Design for the Ocean Environment

Some Major Considerations

- Hydrostatic pressure
- Heat dissipation in housings
- Waves
- Forces on bodies in steady flow

- *But don’t forget:*

  wind and rain, corrosion, biofouling, material fatigue, creep, chemical breakdown, human safety, regulations, etc.

	Young's Modulus, Pascals	Ultimate Strength, Pascals	Coefficient of thermal conductivity, W m / m^2 ^oK	Density, kg/m^3
Steel	200e9	550e6	4400	8000
Aluminum	70e9	480e6	22000	2700
Titanium	100e9	1400e6	1500	4900
Glass	70e9	<35000e6 (compression!)	100	2600
ABS Plastic	1.3e9	34e6	LOW	~1100
Mineral oil		-	17	~900
Water	2.3e9	-	60	1000

Wave Fields

Definition:

SeaState	Height (ft)	Period (s)	Wind (knots)
2	1	7	9
3	3	8	14
4	6	9	19
5	11	10	24
6	16	12	37
7	25	15	51

Wave height $\overline{H}_{1/3}$
Significant wave: Average of one-third highest waves

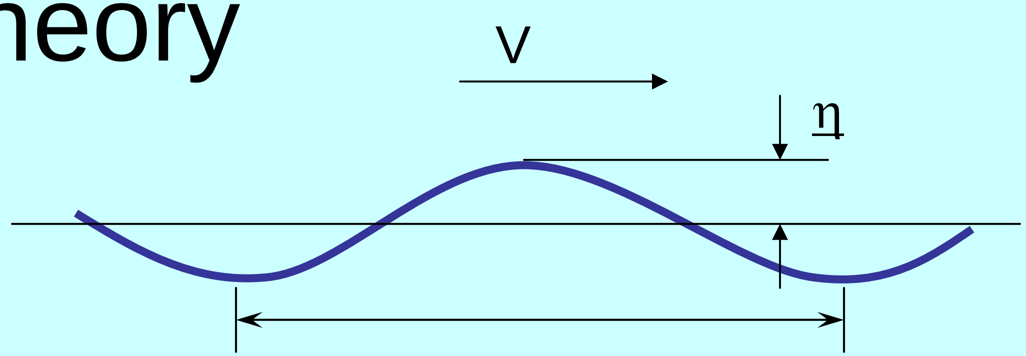
Distribution:

30% of world oceans are at	0-1m height
41%	1-2m
17%	2-3m
6%	3-4m
2%	4-5m

Wave fields depend on storms, fetch, topography

Linear Wave Theory

(deepwater)



Wave elevation:

$\eta = \underline{\eta}$ **cos(** ω **t – k x)** where

$\underline{\eta}$ is amplitude

ω is frequency in rad/s : period $T = 2\pi/\omega$

k is wavenumber in rad/m : wavelength $\lambda = 2\pi/k$

Dispersion Relation: $\mathbf{k = \omega^2 / g}$

Wave speed: $\mathbf{V = \omega / k}$

Particle velocities: $\mathbf{u = k \underline{\eta} V e^{-kz} \cos(\omega t - k x)}$

$\mathbf{w = k \underline{\eta} V e^{-kz} \sin(\omega t - k x)}$ where z is depth

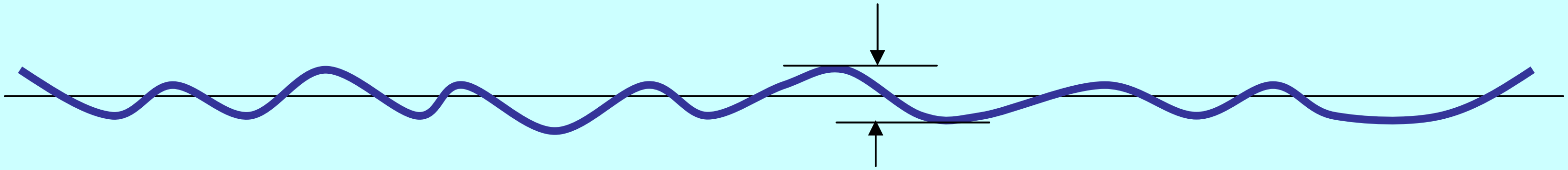
Fluctuating pressure: $\mathbf{p = \rho \underline{\eta} g e^{-kz} \cos(\omega t - k x)}$

Short-Term Statistics of Extreme Waves

- Average of one-third highest waves is significant wave height H_{sig} or $\bar{H}_{1/3} = 4\,\sigma$
- An observer will usually report $\bar{H}_{1/3}$
- $\bar{H}_{1/10} = 1.27 * H_{sig}$
- Expected maxima: $N = 100$; $1.6 * \bar{H}_{1/3}$

  $N = 1000$; $1.9 * \bar{H}_{1/3}$

  $N = 10000$; $2.2 * \bar{H}_{1/3}$



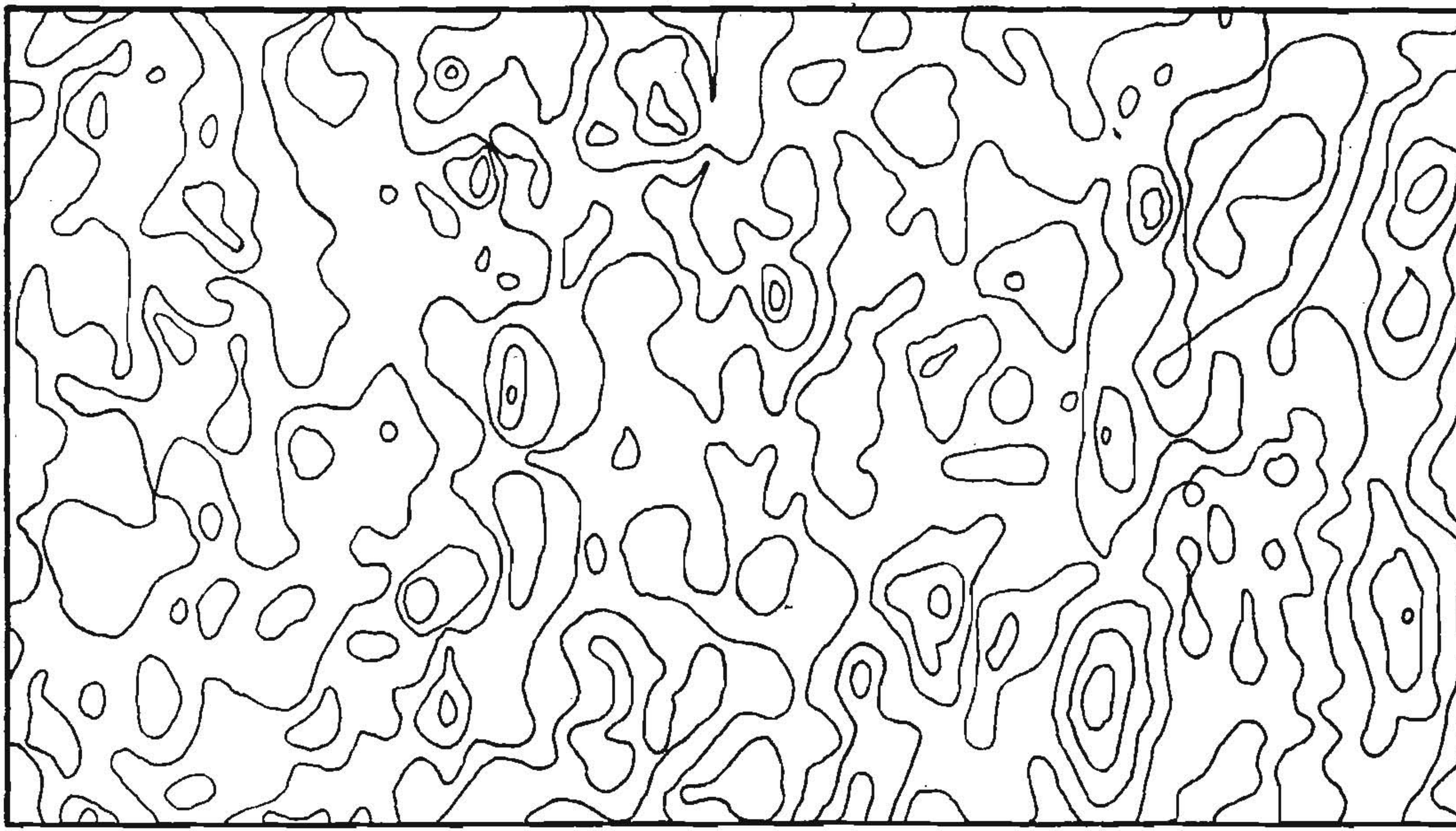


Fig. 22 Typical contour plot of the sea—from stereo photos

Principles of Naval Architecture, E.V. Lewis, ed., SNAME, 1989.

