11	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
				59.5	73	116	148	10-32	24	17.0	985	2500	101
	HURRICANE *	12	>64	>64	>80[b]	>128[b]	>164[b]	10-(35)	(26)	(18)	~	~	~

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a) A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

b) For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

TABLE 2

Selected Sea State Data for Design Purposes

Sea State	Wave Height ft	Wave Length ft	Maximum* Wave Slope deg	Wave** Velocity fps
0	0.1	10 in.	21.6	2.1
1	1.2	20	10.8	10.1
2	3.7	52	12.8	16.3
3	5.8	71	14.7	19.1
4	8.7	99	15.8	22.5
5	16	160	18.0	28.6
6	23	212	19.5	32.9
7	50	392	22.9	44.8
8	73	534	24.6	52.2
9	148	985	27.0	71.0

* $\theta_{max} = 180 \frac{H}{L_w}$ deg

** $V_w = 2.26 \sqrt{L_w}$

are selected as one of the criteria for the design of bottom plating.

The selection of these sea states and waves depends on the operating conditions specified for the craft by the prospective owner. This requires that route environment and mission patterns be thoroughly studied and the craft designed accordingly. For instance, if a craft is intended for operation in a confined area, it is unnecessary to select, say, ability to withstand a State 6 sea as one of the design criteria. Even if a craft is designed to operate in a State 6 sea, it is unnecessary to use this sea state in designing for foilborne speed because the craft may be able to survive such a sea only at the hullborne speed which is much lower.

OPERATING CONDITIONS

As with any engineering problem, the structural designer must examine the realistic environment in which the craft is to operate. Then he selects several operating conditions which he believes the craft should be designed to survive. Operational aspects that should be examined for a hydrofoil craft include those of hullborne, foilborne, takeoff, and landing conditions.

1. Hullborne operating conditions. One of the fundamental design considerations of the craft is that the hull is resting

on calm water. Under this condition, the load imposed on the hull bottom is the buoyancy force and is considered insignificant.

While the craft is planing on the smooth water at certain speed, the pressure distribution on the hull bottom is as shown in Appendix A (see Figure 20).

If the craft is riding on the following sea at a speed that matches the wave celerity, it is nearly the same as the case where the craft is placed on a static wave.

During the time that the craft is moving against the wave, it will introduce pitching motion of the craft and cause slamming at the bow. The pressure distribution on the hull bottom caused by the slamming can be calculated from the previous section and the NSRDC formulas given in Appendix A.

These four hullborne operating conditions are shown in Figure 5.

2. Foilborne operating conditions. As the hydrofoil craft gains speed, the lift on the foils raises the entire hull out of the water. In a fully flying and smooth water condition, it is essentially a static beam problem where the hull is supported by the foils and the struts; see Figure 6.

In a fully flying and rough water condition, the hull bottom may be infrequently subjected to impact when the wave crest reaches the hull bottom or when waves pass across the bow of the craft; see Figure 6. The hull pressure imposed

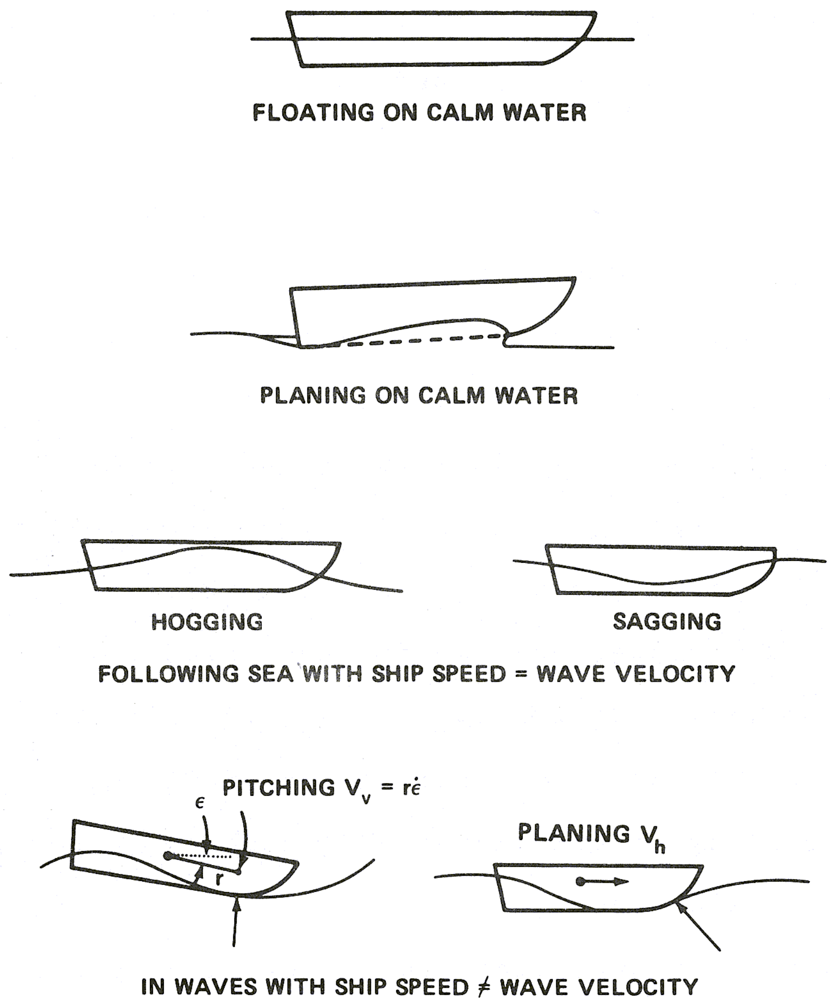


Figure 5 - Hullborne Operating Conditions

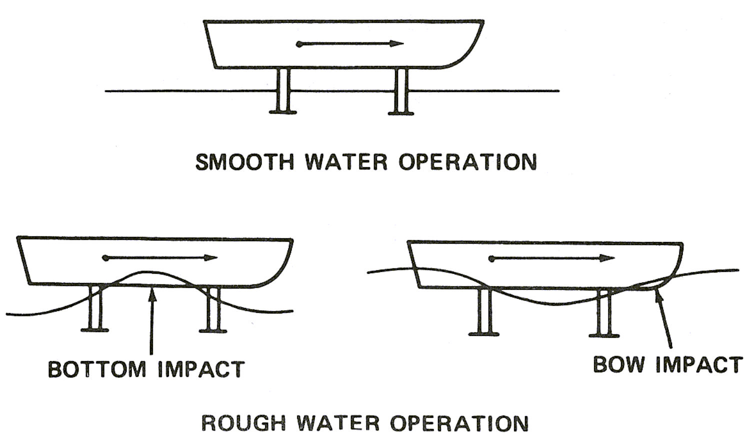


Figure 6 - Foilborne Operating Conditions

by this type of slamming can also be calculated by the method given in the previous section and the NSRDC formulas shown in Appendix A.

3. Takeoff operating conditions. If the sea is calm, the hydrofoil craft encounters only planing loads during takeoff operation. If the sea is rough, takeoff is no longer a smooth process. As the hull lifts out of the water, the bow and the hull bottom are subject to frequent impact.

4. Landing operating conditions. Two situations may occur in landing. If the landing is a smooth process, the sinking speed can be controlled and the forward speed can be reduced gradually. However, if the landing occurs unexpectedly and suddenly (i.e., as a crash landing), the foils may lose their lifting capability completely at a time when the forward speed has not been reduced.

For these four operating conditions, two situations would probably govern the design of all local hull impact areas. One is that of crash landing in a moderately severe sea under which the craft is designed for foilborne operation. The other is the survival condition in which the craft is merely to ride out the storm in a hullborne mode.

In a crash landing, if free fall is assumed when the foils lose all their lift capabilities, the maximum sinking speed will be

$$V_v = \sqrt{2gs}$$

$$= 8\sqrt{s}$$

where s is the hull clearance (in feet) from foilborne water surface to the point of concern at the hull bottom.

This represents an unrealistic upper limit of the sinking speed. Most designers use 5 to 10 fps as a reasonable value; this is about one-half the value given by the above equation. Therefore, for the purpose of design, sinking speed should be used as

$$V_v = 4\sqrt{s} \tag{7}$$

and vertical water velocity v by Equation (1). The horizontal velocity used will be the sum of the horizontal velocities of the craft and the wave (but not the horizontal water velocity); see Figure 7.

Now let us examine specifically under what conditions the craft will encounter the most severe impact loads. To do this, we divide the hull bottom into three portions: the bow, the midship body, and the aft body. There are no definite

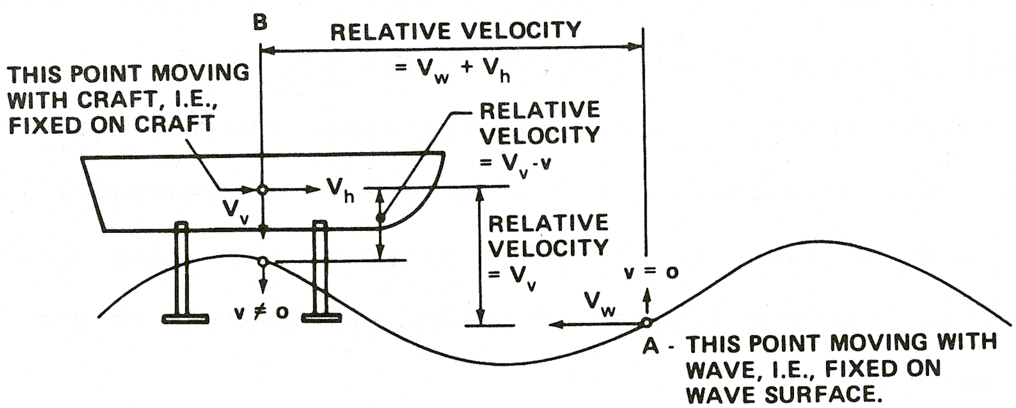


Figure 7 - Velocity Reference Diagram

boundaries among them. Say AP to 1/4 L is the aft body, 1/4 to 3/4 L is the midship body, and 3/4 L to FP is the bow.

The most severe impact for the aft body occurs at the time when the foils lose all their lift and the craft falls on the calm water surface with or without trim and heel and with a sinking speed $V_v = 4\sqrt{s}$. The forward speed has little influence on the loads unless the trim is large.

The most severe impact for the midship body occurs under the same conditions as for the aft body. As determined from experiments, the impact loads due to pitching are much smaller than those due to free falls. Therefore, the calculations for the hull-borne impact can usually be omitted.

The most severe impact for the bow occurs during foil-borne operation in waves or a crash landing in waves. For the purpose of design, we can safely assume that the maximum bow impact occurs during the maximum foilborne speed when the sea has the maximum wave height and wave slope at the specified sea condition. For this speed and condition, the midship- and aft-body impacts occur and are considered severe also.

This narrows down to two severe operating conditions which may be considered as the design criteria, i.e., (a) the craft falls at sinking speed of $4\sqrt{s}$ on the calm water or (b) the craft hits the maximum wave height and wave slope of the specified sea condition at the maximum foilborne speed.

Under these two operating conditions, the hull bottom is investigated and designed as a whole rather than dividing it into three pieces and investigating them separately.

SLAMMING LOADS

After the hull form of the craft, the sea state and waves, and the operating conditions have been specified, the next step is to determine the slamming loads at various locations along the hull. The slamming loads depend on the horizontal and vertical velocities (V_h, V_v) of the craft, the sea state and waves, the deadrise and the buttock and the trim angles (β, α, τ) of the craft, and the configuration of bow and stern. As indicated in Equations (2) to (6) and (9) to (11), the slamming loads are determined from the velocity terms (V_h, V_v, V_w, u, and v) and the angles (β, α, τ, and θ). In using these terms, some confusions may exist. Hopefully, the following discussions would resolve these confusions for the readers.

1. Velocity Terms. When a craft rides on waves of the same speed, the situation is the same as if it is placed on a steady-state static wave. The craft will then encounter no surface slamming load since

$$\text{Total horizontal velocity} = V_h + V_w = o$$

$$\text{Total vertical velocity} = V_v + v = o$$

Now if the craft has zero speed, the craft would feel that the wave is coming at the horizontal velocity of V_w. Since the wave has the surface profile of (see Equation (1))

$$\eta = h \sin k(y - V_w t)$$

at any transverse plane of the craft, the water level is moving up and down at the vertical velocity of (also see Equation (1))

$$\frac{\partial \eta}{\partial t} = v = - k\ h\ V_w \cos k(y - V_w t).$$

However, as indicated previously, the normal and tangential velocities at a point of concern on the wave surface are

$$V_n' = V_w \sin \theta$$

$$V_t' = V_w \cos \theta$$

because this point is moving with the wave on the wave surface.

When the craft gains speed to V_h, the total horizontal planing velocity V_p will be increased to

$$V_p = V_h + V_w$$

The water level is moving up and down at any transverse plane of the craft with the vertical velocity of

$$v = - k h (V_h + V_w) \cos k [y - (V_h + V_w) t]$$

This equation is modified from Equation (1) by considering the wave to move at a horizontal velocity of $(V_h + V_w)$ with the period of encounter

$$T_e = \frac{L_w}{V_h + V_w}$$

The normal and the tangential velocities of the wave surface with reference to the craft become

$$V_n' = (V_h + V_w) \sin \theta$$

$$V_t' = (V_h + V_w) \cos \theta$$

If the sinking speed V_v of the craft is included in the equation, the same reasoning gives

$$\left.\begin{aligned} V_p &= V_h + V_w \\ V_i &= V_v \\ v &= - k\, h\, (V_h + V_w) \cos k\, [y - (V_h + V_w)\, t] \\ V_n &= V_v \cos\theta + (V_h + V_w) \sin\theta \\ V_t &= - V_v \sin\theta + (V_h + V_w) \cos\theta \end{aligned}\right\} \quad (8)$$

where V_p, V_i, V_n, and V_t are referred to the point (point A in Figure 7) on the wave surface moving at the constant velocity V_w with the craft moving at the horizontal velocity V_h and the vertical velocity V_v. But v is referred to the vertical plane (plane B in Figure 7) on the craft in the transverse direction. If v is referred to point A on the wave surface, this equation becomes

$$v = - k\, h\, (V_h + V_w - V_h - V_w) \cos k\, [y - (V_h + V_w - V_h - V_w) t]$$

$$\equiv 0$$

2. Angles. Most small craft have curved keels with initial trims when they rest on the calm water. This is usually the condition for preparing the lines drawing of the craft. The values of β, α, and τ measured from the line drawing must be carefully examined before they are applied to Equation (6) to determine β_{eh}, β_{ev}, and ξ.