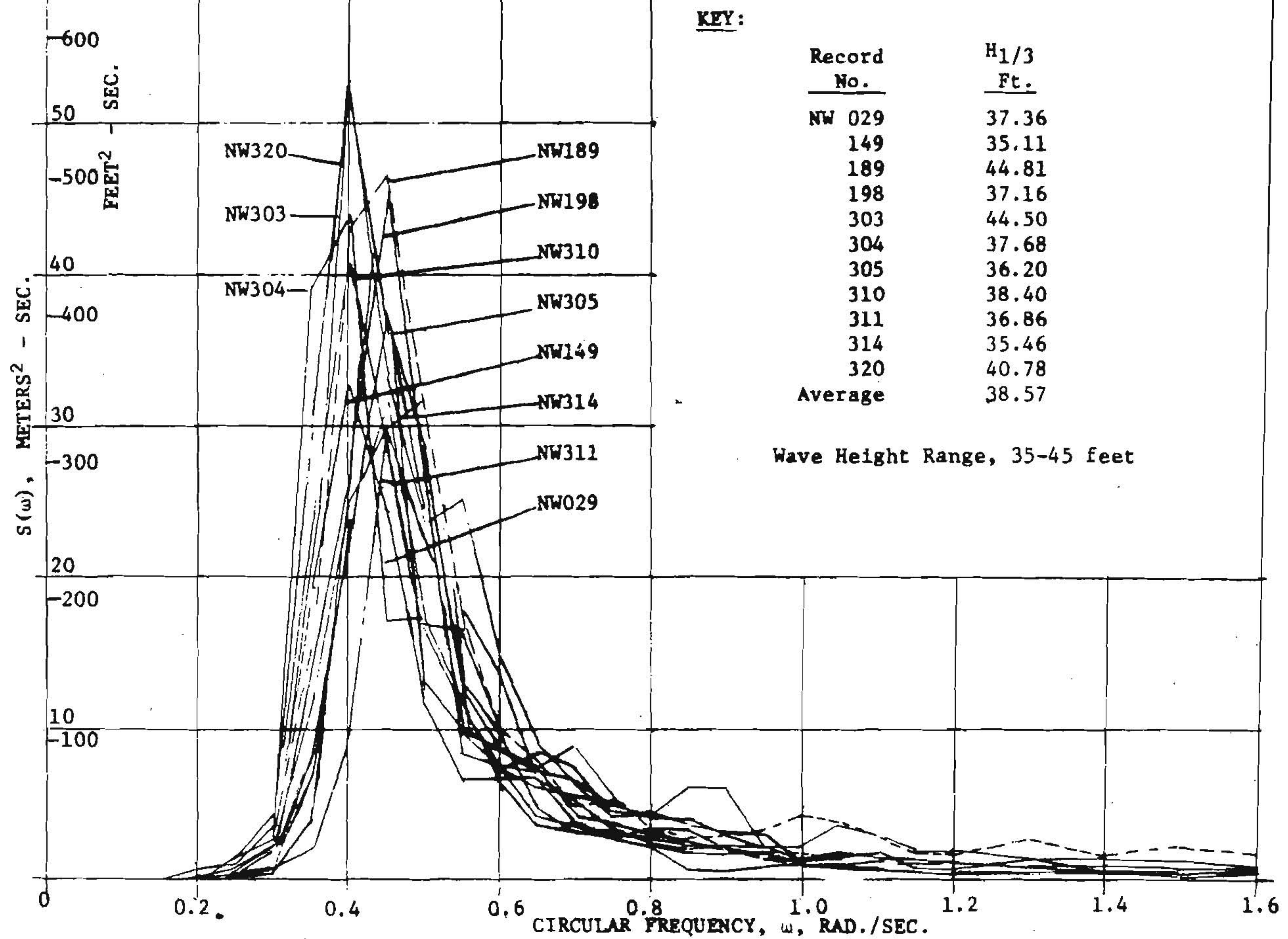


Fig. 23b Typical families of wave spectra significant wave height range of 10.7-13.7 m (35-45 ft) (Hoffman and Miles, 1976)

Principles of Naval Architecture, E.V. Lewis, ed., SNAME, 1989.

Table 6—Annual Sea-State Occurrences in the Open Ocean, North Atlantic

Sea State Number	Significant Wave Height (m)		Significant Wave Height (ft)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean	Range	Mean		Range**	Most Probable***
0-1	0-0.1	0.05	0-0.3	0.15	0-6	3	0.70	—	—
2	0.1-0.5	0.3	0.3-1.6	1.0	7-10	8.5	6.80	3.3-12.8	7.5
3	0.5-1.25	0.88	1.6-4.1	2.9	11-16	13.5	23.70	5.0-14.8	7.5
4	1.25-2.5	1.88	4.1-8.2	6.2	17-21	19	27.80	6.1-15.2	8.8
5	2.5-4	3.25	8.2-13.1	10.7	22-27	24.5	20.64	8.3-15.5	9.7
6	4-6	5	13.1-19.7	16.4	28-47	37.5	13.15	9.8-16.2	12.4
7	6-9	7.5	19.7-29.5	24.6	48-55	51.5	6.05	11.8-18.5	15.0
8	9-14	11.5	29.5-45.9	37.7	56-63	59.5	1.11	14.2-18.6	16.4
>8	>14	>14	>45.9	45.9	>63	>63	0.05	18.0-23.7	20.0

Table 7—Annual Sea State Occurrences in the Open Ocean, North Pacific

Sea State Number	Significant Wave Height (m)		Significant Wave Height (ft)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean	Range	Mean		Range**	Most Probable***
0-1	0-0.1	0.05	3-0.3	0.15	0-6	3	1.30	—	—
2	0.1-0.5	0.3	0.3-1.6	1.0	7-10	8.5	6.40	5.1-14.9	6.3
3	0.5-1.25	0.88	1.6-4.1	2.9	11-16	13.5	15.50	5.3-16.1	7.5
4	1.25-2.5	1.88	4.1-8.2	6.2	17-21	19	31.60	6.1-17.2	8.8
5	2.5-4	3.25	8.2-13.1	10.7	22-27	24.5	20.94	7.7-17.8	9.7
6	4-6	5	13.1-19.7	16.4	28-47	37.5	15.03	10.0-18.7	12.4
7	6-9	7.5	19.7-29.5	24.6	48-55	51.5	7.60	11.7-19.8	15.0
8	9-14	11.5	29.5-45.9	37.7	56-63	59.5	1.56	14.5-21.5	16.4
>8	>14	>14	>45.9	45.9	>63	>63	0.07	16.4-22.5	20.0

* Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$

** Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

*** Based on periods associated with central frequencies included in Hindcast Climatology.

Source: Lee and Bales (1984).

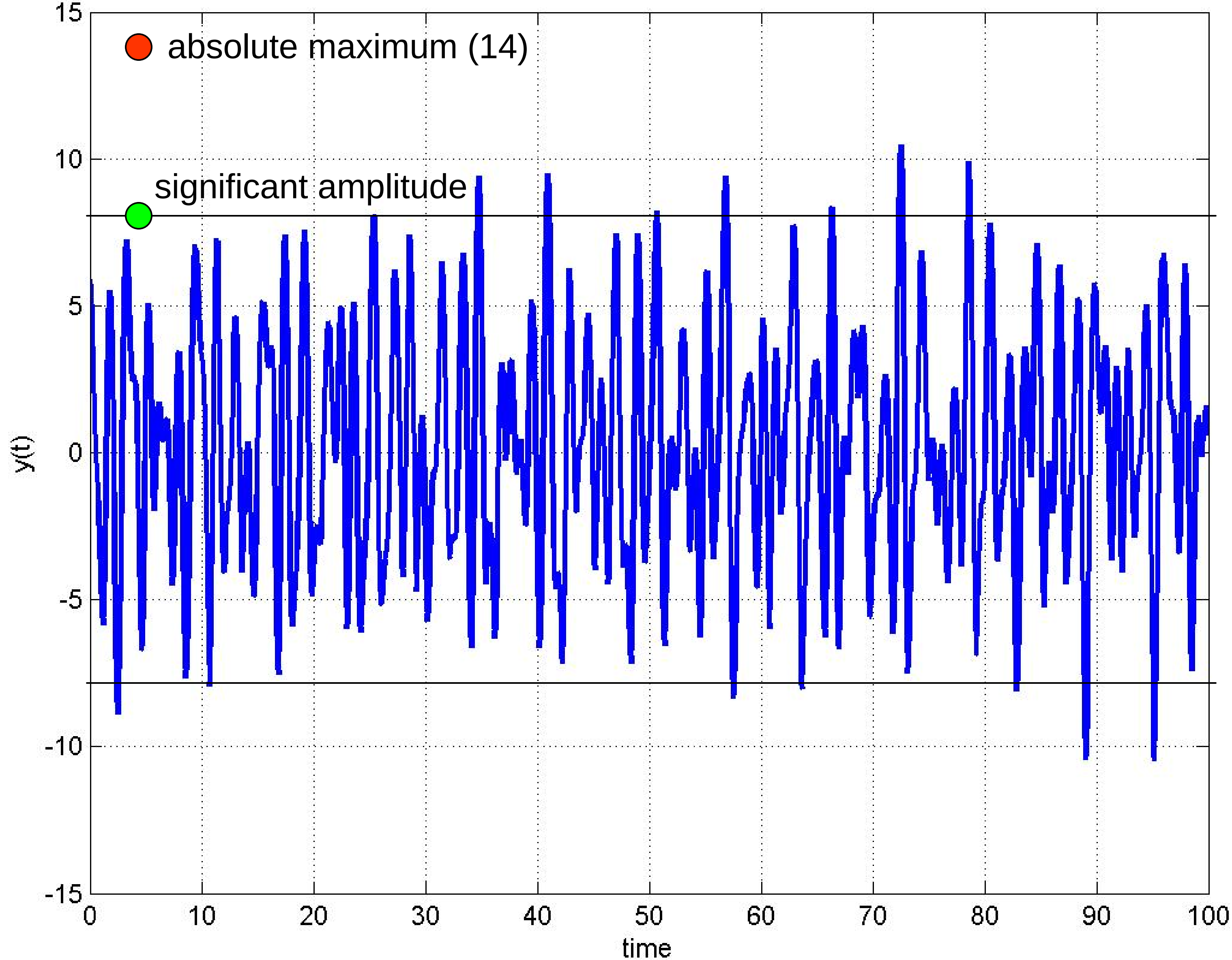
Principles of Naval Architecture, E.V. Lewis, ed., SNAME, 1989.

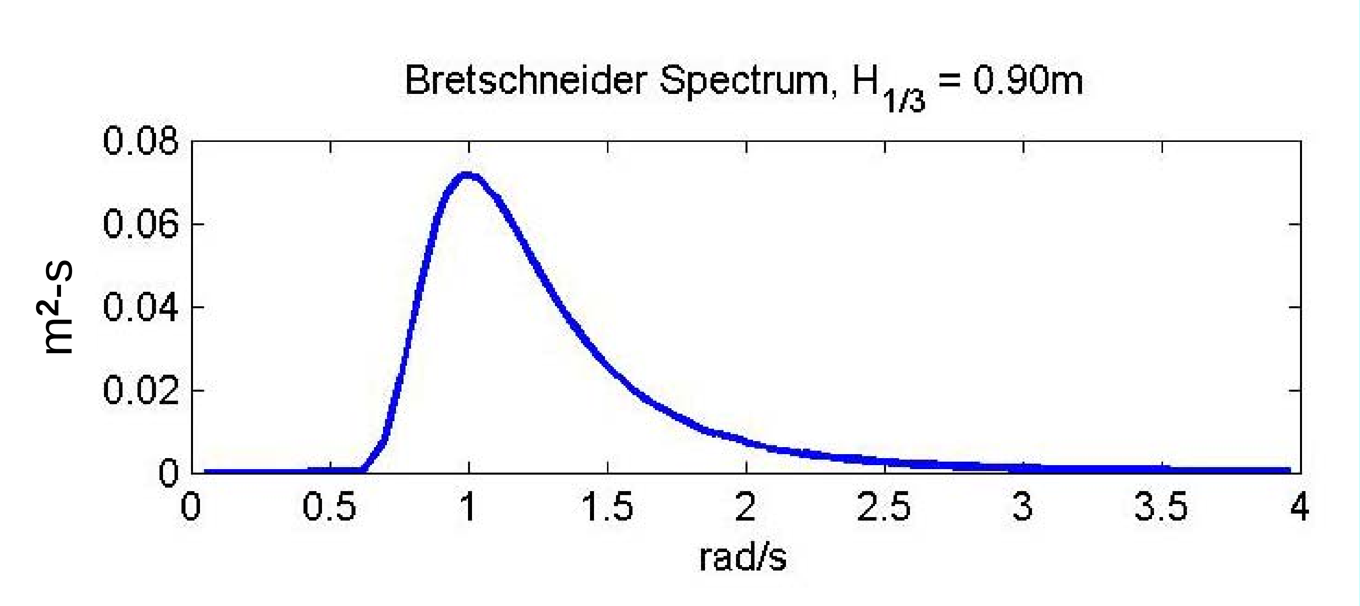
Table 5—Observed Percentage Frequency of Occurrence of Wave Heights and Periods (Hogben and Lumb data)
Northern North Atlantic

Wave height, m	Wave Period T_1, sec 2.5	6.5	8.5	10.5	12.5	14.5	16.5	18.5	20.5	Over 21	Total
0-1	13.7204	3.4934	0.8559	0.3301	0.1127	0.0438	0.0249	0.0172	0.0723	0.3584	19.0291
1-2	11.4889	15.5036	6.4817	1.8618	0.5807	0.1883	0.0671	0.0254	0.0203	0.0763	36.2941
2-3	1.5944	7.8562	8.0854	3.7270	1.1790	0.3713	0.1002	0.0321	0.0091	0.0082	22.9629
3-4	0.3244	2.2487	4.0393	2.9762	1.3536	0.4477	0.1307	0.0428	0.0050	0.0040	11.5724
4-5	0.1027	0.7838	1.6998	1.5882	0.9084	0.3574	0.1443	0.0433	0.0072	0.0049	5.6400
5-6	0.0263	0.1456	0.3749	0.4038	0.2493	0.1200	0.0382	0.0067	0.0027	0.0027	1.3702
6-7	0.0277	0.1477	0.3614	0.4472	0.2804	0.1301	0.0504	0.0113	0.0011	0.0032	1.4605
7-8	0.0084	0.0714	0.1882	0.2199	0.1634	0.0785	0.0353	0.0069	0.0018	0.0034	0.7772
8-9	0.0037	0.0325	0.0856	0.1252	0.1119	0.0558	0.0303	0.0045	0.0027	0.0033	0.4555
9-10	0.0034	0.0204	0.0674	0.1173	0.0983	0.0550	0.0303	0.0173	0.0079	0.0047	0.4220
10-11		0.0005	0.0012	0.0023	0.0031	0.0012		0.0005			0.0088
11+		0.0005	0.0007	0.0019	0.0035	0.0002			0.0005		0.0073
Totals	27.3003	30.3043	22.2415	11.8009	5.0143	1.8493	0.6517	0.2080	0.1306	0.4691	100.000

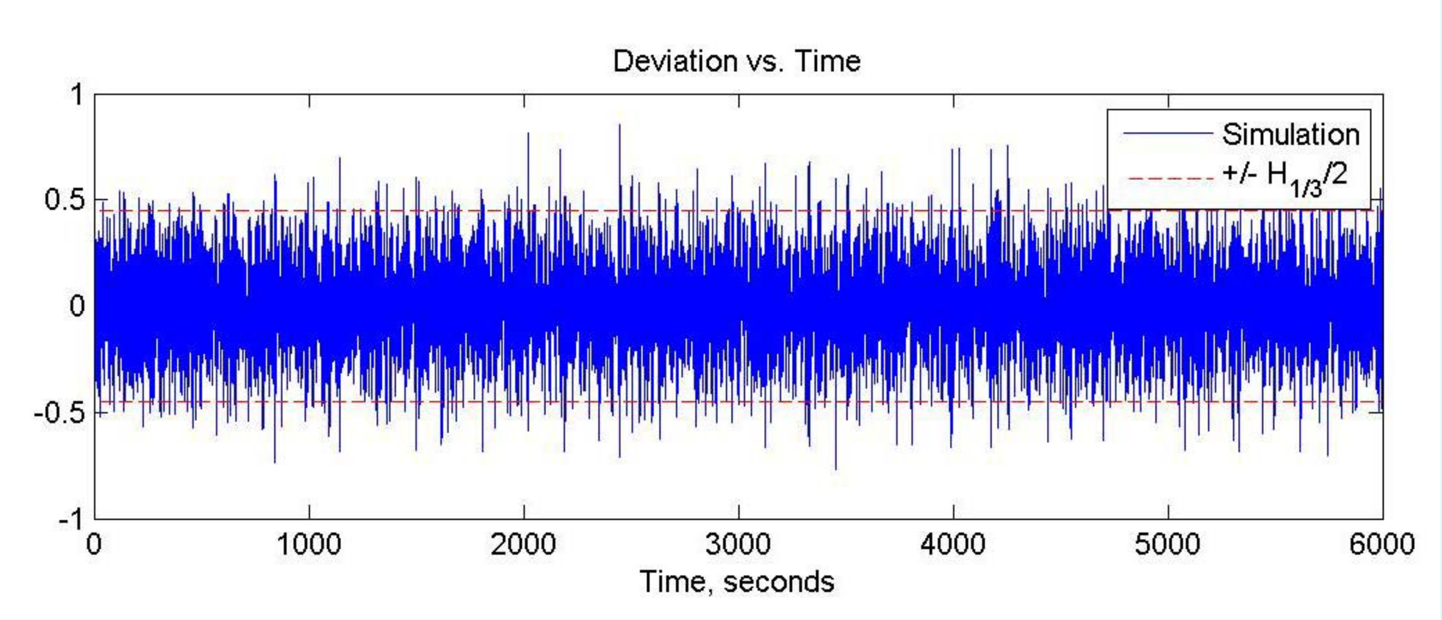
Principles of Naval Architecture, E.V. Lewis, ed., SNAME, 1989.