As shown in Figure 8, Section A-A is part of the body plan drawing. The deadrise angle is measured vertically on Section A-A. For vertical impact without additional trim, this angle is actually the vertical effective angle β_{ev} instead of β which is supposed to be measured perpendicular to the keel line at the point of impact.

Let us examine the second equation of Equation (6)

$$\tan \beta_{ev} = \frac{\tan \beta}{\cos (\tau - \theta) - \tan \alpha \sin (\tau - \theta)}$$

If there is no wave, $\theta = 0$ and $\tan \beta_{ev} = \frac{\tan \beta}{\cos \tau - \tan \alpha \sin \tau}$. If the initial trim τ_o is small and $\tan \alpha < 1$, then $\cos \tau_o \rightarrow 1$ and $\tan \alpha \sin \tau_o \rightarrow 0$. Then, approximately

$$\beta_{ev_o} \approx \beta$$

Therefore, from the practical point of view, Equation (6) still holds if the initial trim τ_o is small. In that case, the deadrise angle can be treated as β with the initial trim angle τ_o to be considered as zero and $\alpha + \tau_o$ as α.

The values of β_{ev} and β_{eh} can also be determined graphically. If on the line plan, a tangent line is drawn through the point of impact on the surface of the hull and parallel to the surface of the wave at its point of impact, the angle measured from that line to the line perpendicular to the centerline of the craft is the angle β_{eh} (see Figure 5 of Reference 8 for the physical meaning of β_{eh}). Similarly β_{ev} can be measured graphically (see Figure 3 of Reference 8 for β_{ev}).

As stated previously, once the velocity terms and angles have been determined, the slamming loads can then be determined from Equations (2) to (6) and (9) to (11).

STRUCTURAL RESPONSE TO SLAMMING LOADS AND BOTTOM PLATING DESIGN

The structural response to slamming loads and bottom plating design has been illustrated in Reference 8. Basic NSRDC equations for structural response are summarized in Appendix A. In a practical design, if the ship bottom is relatively rigid, it may be assumed that a rigid body impact pressure p_r is applied quasi-statically to the ship bottom.

The design loads imposed on the craft hull bottom are illustrated in Figure 9 for the design of a whole hull bottom as well as for an individual panel. The maximum impact load occurs when a dry-chine impact with piled-up water is just about to reach the outboard stiffener of the panel. In any case, the dry-chine impact load should be considered as one of the governing design criteria.

It is not within the scope of this report to present the structural design method in detail. Assuming the ship designer has sufficient knowledge in structural design, the example given in Reference 8 should be sufficient guidance.

SUMMARY

This report is a continuation of Reference 8 which provides a method of estimating impact pressure distributions on wedge-shaped hull bottoms of high-speed craft cruising on smooth water. This report extends the method to rough water cruising and also sets up the design criteria for bottom plating of hydrofoil hulls.

Equations for estimating dry-chine pressures on the hull bottom of high-speed craft are summarized below:

1. Angles β_{eh}, β_{ev}, and ξ: Use Equation (6).

2. Velocities V_n and V_t: Use Equation (2).

3. Impact pressures p_{keel} and p_{max}: Use Equation (9) and replace V_v with V_n.

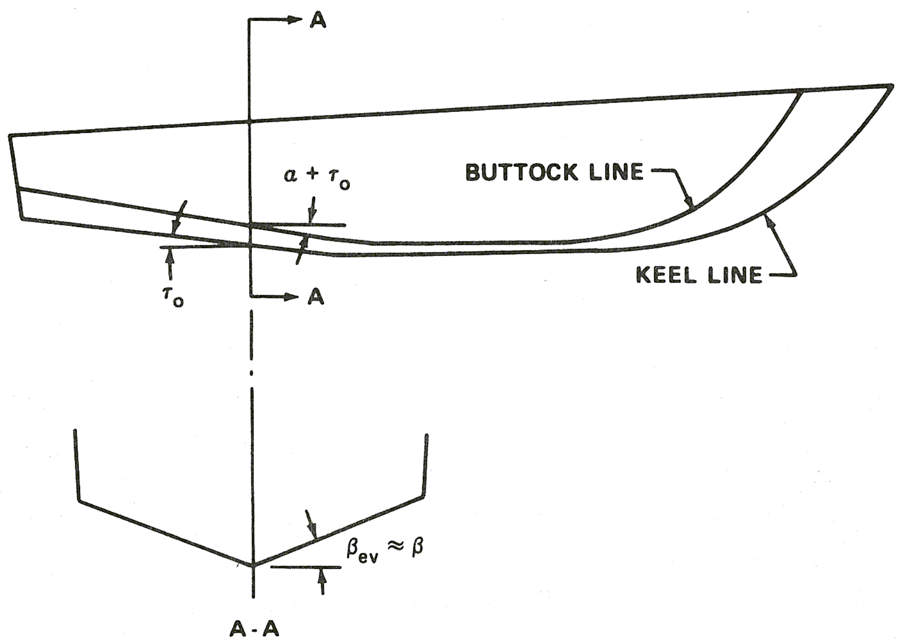


Figure 8 - Measurement of Angles for Craft with Curved Keel Line

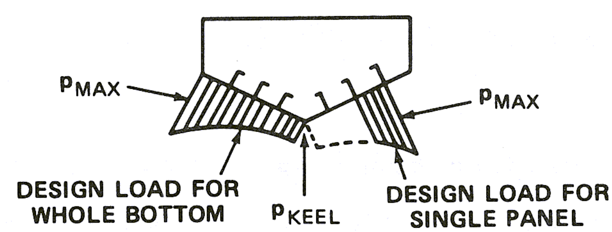


Figure 9 - Design Loads for Whole Bottom and for Single Panel

4. Planing pressure p_h: Use Equation (10) and replace V_h with V_t.

5. Total pressure: Use Equation (11).

The five-step design procedure, including design criteria, for the hydrofoil hull bottom plating is summarized below:

1. Selection of hull bottom form. The hull bottom form is partly governed by the limiting slamming loads imposed on it. The excess of slamming loads may be necessary to change the hull bottom with finer entrance angle and large deadrise angles.

2. Design criteria on sea state and wave. Use Table 2. The selection of sea state is based on the actual environment the craft will encounter.

3. Design criteria on operating conditions. Either (a) the craft falls at sinking speed by Equation (7) and on calm water or (b) the craft hits the maximum wave height and wave slope of the specified sea state (by Table 2) at its maximum foilborne speed.

4. Design criteria on slamming loads. Use equations for estimating dry-chine pressures on the hull bottom of high-speed craft given above as the design criteria for estimating the slamming loads of the hydrofoil craft. Velocities are given by Equation (8).

5. Design criteria on structural response of hull bottom. Use NSRDC formulas given in Appendix A or use quasi-static approximation.

Appendix B illustrates the use of the method for determining the slamming loads on waves. The panel response of hydrofoil craft bottom is available in Appendix C of Reference 8.

ACKNOWLEDGMENTS

The author is indebted to Messrs. A. B. Stavovy, G. O. Thomas, and L. A. Becker for their helpful assistance and valuable suggestions.

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APPENDIX A

SUMMARY OF VARIOUS METHODS FOR DETERMINING IMPACT LOAD ACTING ON HULL BOTTOM

VON KÁRMÁN THEORETICAL EQUATIONS (see Reference 1)

1. Impact force ($\beta > 0$):

$$F = \frac{W}{g}\ddot{z} = \frac{V_o^2 \cot \beta}{\left[1 + \frac{\pi \rho g x^2}{2W}\right]^3} \rho \pi x$$

2. Average pressure ($\beta > 0$):

$$p_{ave} = \frac{F}{2x} = \frac{\rho V_o^2}{2} \frac{\pi \cot \beta}{\left[1 + \frac{\pi \rho g x^2}{2W}\right]^3}$$

3. Maximum pressure ($\beta > 0$):

$$p_{max} = \frac{1}{2} \rho V_o^2 \pi \cot \beta$$

at the moment of first contact of the keel of the hull bottom.

4. Impact pressure for flat-bottom slamming ($\beta = 0$):

$$p = \rho c V_o$$

WAGNER THEORETICAL EQUATIONS (see Reference 2)

1. Pressure distribution ($\beta > 0$):

$$p = \frac{1}{2} \rho V_a^2 \frac{2}{u\sqrt{1 - \frac{x^2}{L^2}}} - \frac{1}{2} \rho V_a^2 \frac{\frac{x^2}{L^2}}{1 - \frac{x^2}{L^2}} - \rho \dot{V}_a \sqrt{L^2 - x^2}$$

where $u = \frac{2}{\pi} \tan \beta$ for the case of straight V-bottom and, for a three-dimensional prismatic float at an angle of trim τ (considering all the angles are small),

$$V_a = V\gamma_r + (V - V_{wi}) \tau_r + V_w \theta$$

For steady planing, Pierson[10] modified the Wagner equation by replacing β with β_e, with β_e defined by the relation

$$\sin^2 \beta_e = \sin^2 \beta + \frac{\pi^2}{4} \sin^2 \tau$$

Later Pierson and Leshnover[11] further modified the Wagner equation as follows:

$$\frac{p}{\frac{1}{2}\rho \dot{f}^2} = \left[\frac{\pi \cot \beta_e}{\sqrt{1 - (\frac{x}{L})^2}} - \frac{1}{(\frac{L}{x})^2 - 1} \right] \sin^2 \tau$$

where

$$\tan \beta_e = \frac{\pi}{2}\sqrt{\frac{\sin^2 \beta + K^2 \tan^2 \tau}{K^2 - 2K \sin^2 \beta - K^2 \sin^2 \beta \tan^2 \tau}}$$

and

$$K \approx \frac{\pi}{2}\left[1 - \frac{3 \tan^2 \beta \cos \beta}{1.7\ \pi^2} - \frac{\tan \beta \sin^2 \beta}{3.3\ \pi}\right]$$

Since the modified Wagner equations are for the case of steady planing in the absence of wind and wave,

$$V_a = V\ (\gamma_r + \tau_r)$$

$$= V \sin\ (\gamma + \tau)$$

$$= \dot{z}$$

And also $\gamma = 0$; therefore $V_a = \dot{z} = \dot{f} \sin \tau$.

2. Maximum pressure ($\beta > 0$):

$$p_{max} = \frac{1}{2}\ \rho\ V_a^2\ (1 + \frac{\pi^2}{4} \cot^2 \beta)$$

3. Keel pressure ($\beta > 0$):

$$p_{keel} = \frac{1}{2} \rho V_a^2 \pi \cot \beta$$

4. Korvin-Kroukovsky and Chabrow wetted-chine equation (see Reference 12):

$$p = \frac{1}{2} \rho V_a^2 \left[1 - \left(\frac{\cos \nu}{1 + \sin \nu}\right)^{2d}\right]$$

where ν is defined by the relations

$$x = 2 kb \cos \beta \int_{\varepsilon}^{\frac{\pi}{2}} (1 + \sin \nu)^d (\cos \nu)^{1-d} \sin \nu \, d\nu$$

$$\frac{1}{k} = 4 \cos \beta \int_{o}^{\frac{\pi}{2}} (1 + \sin \nu)^d (\cos \nu)^{1-d} \sin \nu \, d\nu$$

and

$$d = \frac{\pi - 2 \beta_r}{\pi}$$

For the special case of the rectangular flat plate ($d = 1$),

$$x = \frac{b}{8 + 2 \pi} (\pi - 2\nu + 4 \cos \nu + \sin 2\nu)$$

SMILEY EMPIRICAL FORMULAS

(For $\beta > 0$ and smooth-water landing)

1. From NACA TN 2111 (see Reference 5):

$$p_{max} = \frac{1}{2} \rho V^2 \frac{\pi^2 \sin^2 (\gamma + \tau)}{\pi^2 \sin^2 \tau + 4 \tan^2 \beta \cos^2 \tau}$$

2. From NACA TN 2583 and TN 2816 (see References 4 and 6):

$$p_{max} = \frac{1}{2} \rho \dot{z}^2 \frac{1}{\sin^2 \tau + J^2 \cos^2 \tau}$$

where $J = J(\beta) = \frac{2}{\pi} \tan \beta$ for $\tau = 0$ deg and $\beta \rightarrow 0$ deg and for $\beta = 30$ deg and all trim angles τ. For $\beta = 22.5$ deg and all trim angles τ, $J = 0.293$.