Seven components a_n=[1 2 3 3 2 2 1] at ω_n~[1 2 3 4 5 6 7]rad/s

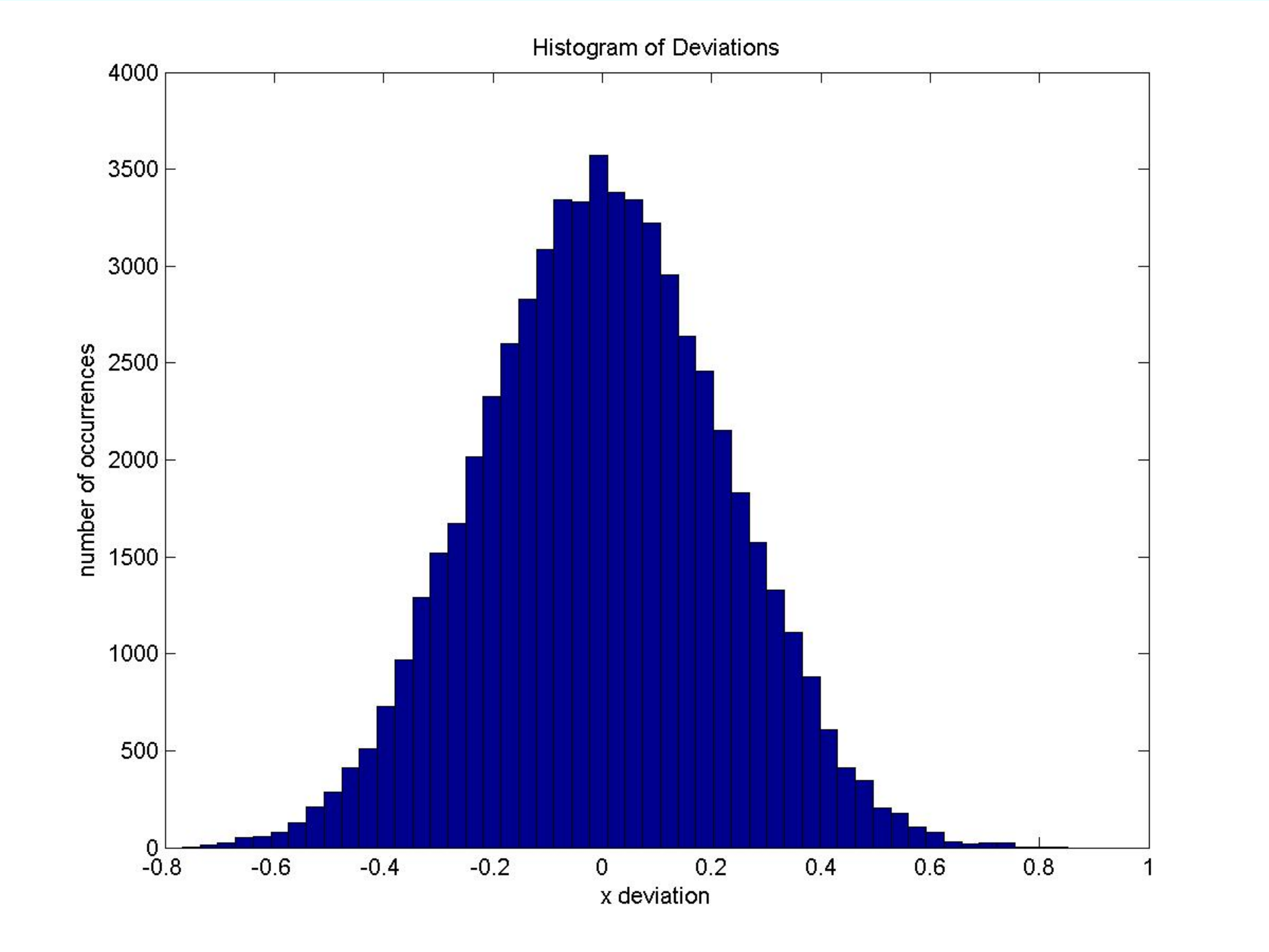


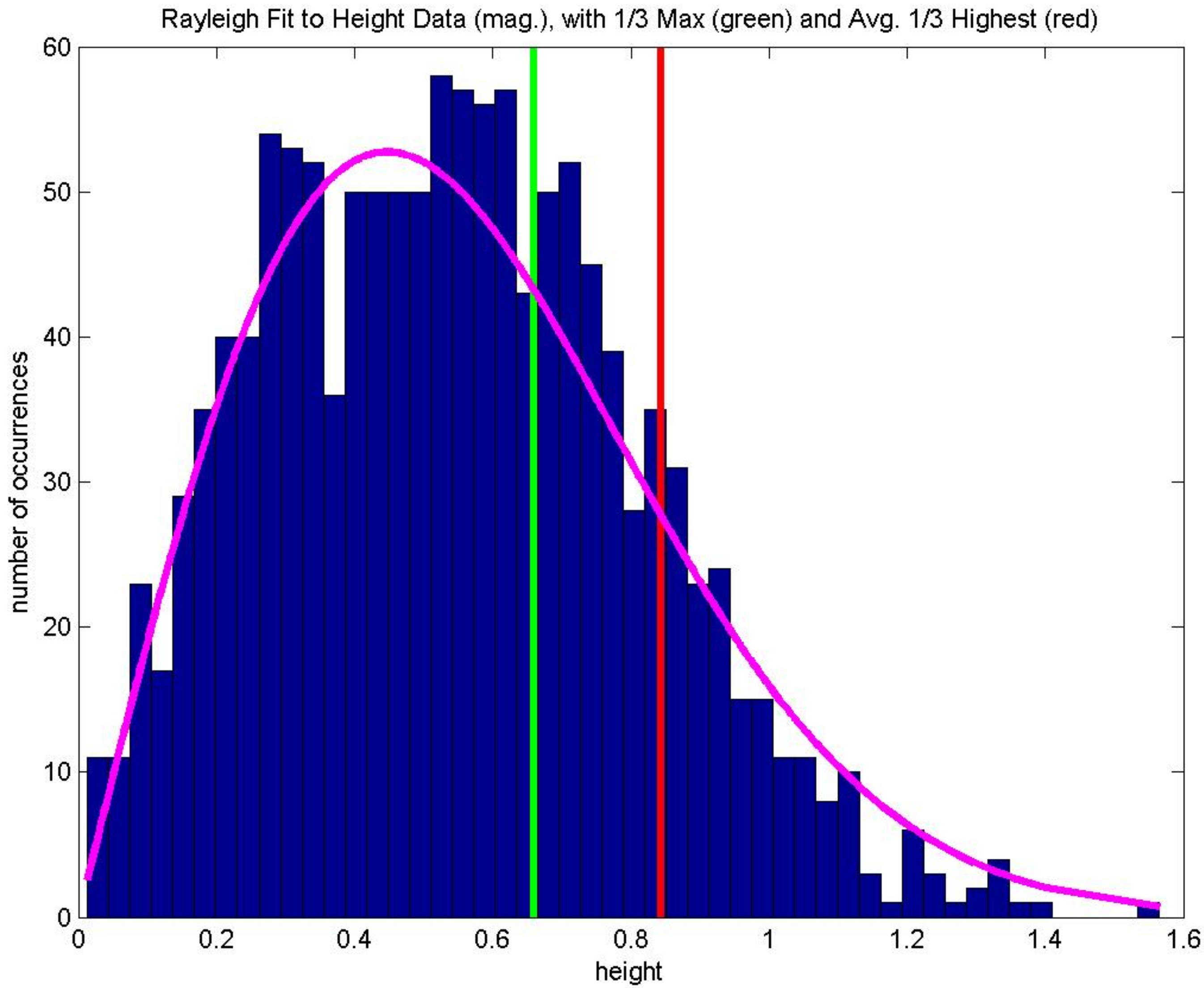


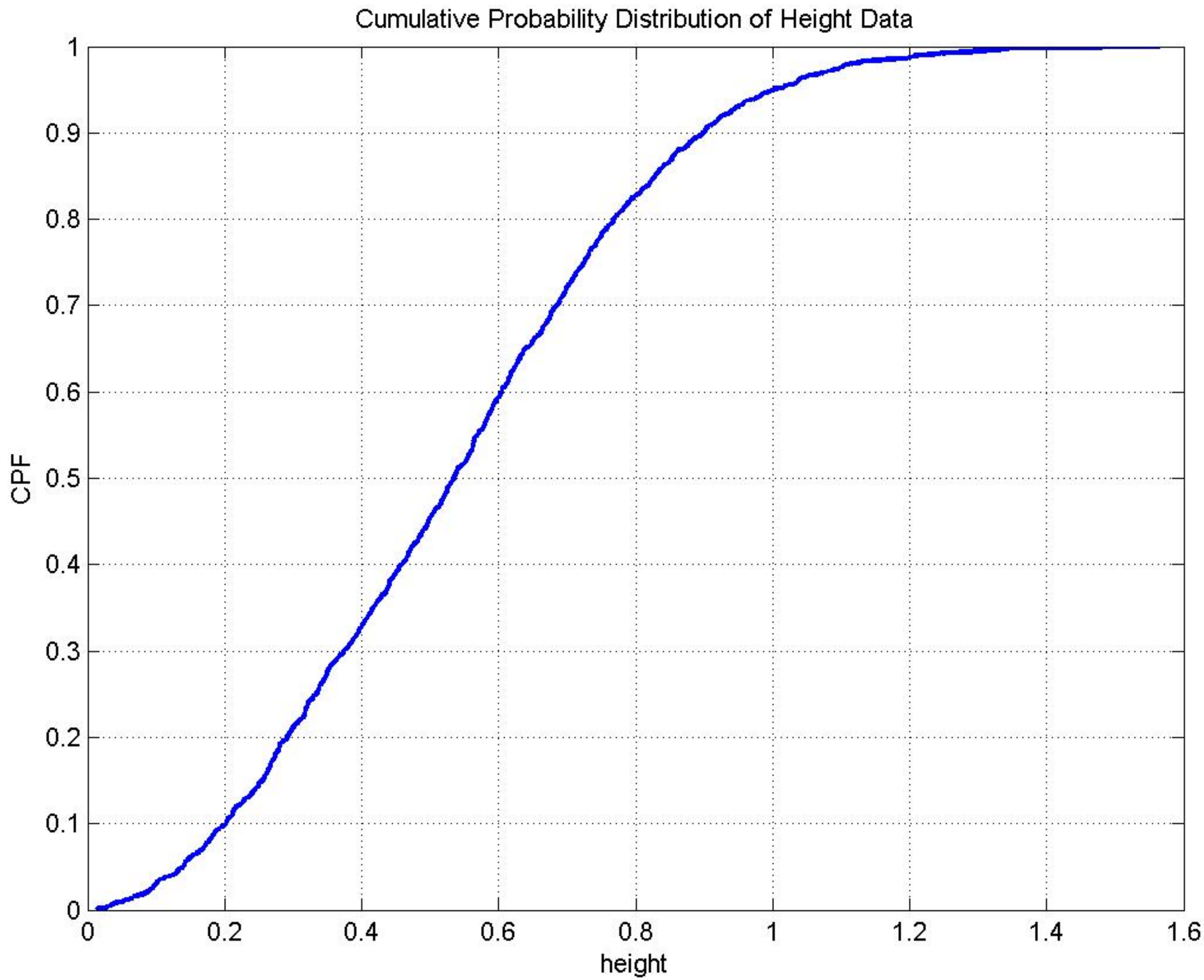
Bretschneider Spectrum, $H_{1/3}$ = 0.90m
0.08
0.06
0.04
0.02
0
m^2-s
0
0.5
1
1.5
2
2.5
3
3.5
4
rad/s

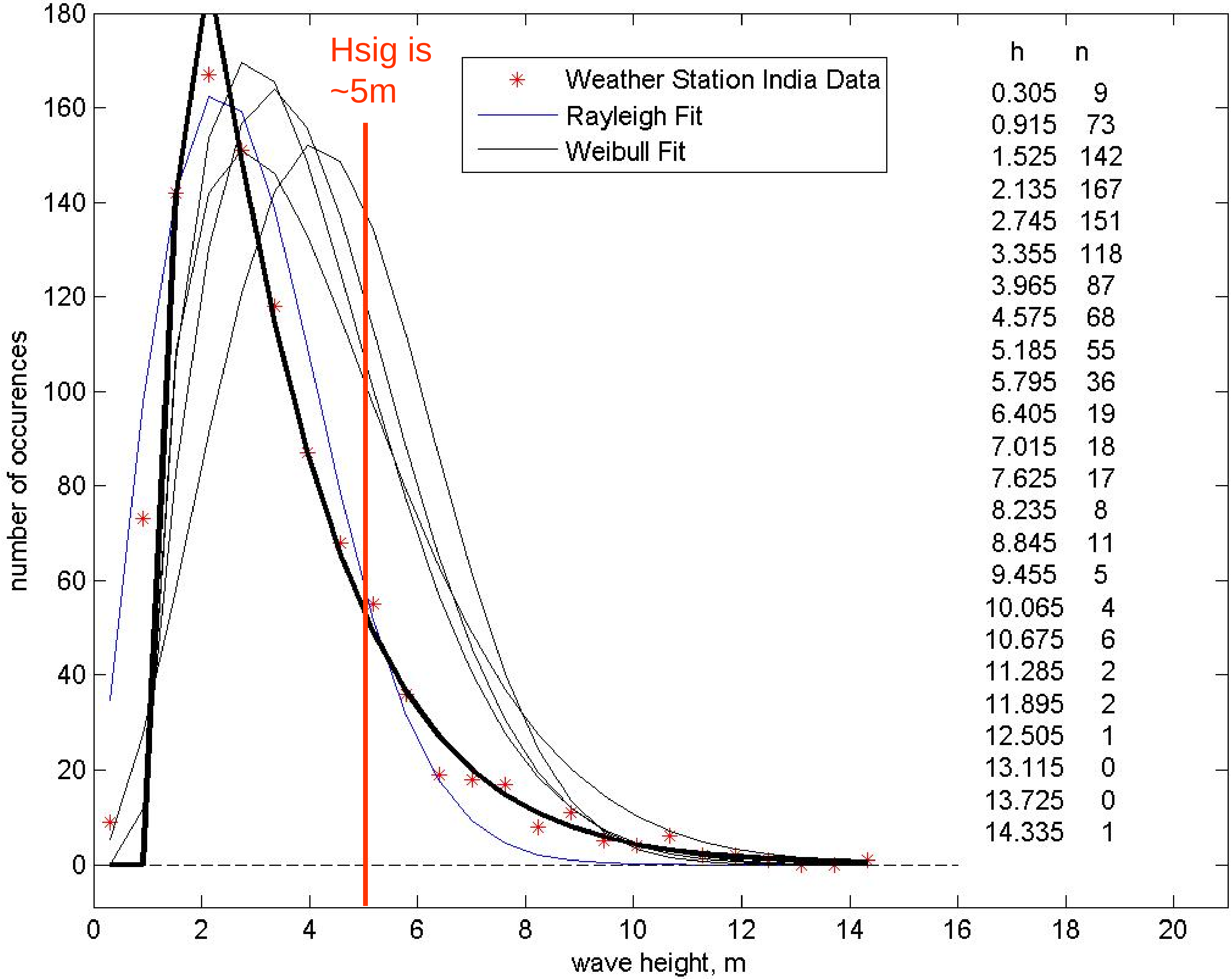


Deviation vs. Time
1
0.5
0
-0.5
-1
0
1000
2000
3000
4000
5000
6000
Time, seconds
Simulation
+/- $H_{1/3}$/2

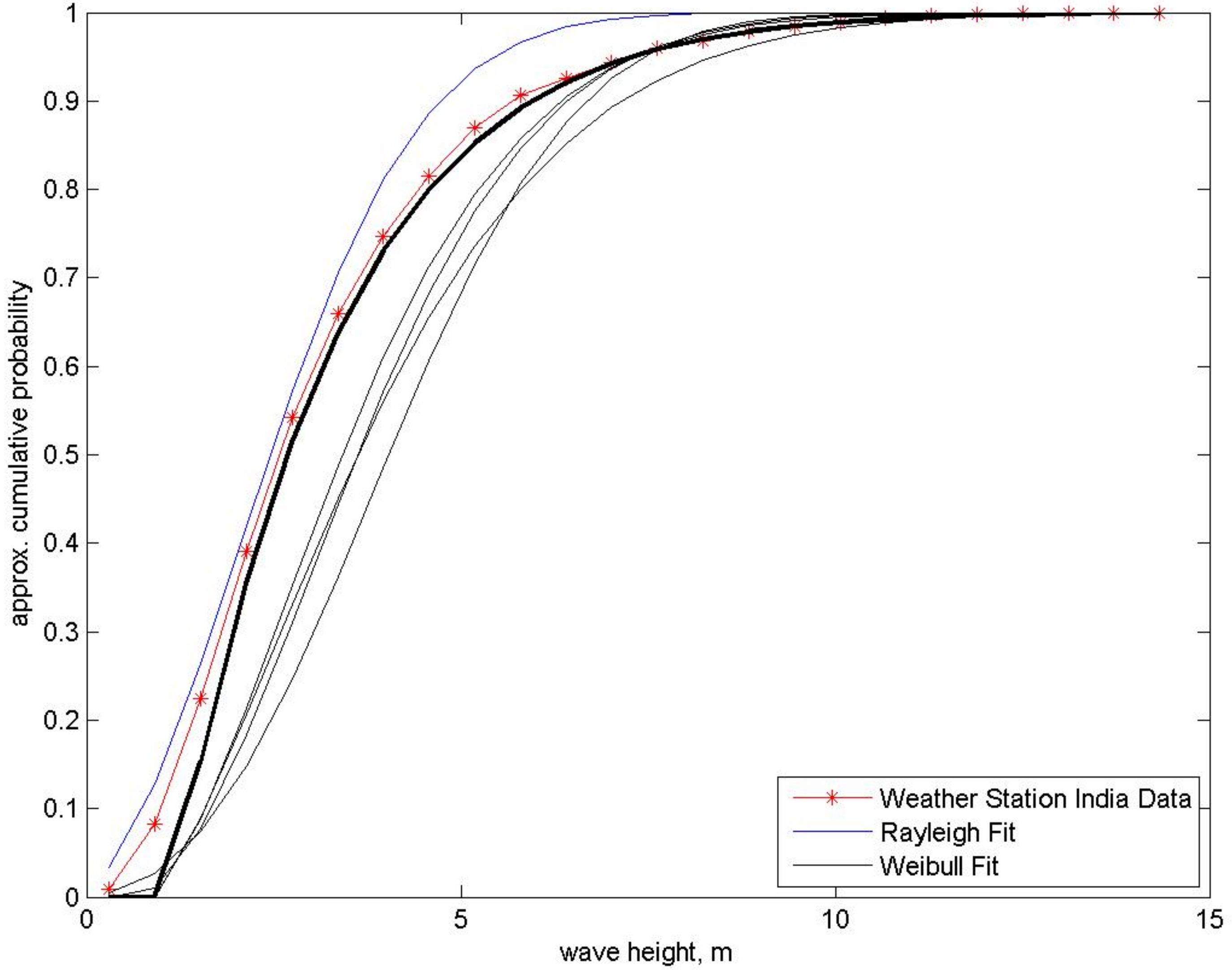

Histogram of Deviations
4000
3500
3000
2500
2000
1500
1000
500
0
number of occurrences
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
x deviation