The transverse pressure distribution in the dry-chine region is

$$\frac{p}{\frac{1}{2}\rho \dot{z}^2} = \frac{\pi \cot \beta_e}{\sqrt{1 - \left(\frac{x}{L}\right)^2}} - \frac{1}{\left(\frac{L}{x}\right)^2 - 1} + \frac{2\ddot{z}L\phi(A)}{\dot{z}^2} \sqrt{1 - \left(\frac{x}{L}\right)^2}$$

where

$$\pi \cot \beta_e = 2\sqrt{\frac{1 - J^2}{\tan^2 \tau + J^2}} \geq 2 \leq \pi \cot \beta_e = \frac{1}{\sin^2 \tau + J^2 \cos^2 \tau}$$

$$\phi(A) = \sqrt{\frac{1}{1 + \frac{1}{A^2}}} \left(1 - \frac{0.425}{A + \frac{1}{A}}\right) \qquad (0 < A < \infty)$$

$$= 1 - \frac{1}{2A} \qquad (1.5 < A < \infty)$$

and

$$A = \frac{(\text{Wetted length at keel})^2}{\text{Wetted area projected normal to keel}} = \frac{\lambda_p^2}{S}$$

For trims below 16 deg, the pressure distribution on the wetted-chine region of a prismatic V-bottom wedge may be predicted from C_{N_p} of Figure 9, Reference 4 (or Figure 10 of this report). For larger trims, the following equation, obtained from the analysis of Reference 13, may be used:

$$C_N = \frac{\phi(A) \sin \tau \cos \tau}{A} \left[\frac{\pi^3}{16} + 0.88\, A \tan \tau\right]$$

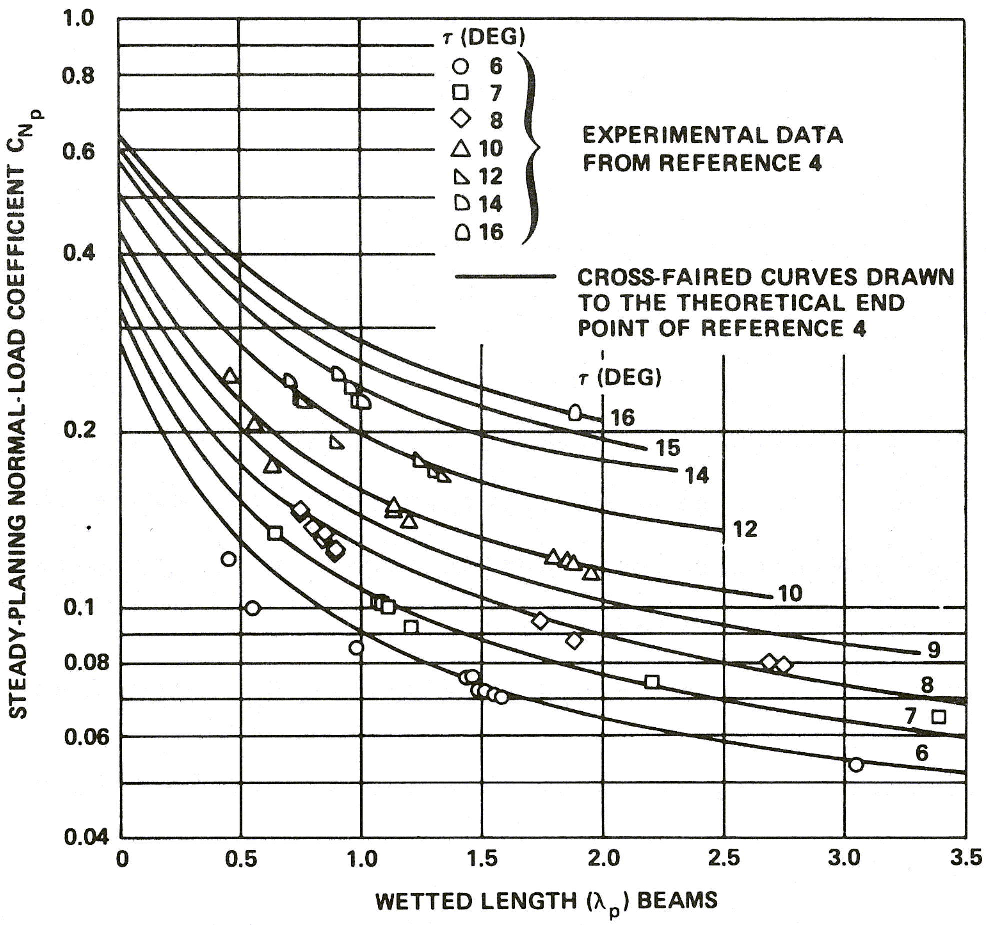

Figure 10 - High-Speed, Steady-Planing, Normal-Load Coefficients

where C_{N_p} is defined as normal-load coefficient for a rectangular flat plate based on λ_p and C_N as that based on A, i.e.,

$$C_{N_p} = \frac{F_N}{\frac{1}{2}\rho \dot{f}^2 b^2 \lambda_p}$$

$$C_N = \frac{F_N}{\frac{1}{2}\rho \dot{f}^2 b^2 A}$$

The method for determining the pressure distribution on the wetted-chine region of a rectangular flat plate as well as a prismatic V-bottom wedge during impact or planing is summarized in the following steps:

a. Obtain the normal-load coefficient C_{N_p} from Figure 9 of Reference 4 (Figure 10 of this report) or from C_N of Reference 13.

b. Compute the centerline normal-force coefficient $(C_{N_p})_c$ from the relation

$$(C_{N_p})_c = \frac{C_{N_p}}{0.95}$$

c. Compute the pressure p_c distribution along the longitudinal line from the relation

$$\frac{p_c}{\frac{1}{2} \rho \dot{f}^2} = f_3 \left[\frac{\lambda}{\lambda_p}, \left(C_{N_p}\right)_c \right]$$

This relation may also be obtained from Figure 4 of Reference 4 (Figure 11 of this report) by substituting the subscript c for t.

d. Compute the transverse pressure distribution as the average of

$$\frac{p}{p_c} = 1$$

and

$$\frac{p}{p_c} = 1 - \left(\frac{\cos \nu}{1 + \sin \nu} \right)^{2d}$$

where ν and d are defined on page 38 (Item 4) of Appendix A.

MARTIN COMPANY FORMULA (see References 14-16)

$$p_{max} = \frac{1}{2} \rho V_n^2 \frac{1}{\sin^2 \tau^* + \frac{4 \tan^2 \beta}{\pi^2} \cos^2 \tau^*}$$

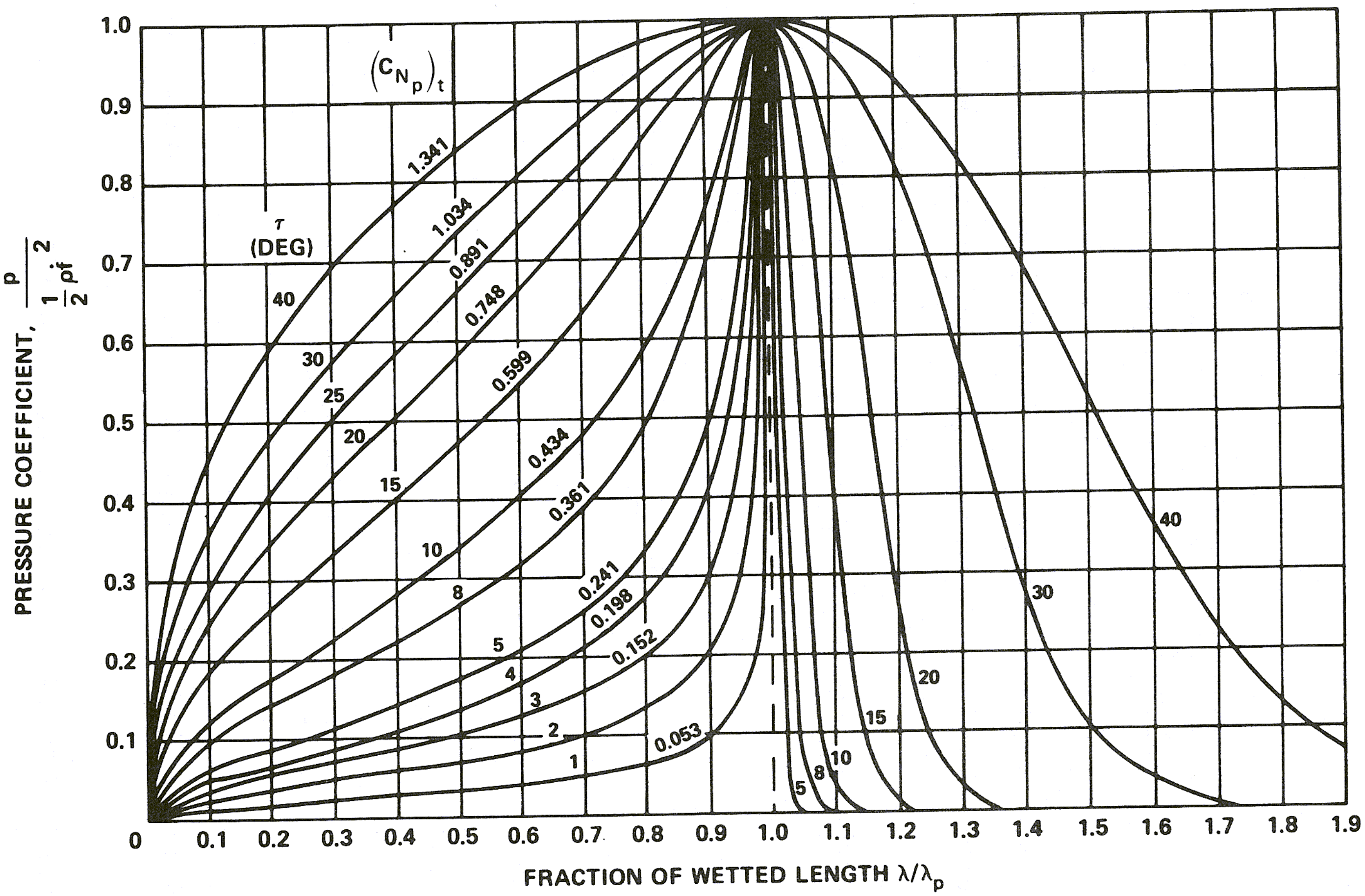

Figure 11 - Theoretical Pressure Distributions for the Two-Dimensional Flat Plate During Steady Planing Calculated from Reference 4

where V_n are the velocity components normal to the average bottom slope including sinking speed V_v, the component of ship speed normal to bottom slope V_h $(\tau + \alpha)$, and the wave orbital velocity V_{w_o}; τ is the hull trim angle; α is the local surface buttock angle; τ^* is equal to $\alpha + \tau - \theta$; and θ is the maximum angle of wave slope = 180 H/λ. The above formula is modified from that of Smiley and has not been experimentally verified. If all the angles are small, then

$$V_n = V_v + V_h (\tau + \alpha) + V_{w_o}$$

with

$$V_v \leq \sqrt{2gs}$$

$$V_{w_o} = H \sqrt{\frac{\pi g}{2L_w}}$$

where s is the free drop height, H is the wave height, and L_w is the wave length.

MIL-A-8629(Aer) FORMULAS (see Reference 3)

(This specification contains Bureau of Aeronautics requirements relative to piloted airplanes.)

The pressures (in pounds per square inch) at the keel and the chine are defined by

$$p = \frac{fK_1 V_{s_L}}{\tan \beta}$$

where f, K_1, and β are specified in Table 3 and Figures 12-15 and V_{s_L} is the landing design stalling speed of airplane.

When the loads are forward of the step, the resultant water loads act normal to line b of Figure 15. When the loads are aft of the step the resultant loads act parallel to the Z-axis. The component of resultant water loads parallel to the Z-axis p_z is defined as a function of time by Figure 14 where

$$p_M = \frac{K_2 K_3 \left[\dfrac{W}{1 + \dfrac{x^2}{i_y^2}} \right]^{\frac{2}{3}} V_{s_L}^{\ 2}}{\tan^{\frac{2}{3}} \beta_c}$$

$$t_m = \frac{W^{\frac{1}{3}} \tan^{\frac{2}{3}} \beta_c}{25 \sqrt{K_2 K_3}\, V_{s_L} \left(1 + \dfrac{x^2}{i_y^2} \right)^{\frac{2}{3}}}$$

TABLE 3

Water Pressures

	Pressures Applicable for	Pressure at	f: Sheltered-Water Operation	f: Rough-Water Operation	K_1	Deadrise Angles*
1	Bottom design, see 3.7.2.1 of Ref. 3	Keel	0.00213	0.00319	From Fig. 12 for hull; 1.0 for auxiliary float	β_k
		Chine	0.0016	0.00239		β_o
2	General design, see 3.7.2.2 (to consider seaplane as a whole) of Ref. 3	Keel and chine (Evenly distributed)	0.00093	0.00133		β_o

* The deadrise angles β are defined in Figure 13. For pressures on the hull, they are the angles at the station for which the pressures are computed. For pressures on the auxiliary float, the angles are those at a station on the auxiliary float one-quarter of the distance from the step to the bow.

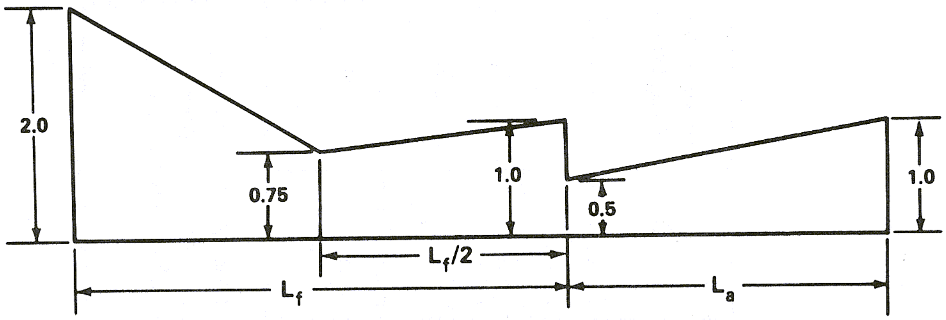

Figure 12 - Variation of Factor K_1 with Hull Length

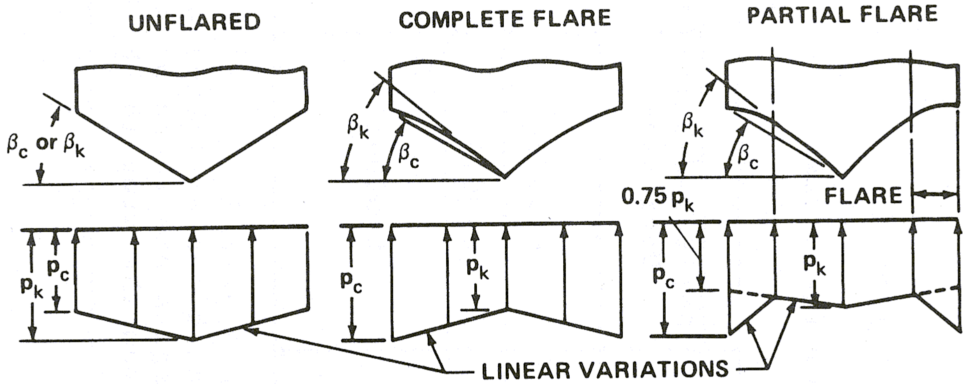

Figure 13 - Transverse Variation of Pressure for Bottom Design

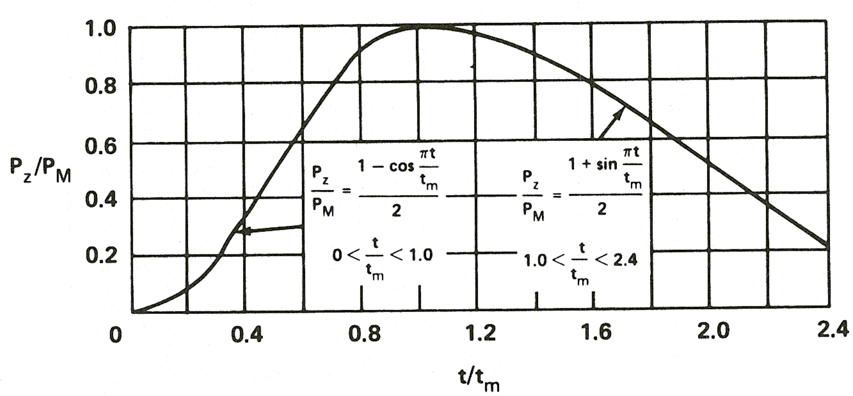

Figure 14 - P_z/P_M as a Function of t/t_m

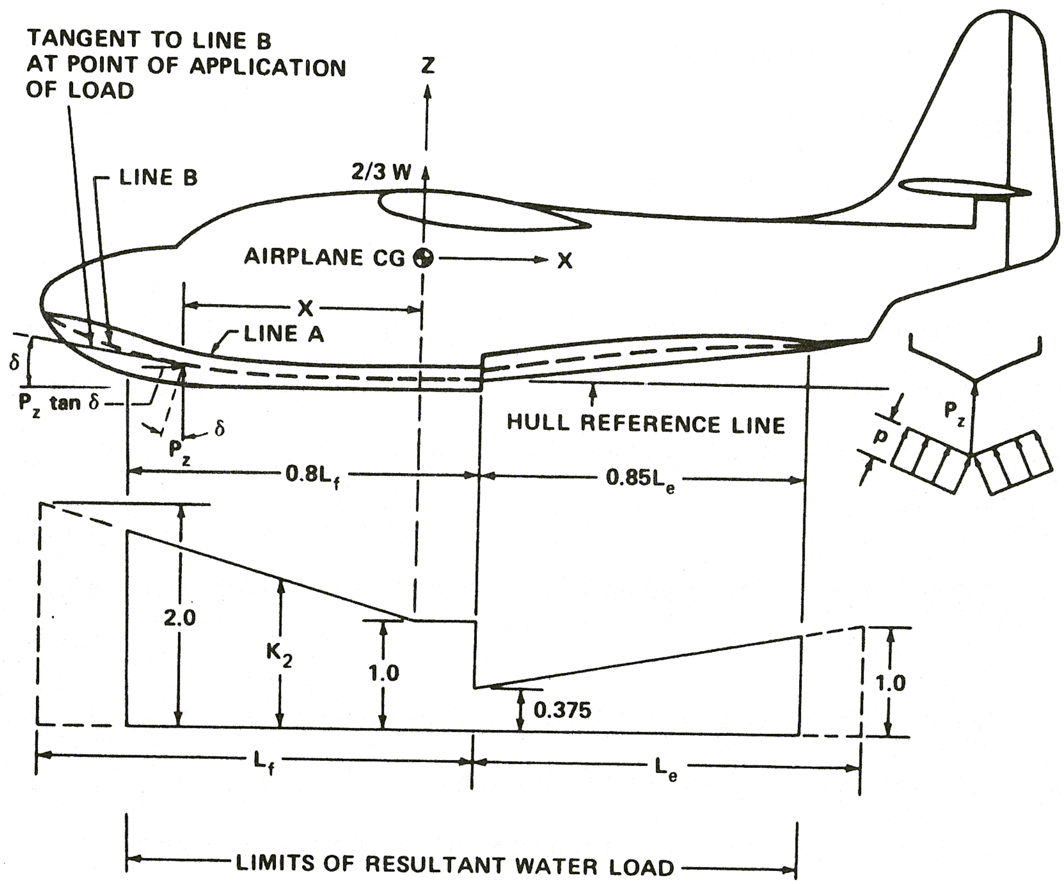

Figure 15 - Symmetrical Water Loads on Hull

1. LINE A IS THE PROJECTION OF THE CHINE ON THE PLANE OF SYMMETRY.
2. LINE B IS IN THE PLANE OF SYMMETRY MIDWAY BETWEEN THE KEEL AND LINE A.
3. THE HULL REFERENCE LINE IS A STRAIGHT LINE IN THE PLANE OF SYMMETRY TANGENT TO LINE B ON THE FOREBODY AT THE STEP.
4. THE X-AXIS IS IN THE PLANE OF SYMMETRY PARALLEL TO THE HULL REFERENCE LINE WITH THE ORIGIN AT THE AIRPLANE CENTER OF GRAVITY, THE Z-AXIS IS IN THE PLANE OF SYMMETRY NORMAL TO THE X-AXIS, AND THE Y-AXIS IS NORMAL TO THE PLANE OF SYMMETRY.
5. δ IS THE ANGLE BETWEEN THE HULL REFERENCE LINE AND THE TANGENT TO LINE B AT THE POINT AT WHICH ANY RESULTANT WATER LOAD ACTS.
6. POSITIVE DIRECTIONS ARE AS SHOWN.

Here i_y is the transverse radius of gyration of the airplane, the value of K_2 is obtainable from Figure 15, K_3 is equal to 0.0120 for sheltered-water operation and to 0.0173 for rough-water operation. Further, t is time, W is airplane weight, x is the distance illustrated in Figure 15, and β_c is the angle of deadrise at chine.

Since MIL-A-8629 (Aer) is written for the purpose of design, the total pressure Σ p may not necessarily be the same value as the resultant water loads p_z.

DESIGN LOADS USED FOR PROTOTYPE HYDROFOIL CRAFT (see Figure 16)

1. Hull Bottom loads for impact and planing of AG(EH)-1 Hydrofoil Research Ship (see Reference 17):

a. For rough water landings at a forward speed of 90 knots, the 45-psi limit design pressure based on MIL-A-8629 is considered adequate.

b. The hull bottom pressure for combined planing and impact is expressed in equation form as

$$L = K_{\ell} V_r^2 \left(\cos \gamma + \frac{\sin \gamma}{\tan \tau}\right)^2 + m\frac{dV_n}{dt} \cos \tau + m V_n \cos \tau$$

based on Leadon for planing, Smiley for penetration acceleration, and Schnitzer for rate of change of added mass.

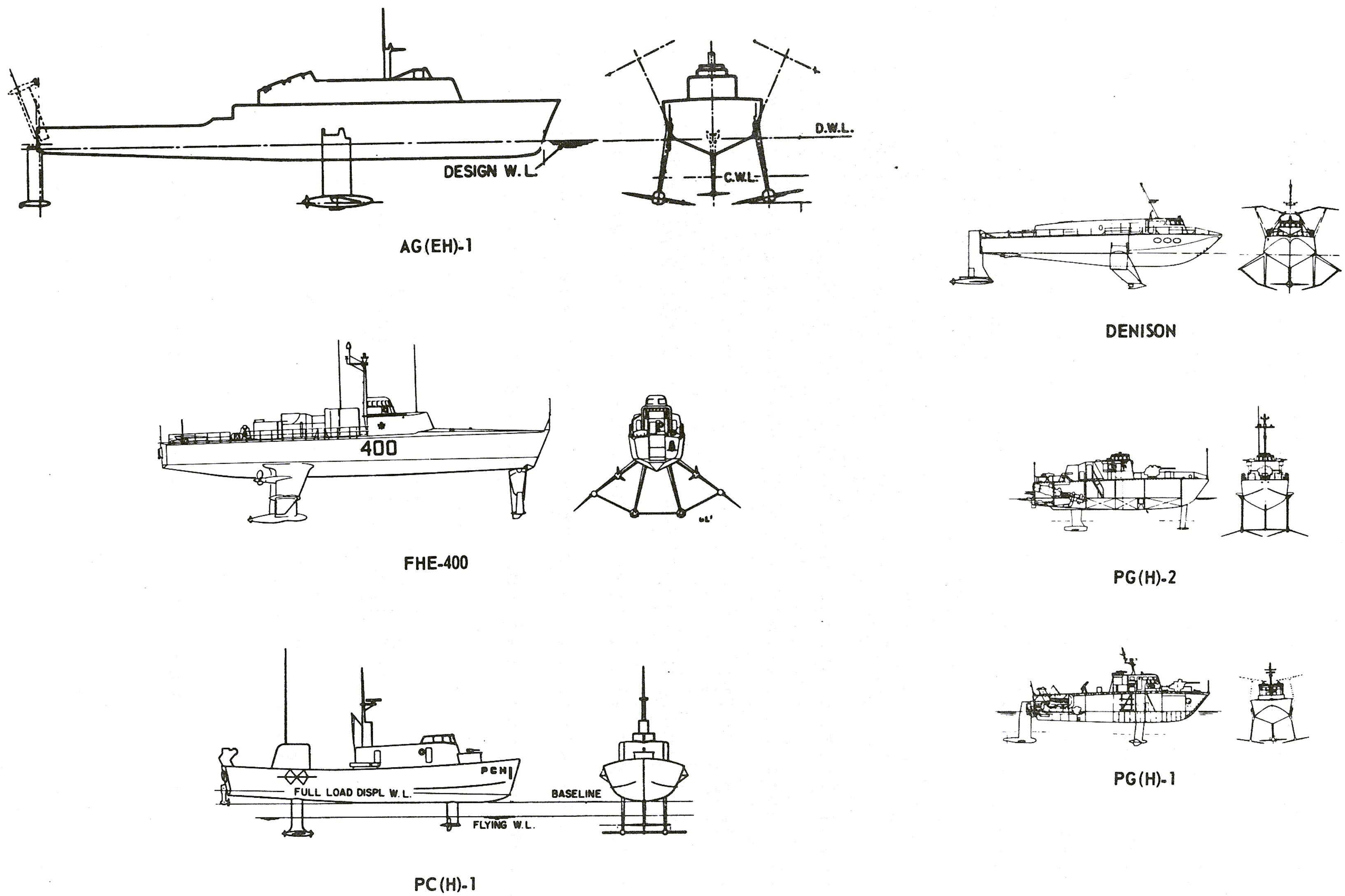

Figure 16 - Hydrofoil Craft

In the above equation, L indicates load, K_ℓ equals $\frac{1}{2}\rho C_{L_S} S$, C_{L_S} equals $\frac{0.5\pi A\tau}{1 + A}\cos^2\tau\,(1 - \sin\beta_e)$ $+ \frac{4}{3}\sin^2\tau\cos^3\tau\cos\beta_e$, τ is the trim angle, β_e is the effective deadrise angle, γ is the glide path angle, A is the aspect ratio = b^2/S, S is the area, V_r is the resultant velocity along the glide path, and V_n is the velocity normal to the keel.

(1) The design condition is assumed to be a crash in which all lift on the foils is lost at a speed of 90 knots and the hull is allowed to drop in free fall from a height of 13 ft (28.92 fps).

(2) Another important design condition is that of a crash in which all lift on the foils is lost and the hull strikes the water at zero trim. Then there is no planing pressure and the load comes from impact, with

$$p_{ave} = \frac{\rho}{2}\left[\frac{90}{\beta} - 1\right]^2 \tan\beta\left[2\dot{z}^2 + z\ddot{z}\right]$$

$$p_{max} = K\,p_{ave}$$

c. Flat bottom impact was not investigated.

d. There are two approaches for determining bow impact loads.

(1) First Approach: Bow impact pressure = 45 psi with a factor of safety of 1.5.

(2) Second Approach: By equation

$$\frac{dF}{dS} = \frac{\pi\rho}{4}\left[2a\frac{da}{dt} V_n + a^2 \frac{dV_n}{dt}\right]$$

where F is the total load, ρ is the mass density of sea water, a is the wetted side length of the hull, keel to chine or wave surface, and V_n is the total water velocity normal to the hull side.

2. Hull bottom impact pressure for FHE-400 (see Reference 18)

Four methods were explored -- those of NACA, Martin, Grumman, and the Marine Aircraft Experimental Establishment (MAEE). The formula of the MAEE method is a derivation of the Wagner pressure distribution formula, originally deduced for a two-dimensional wedge dropping onto the water with zero forward speed. The peak pressure formula proposed is

$$p_{max} = \frac{\dot{Z}^2}{K} \cot^2 \beta$$

The exact value of the constant K will depend on the correction factor chosen between the peak pressure and the observed pressure.

The assumed design data include ρ = 2 pounds-seconds^2/feet^4 and the following:

Wave Data:

L_w = 85 ft

H = 10.4 ft

$V_{w_o} = 7.1\ H/L_w = 8.0$ fps

$V_w = (gL_w/2\pi)^{\frac{1}{2}} = 20.85$ fps

θ = 25.8 deg max

Craft Data:

V_h = 34 fps (20 knots)

V_v = 10 fps

β = 30 deg

$\tau = \tau' + \theta = 10$ deg

where ρ is the mass density of water, L_w is the wave length, H is the wave height, θ is the wave slope at point of impact, V_w is the wave celerity = $(gL_w/2\pi)^{\frac{1}{2}}$, V_{w_o} is the orbital velocity of wave = $\frac{\pi H V_w}{L_w} e^{-2\pi z/L_w}$, V is the instantaneous velocity of the model parallel to the undisturbed water surface or planing speed, V_v is the instantaneous velocity of the model normal to the undisturbed water surface or sinking speed, β is the deadrise angle, and τ is the trim angle.

The results of calculations by the four methods give:

NACA Method: p_{max} = 26.85 psi

Martin Method: p_{max} = 27.4 psi

Grumman Method:* p_{max} = 10.74 psi

MAEE Method: p_{max} = 33 psi

Therefore for the design, assume that the maximum hull bottom impact pressure is 36 psi.

3. Hull bottom pressures for DENISON (see Reference 19). The hull bottom pressures used for the design of DENISON, a Maritime Administration (MARAD) test vehicle, were based on Military Specification MIL-A-8629 (Aer) Sections 3.7 through 3.7.3.1 and Section 3.7.4.1 (see Reference 3). These pressures were calculated for an 80-knot vehicle. Because the vehicle is a boat not a seaplane, the K_1 factor has been modified as shown in Figure 17. The hull deadrise angles are shown in Figure 18, and the calculated pressures are plotted in Figure 19.