Rayleigh Fit to Height Data (mag.), with 1/3 Max (green) and Avg. 1/3 Highest (red)
number of occurrences
height
0
10
20
30
40
50
60
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

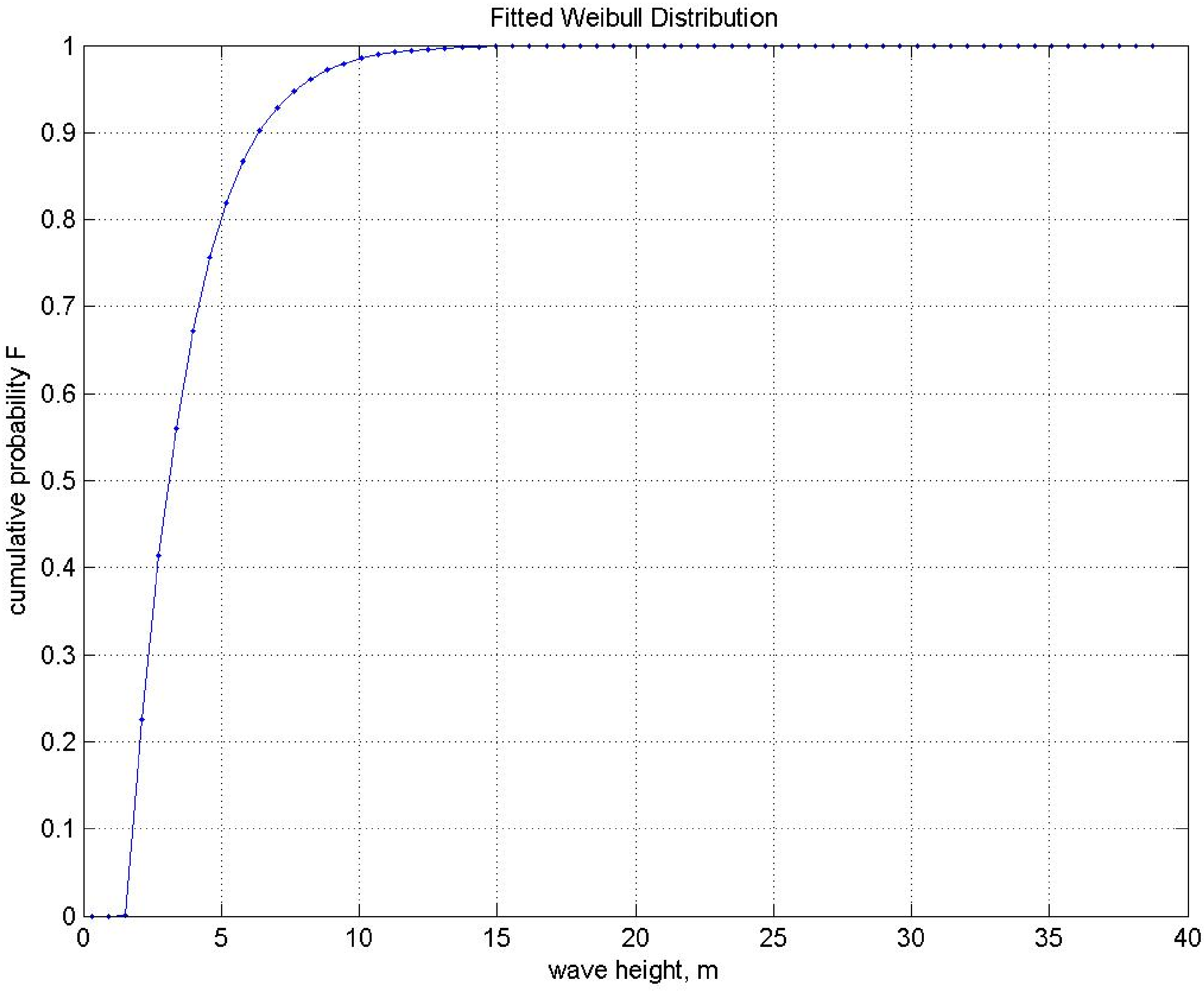

Cumulative Probability Distribution of Height Data
CPF
height
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

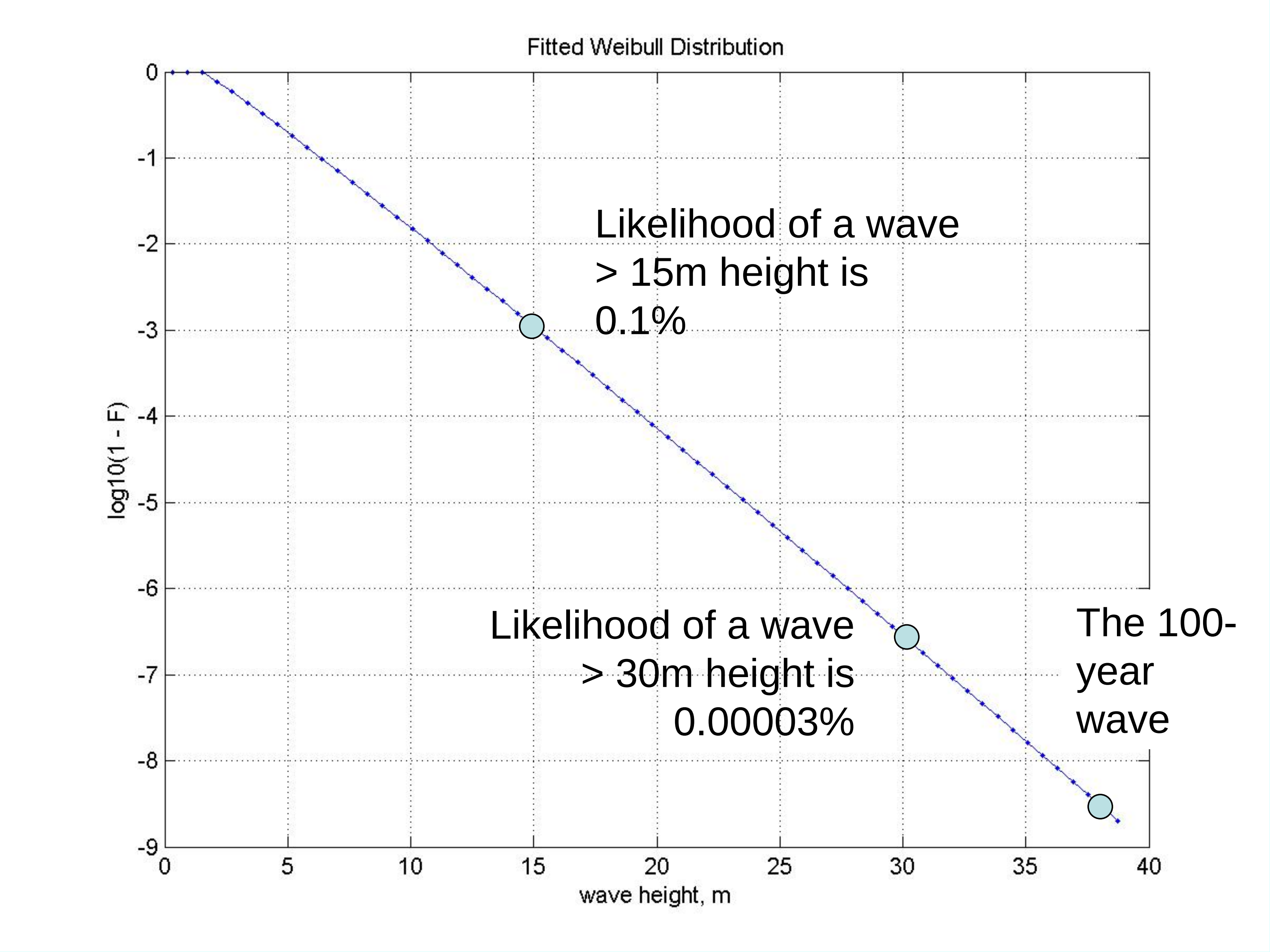


h	n
0.305	9
0.915	73
1.525	142
2.135	167
2.745	151
3.355	118
3.965	87
4.575	68
5.185	55
5.795	36
6.405	19
7.015	18
7.625	17
8.235	8
8.845	11
9.455	5
10.065	4
10.675	6
11.285	2
11.895	2
12.505	1
13.115	0
13.725	0
14.335	1