4. Hull bottom impact loads of PC(H)-1, PG(H)-1, and PG(H)-2. The builders did not clearly define the methods used to determine the hull bottom impact loads of PC(H)-1,

---

* $$p_{max} = \frac{K\rho}{2}\left[\frac{90}{\beta} - 1\right]^2 \tan\beta \left[2\dot{z}^2 + z\ddot{z}\right]$$

$$= 10.74 \text{ psi}$$

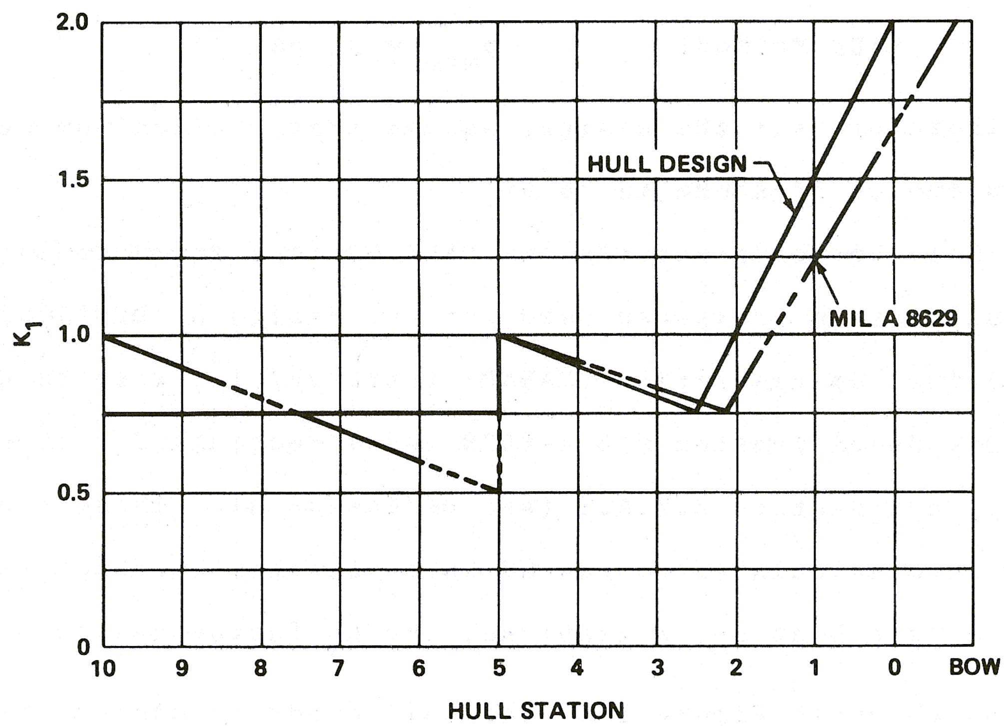

Figure 17 - K_1 versus Hull Station

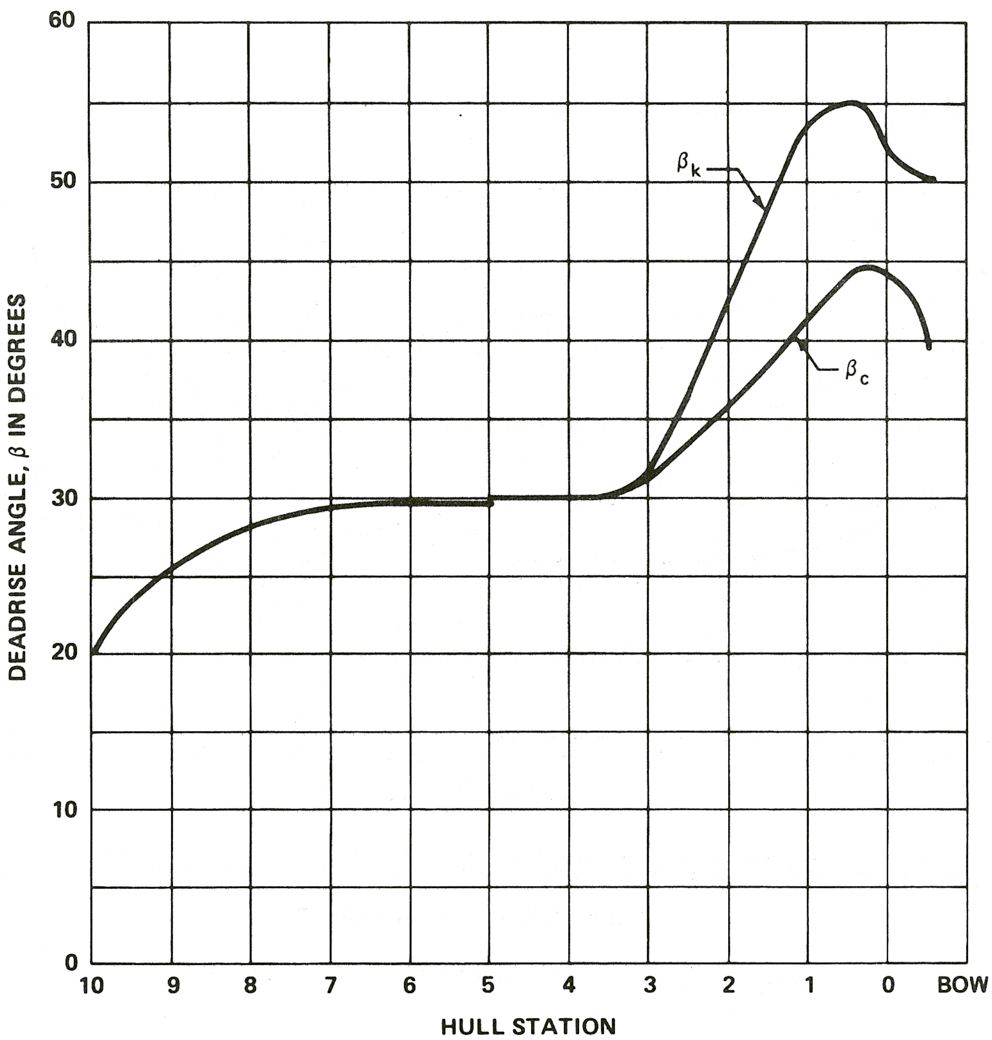

Figure 18 - Deadrise Angle versus Hull Station

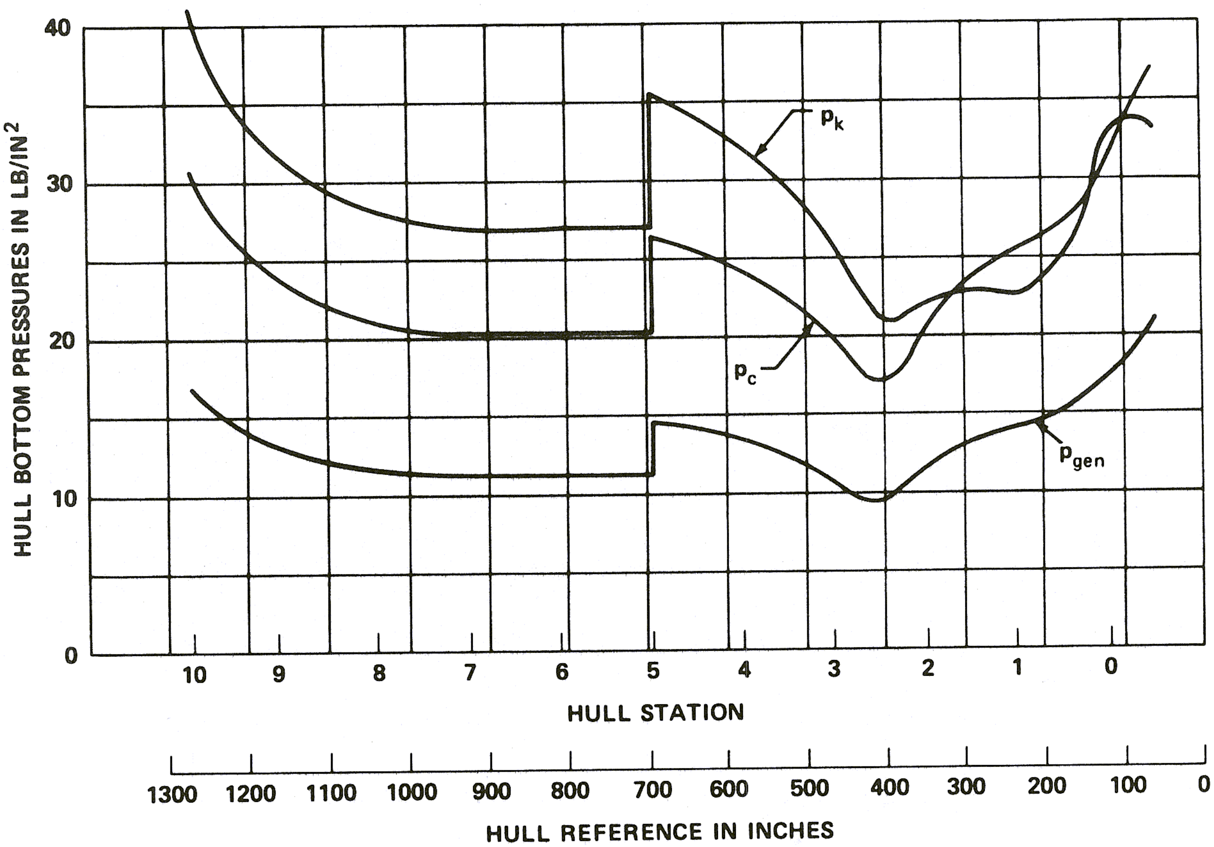

Figure 19 - Hull Bottom Pressures

PG(H)-1, and PG(H)-2. The PC(H)-1 was designed and built by the Boeing Company. The hull bottom impact loads for this boat were assumed to be 30 psi forward and 15 psi aft. The PG(H)-1 was also designed and built by the Boeing Company. Its hull bottom impact loads were assumed to be 30 to 20 psi forward, 74 to 20 psi midship, and 20 to 10 psi aft for the design stress. For ultimate strength, the values were assumed to be 45 to 20 psi forward, 110 to 30 psi midship, and 30 to 15 psi aft, with an assumed safety factor of 1.5 between the design stress and the ultimate strength. The PG(H)-2 was designed and built by the Grumman Aircraft Engineering Corporation; its hull bottom impact loads were assumed to be 30 psi forward and 15 psi aft midship based on the yield stress, 26 psi forward and 13 psi aft midship based on limit stress, and with a safety factor of 1.15 between the two bases of stress.

NSRDC FORMULAS (see Reference 8)

For the smooth-water slamming of a high-speed craft, the pressure acting normal to the hull bottom may be separated into two components: (1) the impact pressure V_v due to the vertical velocity of the craft and (2) the planing pressure V_h due to the longitudinal horizontal velocity of the craft.

For the estimation of vertical impact pressure in the dry-chine region, the following set of equations may be used (from Reference 7 with slight revisions):

$$
\left.
\begin{array}{ll}
\text{1. Flat bottom:} & \\
\text{At and away from keel:} & p_{max} = p_{keel} = 0.443\ \rho\ V_v^{\,2} \\
\text{2. 1-deg effective impact angle:} & \\
\text{At keel:} & p_{keel} = 0.516\ \rho\ V_v^{\,2} \\
\text{Away from keel:} & p_{max} = 0.516\ \rho\ V_v^{\,2} \\
\text{3. 3-deg effective impact angle:} & \\
\text{At keel:} & p_{keel} = \frac{1}{2}\ \rho\ V_v^{\,2}\ \pi\ \cot\ \xi\ (\frac{1}{144}) \\
\text{Away from keel:} & p_{max} = 0.886\ \rho\ V_v^{\,2} \\
\text{4. 6-deg effective impact angle:} & \\
\text{At keel:} & p_{keel} = \frac{1}{2}\ \rho\ V_v^{\,2}\ \pi\ \cot\ \xi\ (\frac{1}{144}) \\
\text{Away from keel:} & p_{max} = 0.385\ \rho\ V_v^{\,2} \\
\text{5. 10-deg effective impact angle:} & \\
\text{At keel:} & p_{keel} = \frac{1}{2}\ \rho\ V_v^{\,2}\ \pi\ \cot\ \xi\ (\frac{1}{144}) \\
\text{Away from keel:} & p_{max} = 0.186\ \rho\ V_v^{\,2} \\
\text{6. 15-deg effective impact angle:} & \\
\text{At keel:} & p_{keel} = \frac{1}{2}\ \rho\ V_v^{\,2}\ \pi\ \cot\ \xi\ (\frac{1}{144}) \\
\text{Away from keel:} & p_{max} = 0.103\ \rho\ V_v^{\,2}
\end{array}
\right\} \quad (9)
$$

7. 20-deg effective impact angle and above:

$$\left.\begin{aligned} &\text{At keel:} && p_{keel} = \frac{1}{2} \rho V_v^2 \pi \cot \xi \left(\frac{1}{144}\right) \\ &\text{Away from keel:} && p_{max} = \frac{1}{2} \rho V_v^2 \left[1 + \frac{\pi^2}{4} \cot^2 \xi\right] \frac{1}{144} \end{aligned}\right\} \quad (9)$$

In the above equation, V_v is given in feet/second, ρ in pounds-seconds^2/feet^4, and p in pounds per square inch. The effective impact angle ξ may be calculated from

$$\tan \xi = \cos \beta_{eh} \tan (\tau + \alpha) + \sin \beta_{eh} \tan \beta_{ev}$$

with β_{eh} and β_{ev} given by

$$\tan \beta_{eh} = \frac{\tan \beta}{\sin \tau + \tan \alpha \cos \tau}$$

$$\tan \beta_{ev} = \frac{\tan \beta}{\cos \tau - \tan \alpha \sin \tau}$$

The pressure distribution on the hull bottom is similar to Wagner formula with p_{max} and p_{keel} given in Equation (9). Since the craft is moving downward in the vertical direction during impact, the location of the maximum pressure p_{max} is moving towards the chine of the craft. As soon as this p_{max} reaches the chine, it has to be dropped to zero pressure (i.e., the atmospheric pressure). The pressure distribution is approximately elliptical with the keel pressure determined by Equation (9).

When the craft hull is planing on the water surface, the planing pressure acting on the hull bottom is

$$\max p_h \text{ (psi)} = \frac{1}{2} \rho V_h^{2} \cos \beta_{eh} \left(\frac{1}{144}\right) \tag{10}$$

with the pressure distribution shown in Figure 20.

Since the tangential pressure is small because nonviscous fluid is assumed, both the impact pressure due to vertical velocity and the planing pressure due to the horizontal velocity are assumed to be normal to the hull bottom. Therefore, the total pressure due to vertical and horizontal velocities is the sum of the impact and planing pressures. This is defined as the total normal pressure p_n which is

$$p_n = p_v + p_h \tag{11}$$

The impact of ship bottom generates the interaction between the ship bottom structure and the fluid. The total impact pressure p_t felt by the ship includes the interacting

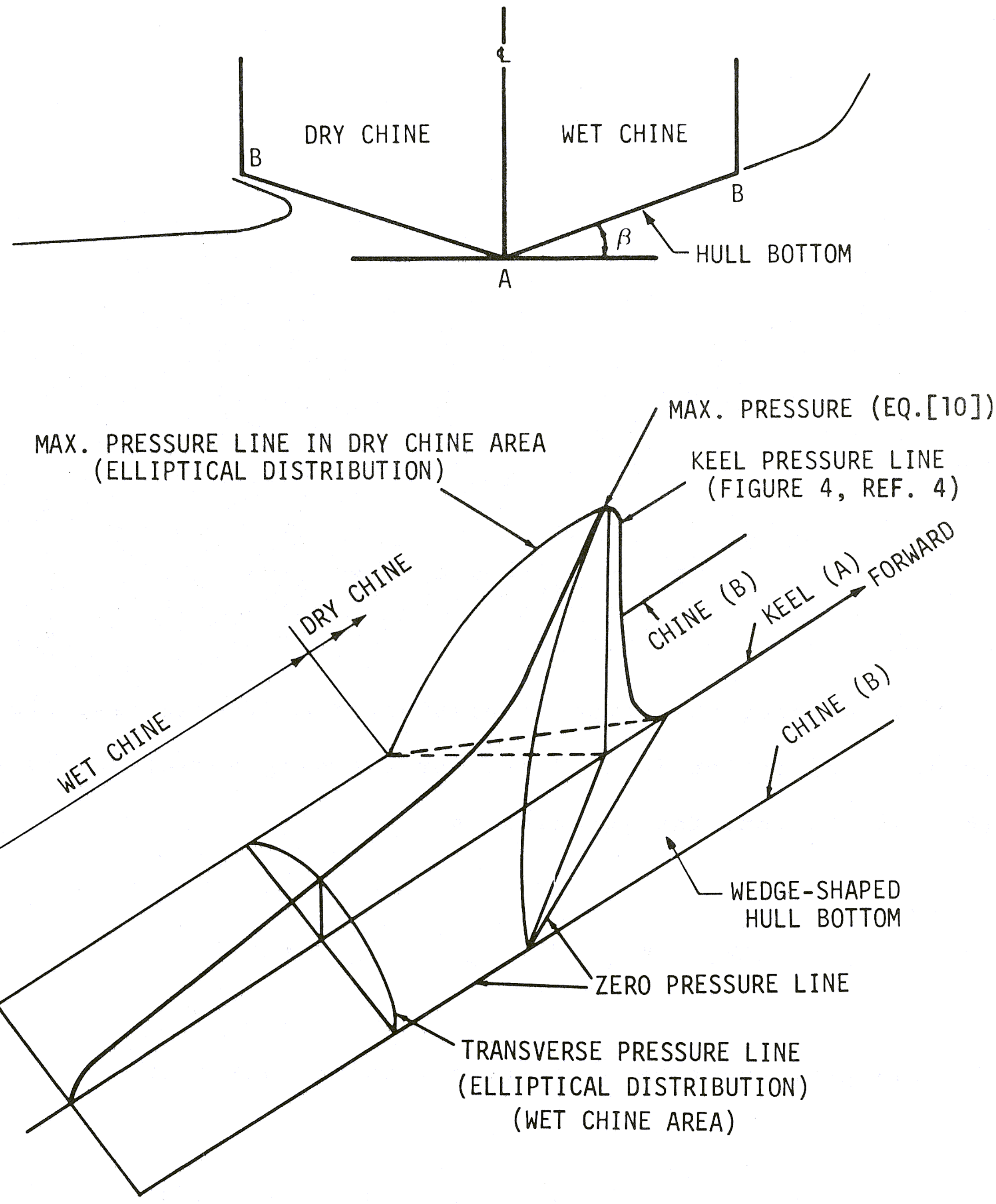

Figure 20 - Planing Pressure Distribution due to Horizontal Velocity Only

pressure p_{i_1} in addition to the rigid body pressure p_r; it may be expressed by

$$p_t = p_r + p_{i_1} \tag{12}$$

where

$$p_r \equiv p_n \tag{13}$$

and

$$p_{i_1} = m_{zz}\,\ddot{w} + c_v\,\dot{w} + k_f\,w \tag{14}$$

In solving this type of problem, the dynamic response equation of motion is needed. For the single plate panel of the hull bottom, the equation is

$$(m_s + m_{zz})\,\ddot{w} + c_v\,\dot{w} + D\,\nabla^4\,w = p_r \tag{15}$$

For the grillage-type ship bottom, the equation is

$$(m_s + m_{zz})\,\ddot{w} + c_v\,\dot{w} + \left[D_x\frac{\partial^4}{\partial x^4} + 2H\,\frac{\partial^4}{\partial x^2 \partial y^2} + D_y\,\frac{\partial^4}{\partial y^4}\right]w = p_r \tag{16}$$

For the ship bottom with thin-plate cylindrical shell, a set of equations is needed, i.e.,

$$\left.\begin{aligned} r \frac{\partial \sigma}{\partial \theta} &= \frac{E}{1 - \nu^2} \ddot{v} \\ \sigma &= -\frac{r}{h} p_t - \frac{E}{1 - \nu^2} \frac{\ddot{w}}{r} \\ \varepsilon &= \left(\frac{\partial v}{\partial \theta} + w\right) \frac{1}{r} \\ \sigma &= \frac{E}{1 - \nu^2} \varepsilon \end{aligned}\right\} \qquad (17)$$

where σ is the shell stress, ε is the strain, w is the radial displacement, v is the tangential displacement, r is the shell radius, and h is the shell thickness.

If the ship bottom is relatively rigid, then for the purpose of design, it may be assumed that a rigid body impact pressure p_r is applied quasi-statically to the ship bottom.[20]

Reference 21 provides a bibliography on slamming.

APPENDIX B

ILLUSTRATION OF METHOD WITH NUMERICAL EXAMPLES

Two numerical examples are given here to illustrate the use of the present method. One is for the FHE-400 hydrofoil craft and the other for the AG(EH)-1 hydrofoil craft.

FHE-400 HYDROFOIL CRAFT

The FHE-400 hydrofoil craft was designed and built by the De Havilland Aircraft Company of Canada. Their design method is given in Appendix A.[18] The assumed design data for this craft are:

<u>Wave Data:</u>

$L_w = 85$ ft

$H = 10.4$ ft

$V_{w_o} = \pi H V_w / L_w = 8.0$ fps

$V_w = \sqrt{\frac{gL_w}{2}} = 20.85$ fps

$\theta = 25.8$ deg max

$\rho = 2$ slug/ft^3 sea water

<u>Craft Data:</u>

$V_h = 34$ fps (= 20 knots)

$V_v = 10$ fps (assumed sinking speed)

$\beta = 27.5$ deg

$\tau' = \tau + \alpha = 10$ deg

The deadrise angles at various stations are plotted in Figure 21. First, assume that the craft is dropped on calm water at the sinking speed of 10 fps without including the forward speed V_h, initial trim τ_o, and buttock angle α. With these assumptions, the maximum impact pressures away from keel and the keel impact pressures can then be calculated from Equation (9). These results are plotted in Figure 22.

Pressures at the forward end are affected by the forward velocity V_h of the craft. Data on trim and buttock angles are needed in order to calculate β_{eh} by Equation (6). However, values of buttock angles are not available at this time without extensive work. The effective planing angle β_{eh} is actually the angle shown on the waterplane of the lines drawing. However, this drawing is not available either. Since β_{eh} is needed for the estimation of the planing pressure p_p, this calculation is therefore omitted.

The pressures are maximum when the craft hits the maximum wave height on the maximum wave slope during its maximum foilborne speed. If it is assumed that there is no sinking speed, the velocities at the point of impact are

$$V_v = o \text{ fps}$$

$$V_h + V_w = 34 + 20.85 = 55 \text{ fps}$$

$$\theta = 25.8 \text{ deg max}$$

By Equation (2), V_n = 23.9 fps and V_t = 49.5 fps. The values of β_{ev} and β_{eh} may be extrapolated from the body plan. At the bow, $\beta_{ev} \approx$ 85 deg, $\beta_{eh} \approx$ 70 deg, and $\xi \approx \beta_{ev}$. Thus $p_i \rightarrow o$. By Equation (10), p_p = 6 psi.

As the wave hits further aft, the planing pressure p_p is diminishing but the impact pressure p_i is increasing considerably. Assume that trim and buttock angles are small at and aft midship section. Then

$$\tan \beta_{ev} = \frac{\tan \beta}{\cos \theta} = \frac{\tan 27.5}{\cos 25.8} = \tan 30^{o}$$

This gives p_i = 36 psi max and p_p = o. These results are also plotted in Figure 22. Also included in Figure 22 is the calculated maximum hull impact pressure given in a final hull structures report for FHE-400 prepared by De Havilland Aircraft of Canada.[22] The assumed operating conditions are (1) maximum heave velocity of 10 fps, (2) maximum pitch velocity at bow foil of ±10 fps, (3) maximum forward velocity of 50 knots (85 fps), and (4) maximum trim angle of 5 deg.

Because a lines drawing is not available for this craft, all the calculated values of angles are interpreted from the body plan. Therefore, these are so rough that they are included only to show how the method can be used when detailed drawings are not available. However, the next example shown contains more detailed calculations.

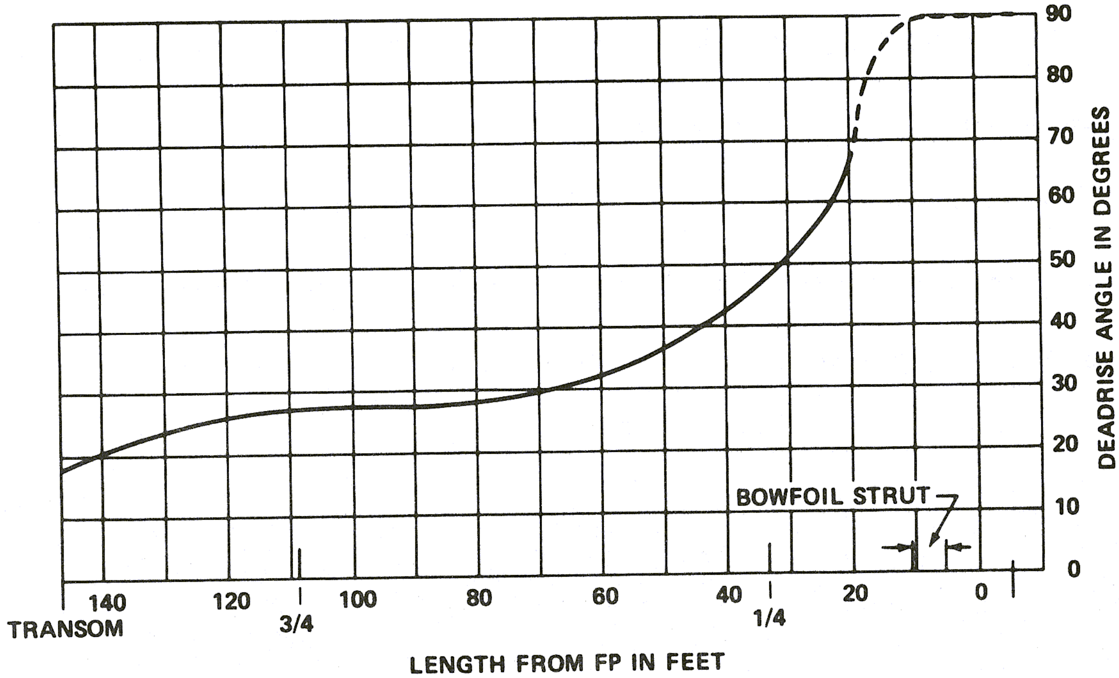

Figure 21 - Deadrise Angles at Various Stations of FHE-400 Hydrofoil Craft

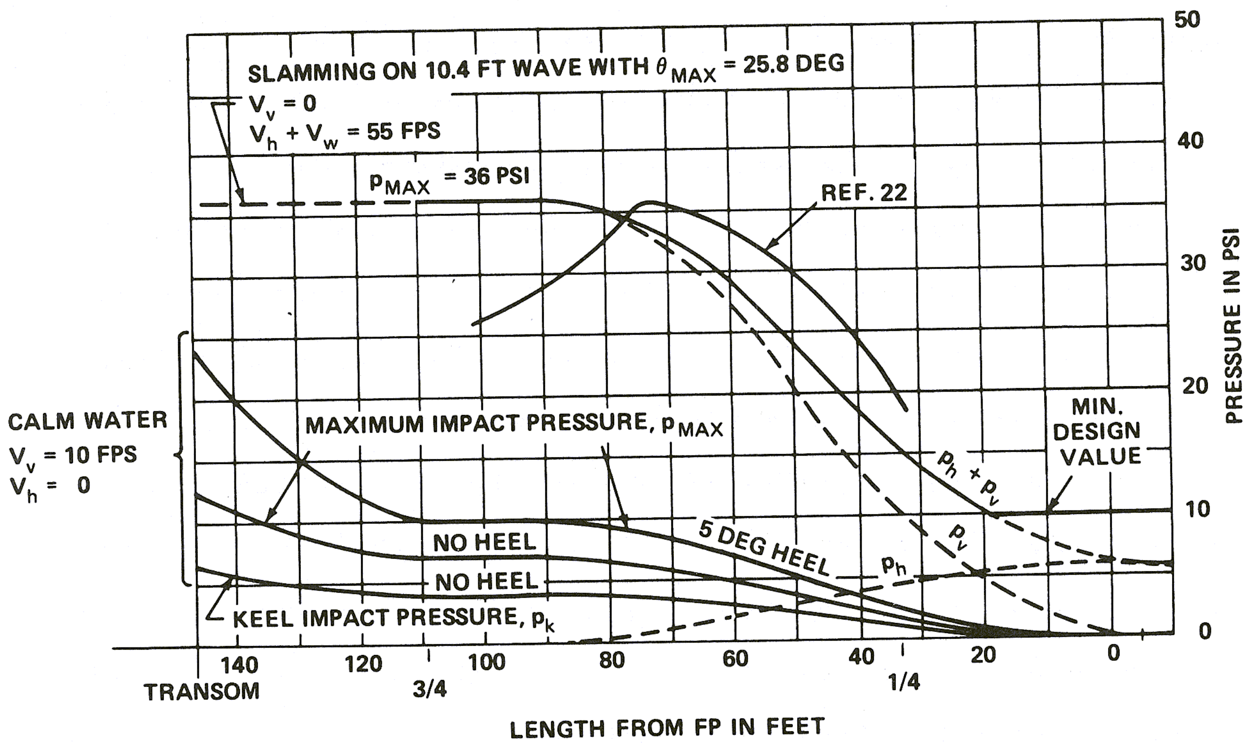

Figure 22 - Bottom Impact Pressure of FHE-400 Hydrofoil Craft with Sinking Speed of 10 FPS

THE AG(EH)-1 HYDROFOIL CRAFT

The assumed design data for this craft are:

Wave Data:

$L_w = 20H - 10H = 640\text{ ft} - 320\text{ ft}$

$H = 32\text{ ft}$

$V_{w_o} = \pi H V_w / L_w = 9.0 - 7.74\text{ fps}$

$V_w = \sqrt{\dfrac{gL_w}{2\pi}} = 57.3 - 40.5\text{ fps}$

$\theta = \pi \dfrac{H}{L_w} = 9 - 18\text{ deg}$

$\rho = 2\text{ slug/ft}^3$ sea water

Craft Data:

$V_h = 90\text{ knots} = 152\text{ fps}$

$V_v = 4\sqrt{s} = 10\text{ fps}$ (sinking speed)

$d_h = 22.73\text{ ft}$

$d_f = 8.00\text{ ft}$

$s = 8.73\text{ ft}$

The deadrise angles β at various stations are plotted in Figure 23, the trim and buttock angles τ, α in Figure 24, and the effective horizontal planing angles in Figure 25. First, assume that the craft drops at a sinking speed of 10 fps without forwarding speed and without including trim and buttock angles. The maximum impact pressures away from the keel can be estimated from Equation (9); the results are plotted in Figure 26.