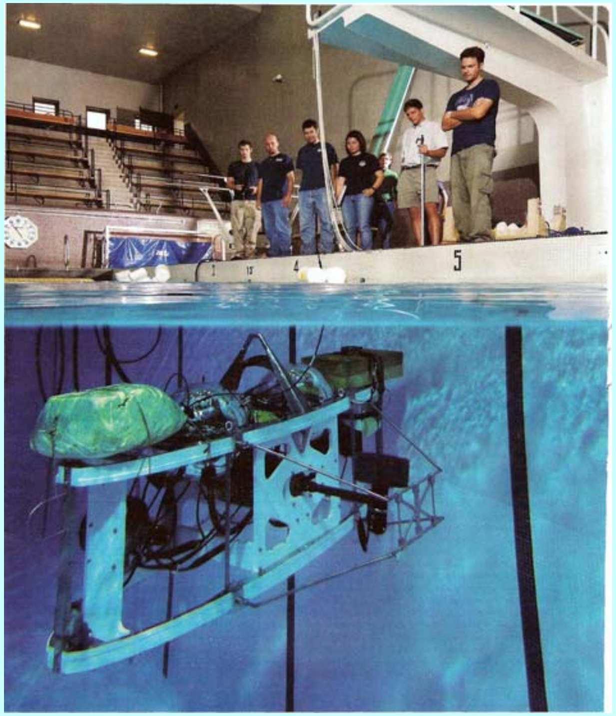
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
approx. cumulative probability
0
5
10
15
wave height, m
Weather Station India Data
Rayleigh Fit
Weibull Fit


Fitted Weibull Distribution
cumulative probability F
wave height, m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40

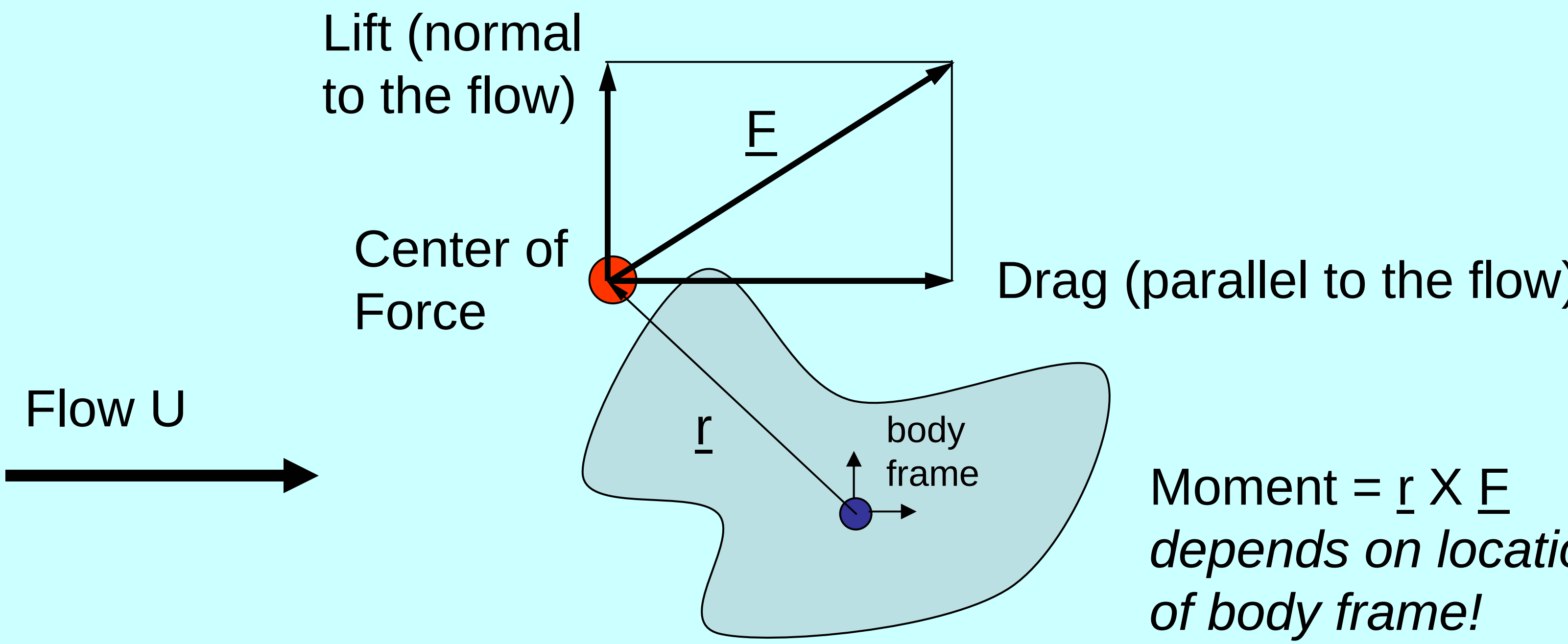

Fitted Weibull Distribution
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
log10(1 - F)
0
5
10
15
20
25
30
35
40
wave height, m
Likelihood of a wave > 15m height is 0.1%
Likelihood of a wave > 30m height is 0.00003%
The 100-year wave

Vehicles: Some Basic Catagories

- Streamlined vs. Bluff Bodies
  - Bluff: Cylinders, blocks, higher drag, lower lift, large-scale separation and wake
  - Streamlined: airplanes and ship hulls, Lower drag but higher lift, avoids separation to minimize wake
  - Tradeoff in Directional Stability of the body:
    - A fully streamlined fuselage/fairing is unstable.
    - Drag aft adds stability, e.g., a bullet
    - Wings aft add stability, e.g., fins, stabilizers
    - Wings forward decrease stability, but improve maneuverability.
- Turbulent vs. Laminar flow
- High- vs. low-speed flow



Concept of Drag, Lift, Moment (2D)



Moment = r X F
depends on location of body frame!

Typical nondimensionalization:

Drag = $\frac{1}{2} \rho U^2 A C_d$, where A is (typically) frontal area or wetted area
Lift = $\frac{1}{2} \rho U^2 A C_l$, where A is usually a planform area
Moment = $\frac{1}{2} \rho U^2 DL^2 C_m$, where L is characteristic body length, and D is characteristic width (or diameter)

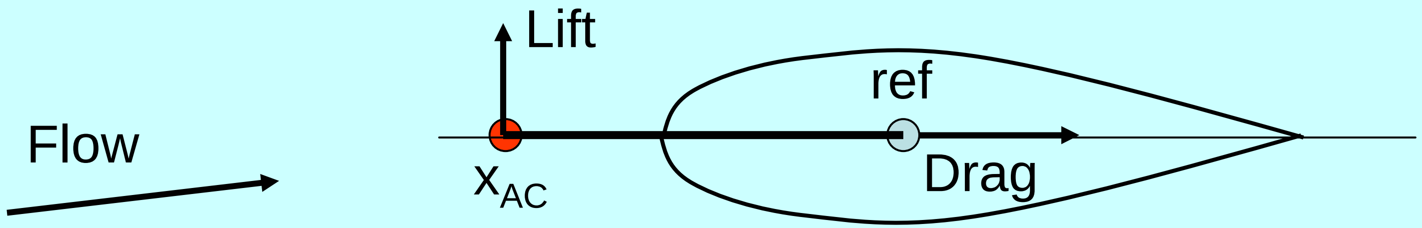
Aerodynamic Center

Consider streamlined, balanced (symmetric) forms in free flight.