Consider now that the craft has a 3-deg trim. This time assume that the craft has 10-fps vertical velocity and 152-fps horizontal velocity. The values of trim and buttock angles plotted in Figure 24 are needed for determining β_{ev} and β_{eh}.

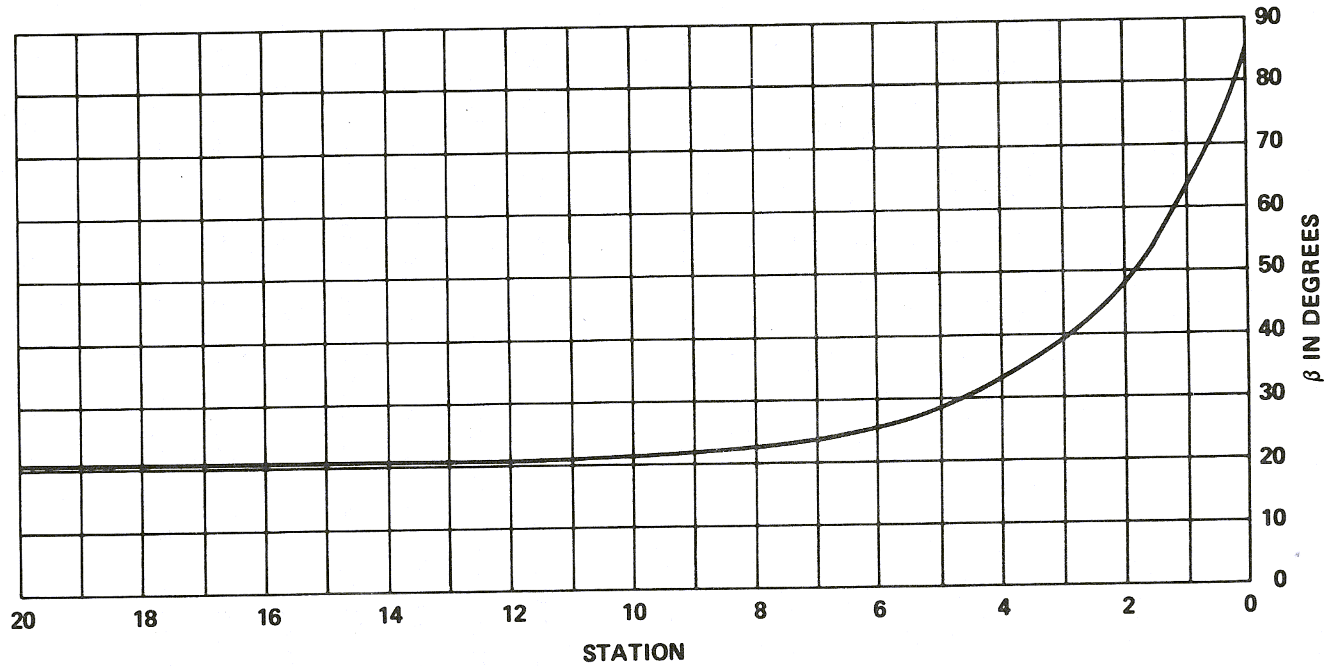

Figure 23 - Deadrise Angles at Various Stations of AG(EH)-1 Hydrofoil Craft

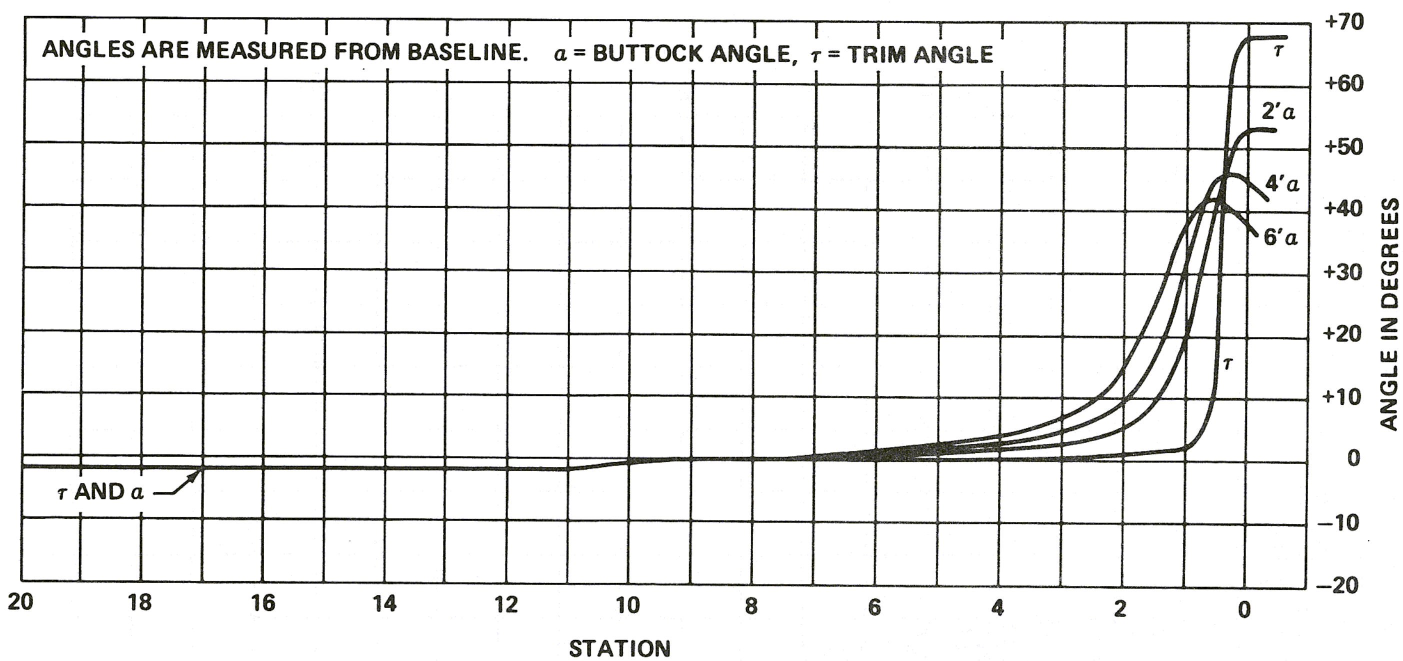

Figure 24 - Trim and Buttock Angles at Various Stations of AG(EH)-1 Hydrofoil Craft

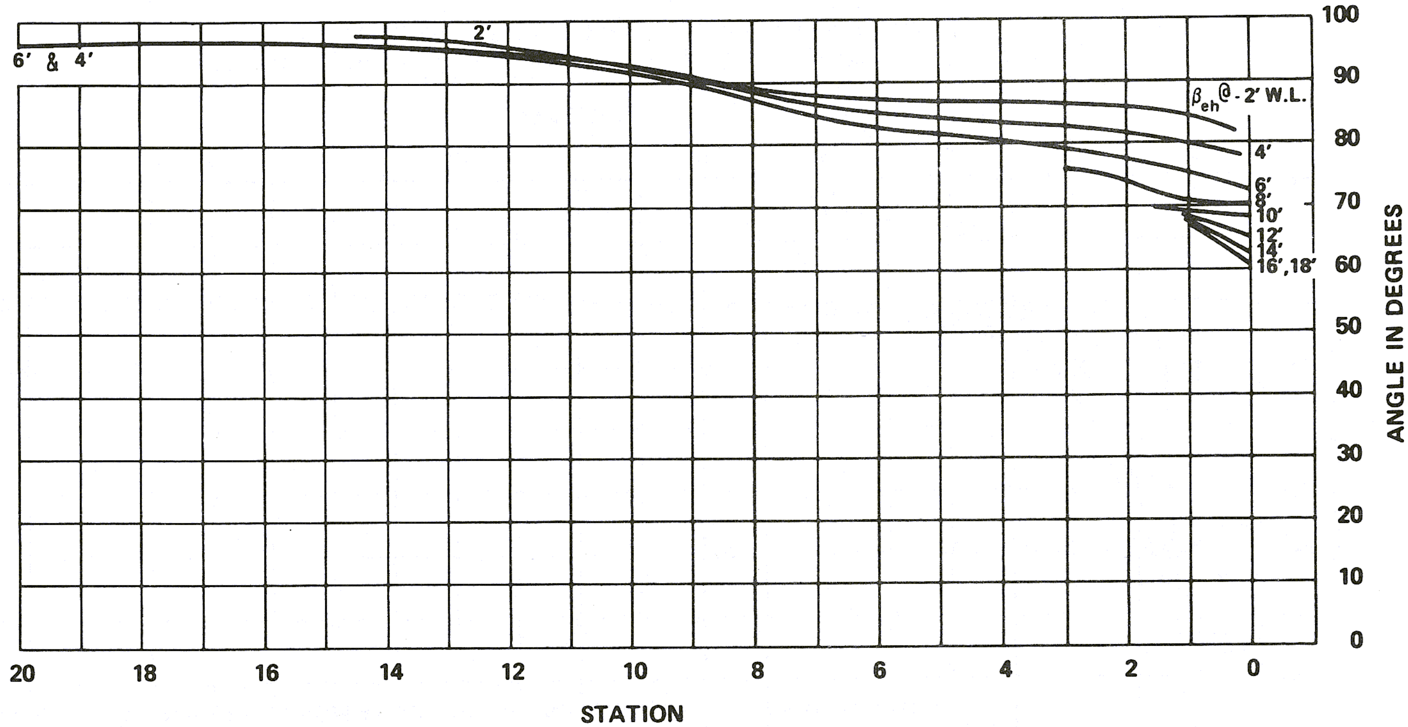

Figure 25 - Effective Horizontal Planing Angles at Various Stations of AG(EH)-1 Hydrofoil Craft

The calculations and results of β_{ev} and β_{eh} are given in Table 4. The calculated p_v, p_h, and p_n are indicated in Table 5. The values of p_n are plotted in Figure 26.

Consider now that the craft has maximum foilborne speed and is hit by a 32-ft wave with a maximum wave slope of 18 deg. Then

$$V_n = (152 + 40.5) \sin 18 \text{ deg} = 59.5 \text{ fps}$$

$$V_t = (152 + 40.5) \cos 18 \text{ deg} = 183 \text{ fps}$$

Values of β_{eh} and β_{ev} may be obtained graphically from the lines drawing or from the equations given in this report. Now, consider only the 6-ft waterline which is about 6 in. below the chine. Values of β_{eh}, β_{ev}, and other calculated values are given in Table 6. Values of p_n are plotted in Figure 26. Similar calculation can be performed in the same manner for other portions of the hull bottom.

TABLE 4

Calculations of β_{eh} and β_{ev} for Calm Water Slamming

Station	τ deg	β, deg			α, deg			tan β			tan α			β_{eh}, deg			β_{ev}, deg		
		2	4	6	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
		ft off centerline																	
0	3	69	60	52	53	45	37	2.605	1.732	1.280	1.327	1	0.754	62	59	56	70.8	61.4	53.2
1/2		71	66	61	43	45	42	2.904	2.246	1.804	0.933	1	0.900	71.5	65	62	71.9	67.2	62.2
1		63			20	33	38	1.963			0.364	0.649	0.781	77	70.5	67	63.5	63.8	64
2		48			5	10	15	1.111			0.088	0.176	0.268	82.8	78.5	74	48.2	48.4	48.5
3		39			2.5	5	7	0.810			0.044	0.088	0.123	83.2	80	78	39		
4		33			1.5	3	4	0.649			0.026	0.052	0.070	83	81	79	33		
5		28.5			1	2	3	0.543			0.018	0.035	0.052	82.5	81	79	28.5		
6		26			1	1	1.5	0.488			0.018	0.018	0.026	81.8	81.8	81	26		
7		24			1			0.445			0.018			81.8			24		
8		23			0			0.425			0			83			23		
9		22			-1			0.404			0			83.6			22		
10		21.5			-2			0.394			-0.018			84.9			21.5		
11		21.2						0.389			-0.035			87.5			21.2		
12		21						0.384						87.4					
13																			
14																			
15																			
16																			
17																			
18																			
19																			
20																			

Note: $\tan \beta_{eh} = \dfrac{\tan \beta}{\sin \tau + \tan \alpha \cos \tau}$

$\tan \beta_{ev} = \dfrac{\tan \beta}{\cos \tau - \tan \alpha \sin \tau}$

with $\sin 3^\circ = 0.0523$, $\cos 3^\circ = 0.9986$

TABLE 5

Calculations of ξ, p_i, p_p and p_n for Calm Water Slamming

Station	$(\tau+\alpha)$, deg			$\tan(\tau+\alpha)$			$\cos \beta_{eh}$			$\sin \beta_{eh}$			$\tan \beta_{ev}$			$\cos \beta_{eh} \tan(\tau+\alpha)$		
	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
	ft off centerline																	
0	56	48	40	1.483	1.111	0.839	0.469	0.515	0.559	0.883	0.857	0.829	2.87	1.83	1.335	0.696	0.572	0.468
1/2	46	48	45	1.036	1.111	1.000	0.317	0.423	0.469	0.948	0.906	0.883	3.06	2.37	1.9	0.328	0.470	0.469
1	23	36	41	0.424	0.727	0.869	0.225	0.334	0.391	0.974	0.943	0.921	2.01	2.03	2.05	0.095	0.243	0.340
2	8	13	18	0.141	0.231	0.325	0.125	0.199	0.276	0.992	0.980	0.961	1.12	1.125	1.13	0.018	0.046	0.090
3	5.5	8	10	0.096	0.141	0.176	0.119	0.165	0.208	0.993	0.985	0.978		0.81		0.011	0.023	0.037
4	4.5	6	7	0.079	0.105	0.123	0.122	0.156	0.191	0.993	0.988	0.982		0.65		0.010	0.016	0.024
5	4	5	6	0.070	0.088	0.105	0.131	0.156	0.191	0.991	0.988	0.982		0.55		0.009	0.014	0.020
6	4	4	4.5	0.070	0.070	0.079	0.142	0.142	0.156	0.990	0.990	0.988		0.49		0.010	0.010	0.012
7		4			0.070			0.153			0.988			0.45			0.011	
8		3			0.052			0.122			0.993			0.43			0.006	
9		2			0.052			0.113			0.992			0.41			0.005	
10		1			0.035			0.090			0.996			0.40			0.003	
11					0.018			0.044			0.999			0.39			0.0008	
12																		
13																		
14																		
15																		
16																		
17																		
18																		
19																		
20																		

TABLE 5 (contd.)

Station	$\sin\beta_{eh}\tan\beta_{ev}$			$\tan\xi$			ξ, deg			p_p, psi			p_i, psi			p_n, psi			Buttock Ht. abv ℄		
	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
	ft off centerline																				
0	2.530	1.567	1.107	3.226	2.139	1.575	72.8	64.9	57.6	73.5	82.5	89.5	2	2	2	75.5	84.5	91.5	13-10-1	18- 1-4	21- 0-7
1/2	2.900	2.145	1.675	3.228	2.615	2.144	72.8	69.1	65.0	50.8	67.7	75	2	2	2	52.8	69.7	77	7- 9-2	12- 9-5	16- 8-3
1	1.960	1.912	1.889	2.055	2.155	2.229	64.0	65.1	65.8	36	53.5	62.6	2	2	2	38	55.5	64.6	4- 3-6	8- 4-1	12- 3-1
2	1.110	1.100	1.086	1.128	1.146	1.176	48.2	48.9	49.6	20	31.9	44.2	2	2	2	22	33.9	46.2	2- 3-4	4- 5-7	6- 8-1
3	0.805	0.797	0.791	0.816	0.820	0.828	39.2	39.3	39.6	19.1	26.4	33.3	3	3	3	22.1	29.4	36.3	1- 7-4	3- 2-5	4- 9-7
4	0.645	0.641	0.639	0.655	0.657	0.663	33.2	33.3	33.5	19.5	25	30.6	4	4	4	23.5	29	34.6	1- 3-3	2- 6-6	3-10-1
5	0.545	0.544	0.540	0.554	0.558	0.560	29.0	29.1	29.2	20.9	25	30.6	6	6	6	26.9	31	36.6	1- 1-0	2- 2-0	3- 3-0
6	0.485	0.485	0.484	0.495	0.495	0.496		26.3		22.7	22.7	25		7		29.7	29.7	32.0	0-11-4	1-11-0	2-10-4
7		0.445			0.456			24.5			24.3			8			32.3		0-10-4	1- 9-0	2- 7-4
8		0.427			0.433			23.4			19.5			9			28.5		0-10-0	1- 8-0	2- 6-0
9		0.407			0.412			22.5			18.0			10			28		0-10-3	1- 8-1	2- 6-0
10		0.399			0.402			21.9			14.4			11			25.4		1- 0-0	1- 9-6	2- 7-3
11		0.389			0.390			21.3			7.0			11.5			18.5		1- 3-4	2- 1-0	2-10-4
12																			1- 8-0	2- 5-2	3- 2-4
13																			2- 1-1	2-10-1	3- 7-3
14																			2- 6-2	3- 3-2	4- 0-2
15																			2-11-5	3- 8-5	4- 5-5
16																			3- 4-7	4- 1-7	4-10-7
17																			3-10-0	4- 7-1	5- 4-1
18																			4- 3-3	5- 0-3	5- 9-3
19																			4- 8-5	5- 5-5	6- 2-6
20																			5- 1-7	5-10-7	7- 4-2

ft-in-$\frac{1}{8}$ in

Note: $\tan\xi = \cos\beta_{eh}\tan(\tau + \alpha) + \sin\beta_{eh}\tan\beta_{ev}$

Max $p_i = f(\xi)$, Equation [9]

Max $p_p = \frac{1}{2}\rho V_h^2 \cos\beta_{eh}$

$= \frac{152^2}{144}\cos\beta_{eh}$

$= 160 \cos\beta_{eh}$

TABLE 6

Calculations of β_{eh}, β_{ev}, ξ, p_i, p_p, and p_n for Craft Slamming on Wave at 6-Foot Waterline

Station	β deg	$\tau+\alpha$ deg	tan β	tan $(\tau_o+\alpha)$	0.951 tan $(\tau_o+\alpha)$	-0.309 + 0.951 tan $(\tau_o+\alpha)$	tan β_{eh}	β_{eh} deg	0.309 tan $(\tau_o+\alpha)$	0.951 + 0.309 tan $(\tau_o+\alpha)$	tan β_{ev}
0	81	68	6.31	2.475	2.35	2.041	3.1	72.1	0.763	1.714	3.69
1/2	73	40	3.27	0.839	0.797	0.488	6.7	81.5	0.256	1.207	2.71
1	63.5	25.5	2.006	0.477	0.454	0.145	13.84	85.86	0.1472	1.0982	1.828
2	48	13.7	1.111	0.244	0.232	-0.077	-14.45	180-86.14	0.0753	1.0263	1.084
3	39	8.5	0.810	0.1494	0.142	-0.167	-4.85	↓ -78.33	0.0461	0.9971	0.812
4	32.5	6.6	0.637	0.1157	0.110	-0.199	-3.21	↓ -72.7	0.0357	0.9867	0.647
5	28.5	4.8	0.543	0.0836	0.0795	-0.22	-2.47	↓ -67.95	0.0258	0.9768	0.556
6	25.5	3.6	0.477	0.0628	0.0597	-0.25	-1.91	↓ -62.35	0.0194	0.9704	0.492
7	24	1	0.445	0.0175	0.0166	-0.292	-1.52	↓ -56.6	0.0054	0.956	0.465
8	23	0	0.424	0	0	-0.309	-1.37	↓ -53.85	0	0.951	0.445
9	22	0	0.404	0	0	-0.309	-1.308	↓ -52.6	0	0.951	0.425
10	21.5	-1	0.394	-0.0175	-0.0166	-0.326	-1.208	↓ -50.4	-0.0054	0.946	0.416
11	21.2	-2	0.389	-0.0349	-0.0332	-0.342	-1.135	↓ -48.6	-0.0108	0.940	0.414
12	21	↓	0.384	↓	↓	↓	-1.123	↓ -48.3	↓	↓	0.409
13	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
14	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
15	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
16	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
17	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
18	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
19	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓
20	↓	↓	↓	↓	↓	↓	↓	↓ ↓	↓	↓	↓

TABLE 6 (contd.)

Station	β_{ev} deg	$(\tau_o+\alpha-\theta)$ deg	tan $(\tau_o+\alpha-\theta)$	cos β_{ev} tan $(\tau_o+\alpha-\theta)$	sin β_{eh} tan β_{ev}	tan ξ	ξ deg	p_i psi	p_p psi	p_n psi
0	74.82	58	1.6	0.492	3.51	4.002	75.8	30	72	102
1/2	69.76	22	0.404	0.057	2.68	2.737	69.7	32	40	72
1	61.3	7.5	0.1317	0.010	1.821	1.831	61	41	17	58
2	47.3	-4.3	-0.075	0.005	1.082	1.087	47	75	-16	59
3	39.1	-9.5	-0.1675	0.034	0.795	0.829	40	120	-47	73
4	32.9	-11.4	-0.202	0.060	0.615	0.675	34.4	160	-69	91
5	29.1	-13.2	-0.235	0.088	0.513	0.601	31.4	200	-88	112
6	26.2	-14.4	-0.257	0.119	0.436	0.555	29.35	220	-107	113
7	24.9	-17.0	-0.306	0.168	0.388	0.556	29.4		-127	93
8	24	-18	-0.325	0.192	0.359	0.551	29.2		-136	84
9	23	-18	-0.325	0.197	0.338	0.535	28.5		-140	80
10	22.6	-19	-0.3445	0.220	0.320	0.540	28.7		-147	73
11	22.4	-20	-0.364	0.240	0.310	0.550	29.1		-152	68
12	22.2			0.242	0.306	0.548	29.0		-153	67
13										
14										
15										
16										
17										
18										
19										
20										

TABLE 6 (contd.)

Note:

$$\tan \beta_{eh} = \frac{\tan \beta}{\sin (\tau - \theta) + \tan \alpha \cos (\tau - \theta)}$$

$$= \frac{\tan \beta}{\sin (-18°) + \tan (\tau_o + \alpha) \cos (-18°)}$$

$$= \frac{\tan \beta}{-0.309 + 0.951 \tan (\tau_o + \alpha)}$$

$$\tan \beta_{ev} = \frac{\tan \beta}{\cos (\tau - \theta) - \tan \alpha \sin (\tau - \theta)}$$

$$= \frac{\tan \beta}{0.951 + 0.309 \tan (\tau + \alpha)}$$

$$\tan \xi = \cos \beta_{eh} \tan (\tau_o + \alpha - \theta) + \sin \beta_{eh} \tan \beta_{ev}$$

$$p_i = f(\xi, v_n), \; v_n = 59.5 \text{ fps}$$

$$p_p = \frac{1}{2} \rho v_t^2 \cos \beta_{eh} = \frac{183^2}{144} \cos \beta_{eh} = 233 \cos \beta_{eh}$$

Quadrant	Deg	SIN	COS	TAN	Trim Fwd (Figure 3)	Trim Aft (Figure 4)
I	0-90	+	+	+	All angles	β_{ev}, ξ
II	90-180	+	-	-		β_{eh}
III	-(90-180)	-	-	+		
IV	-(0-90)	-	+	-		$(\tau + \alpha - \theta)$

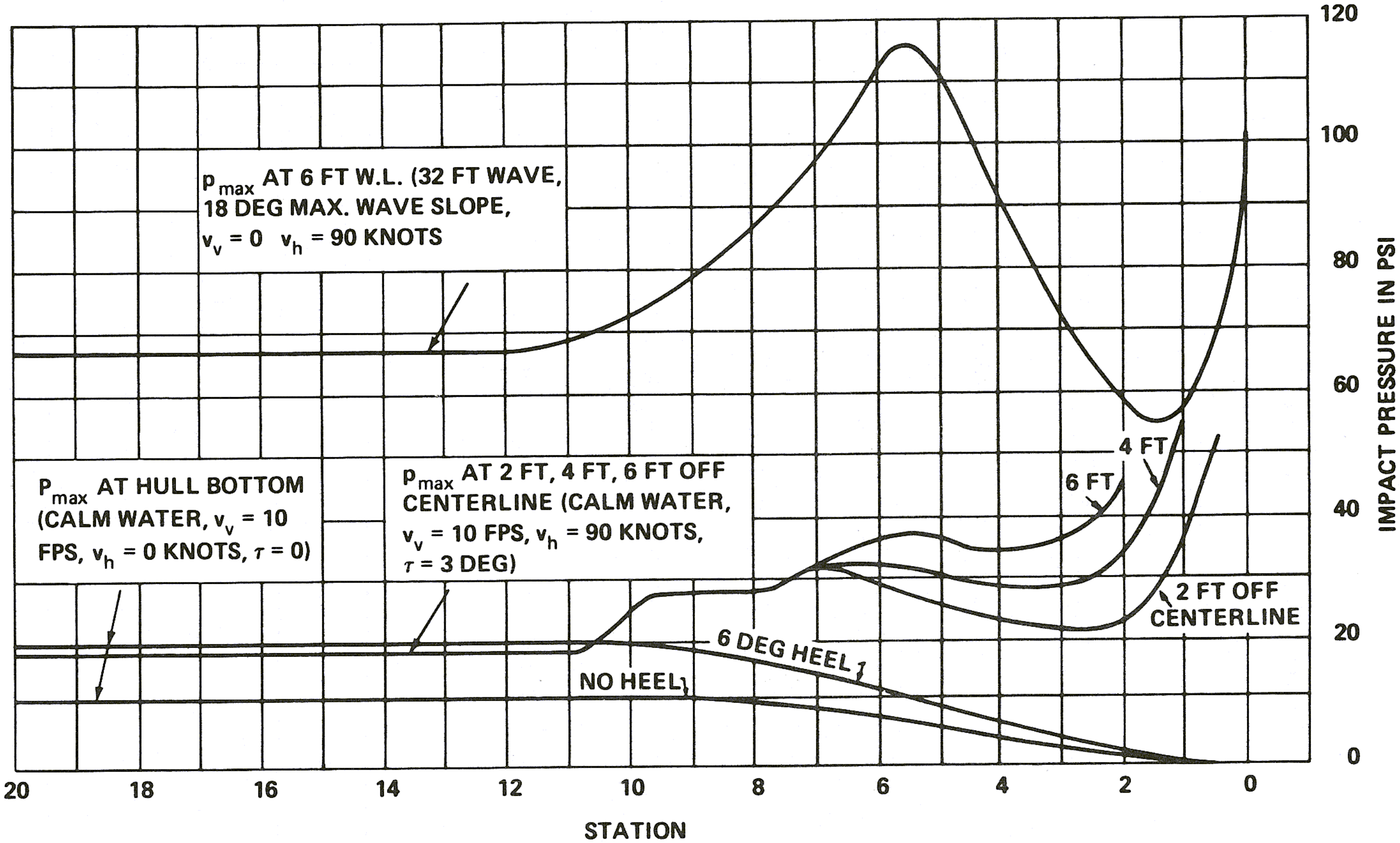

Figure 26 - Bottom Impact Pressure of AG(EH)-1 Hydrofoil Craft

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