Aerodynamic center is the location on the body of lift force that would create the observed moment, e.g.,

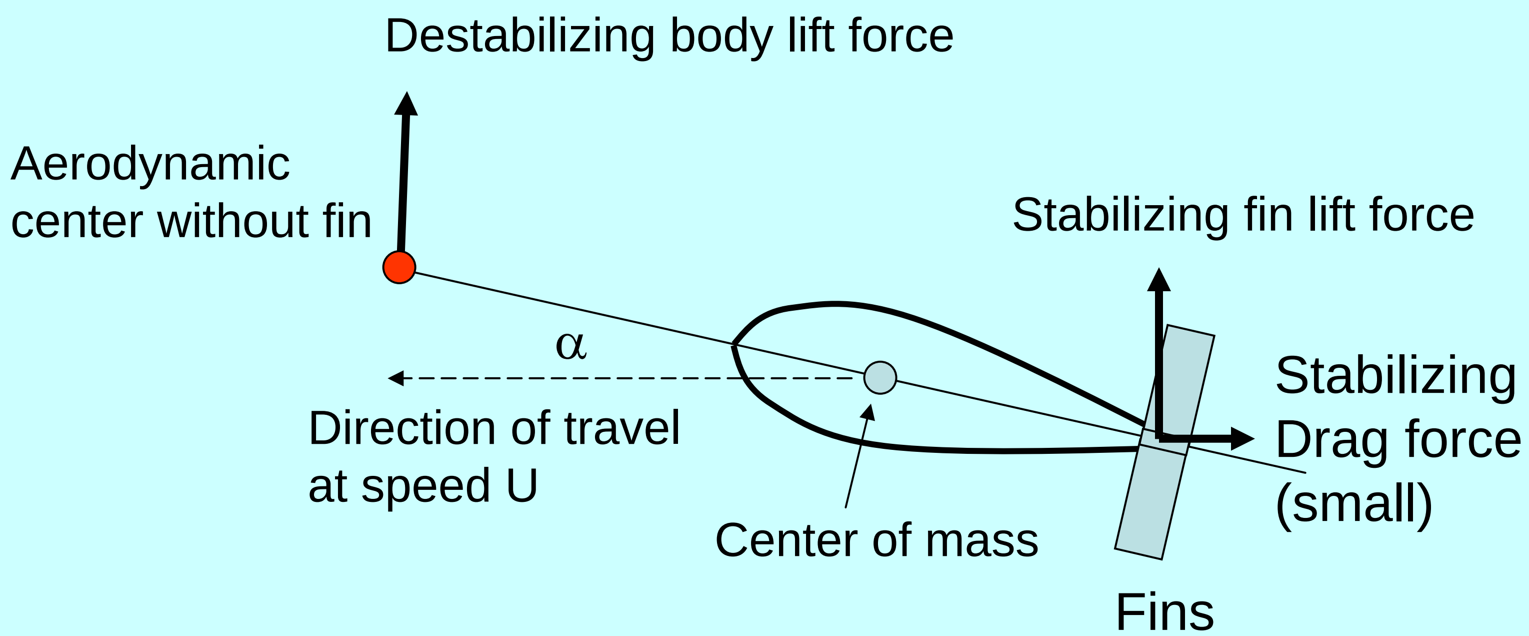
$$\mathbf{x_{AC} = C_m\, DL^2 / C_L\, A}\ ,$$

referenced to the same location as for C_m



- For an *Odyssey-like shape*, x_{AC} is up to one body length forward of the nose → Extremely unstable!
- For a typical *zero-camber foil section*, x_{AC} is around 20-30% of the chord length aft from the leading edge → more stable but can flutter

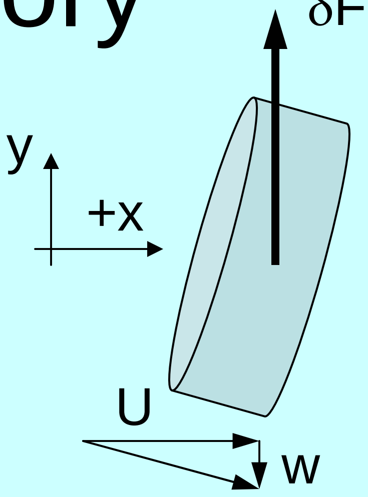
Streamlined Vehicle Design using Aft Lifting Surfaces



Body is neutrally directionally stable if sum of moments about center of mass is zero:

$$\Sigma M \sim L_{body}\, x_{AC} + L_{fins}\, x_{fins} + D_{fins}\, x_{fins}\, \alpha$$

Origins of the Destabilizing Moment: Slender-Body Theory



Derivative of property ζ *with the particle motion*:

$$
\begin{aligned}
D\zeta/Dt &= \lim\, (\zeta(t+\delta t, x+\delta x) - \zeta(t,x)) / \delta t \\
&= \zeta_t + \zeta_x\, \delta x / \delta t \text{ (Taylor series expansion)} \\
&= \zeta_t + \zeta_x\, U \\
&= (d/dt + U\, d/dx)\, \zeta
\end{aligned}
$$

Diff. lateral force on body is derivative of fluid momentum (as drawn):

$$\delta F = D(\, m_a(x)\, w\, \delta x\,)/Dt = (d/dt + U\, d/dx)\, (m_a(x)\, w\, \delta x)$$

Assume steady-state and uniform cross-section so all d()/dt = 0 →

$$\delta F = U\, d/dx\, (\, m_a(x)\, w\, \delta x\,)$$

Integrate by parts to get the moment:

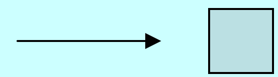
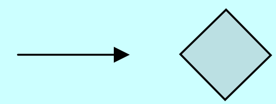
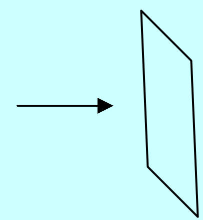
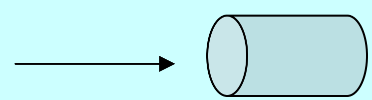
$-Uwm_{33}$

$$M = \int x\, \delta F = U\, w \left[\, x_{stern}\, m_a\, (x_{stern}) - x_{bow}\, m_a(x_{bow}) - \int m_a(x)\, dx \,\right]$$

Forces in steady flow

- Streamlined vs. Bluff Bodies
  - Bluff: Cylinders, blocks, higher drag, lower lift, large-scale separation and wake
  - Streamlined: airplanes and ship hulls, Lower drag but higher lift, avoids separation to minimize wake
  - Tradeoff in Directional Stability of the body:
    - A fully streamlined fuselage/fairing is unstable.
    - Drag aft adds stability, e.g., a bullet
    - Wings aft add stability, e.g., fins, stabilizers
    - Wings forward decrease stability, but improve maneuverability.
- Turbulent vs. Laminar flow
- High- vs. low-speed flow

Typical Drag Coefficients (frontal area)

- Square cylinder section  2.0
- Diamond cylinder section  1.6
- Thin rect. plate AR=1 1.1
- AR=20  1.5
- AR>>1 2.0
- Circular cylinder section 1.1
- Circular cylinder end on  1.0
- 1920 Automobile 0.9
- Volkswagon Bus 0.42
- Modern Automobile < 0.3
- MIT Solar Car?

Potter & Foss (1982)

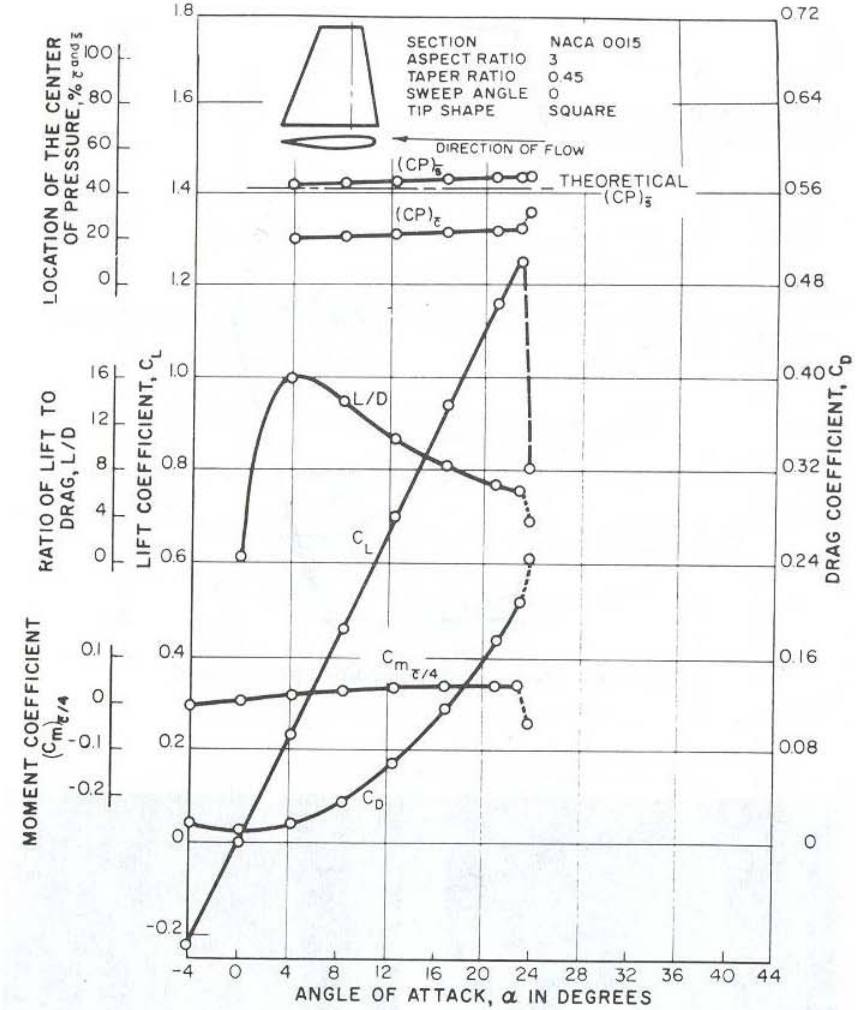


Fig. 132 Free-stream characteristics of an NACA 0015 section in ahead condition of a Reynolds number of 2.70 × 10^6 (Whicker and Fehlner, 1958)

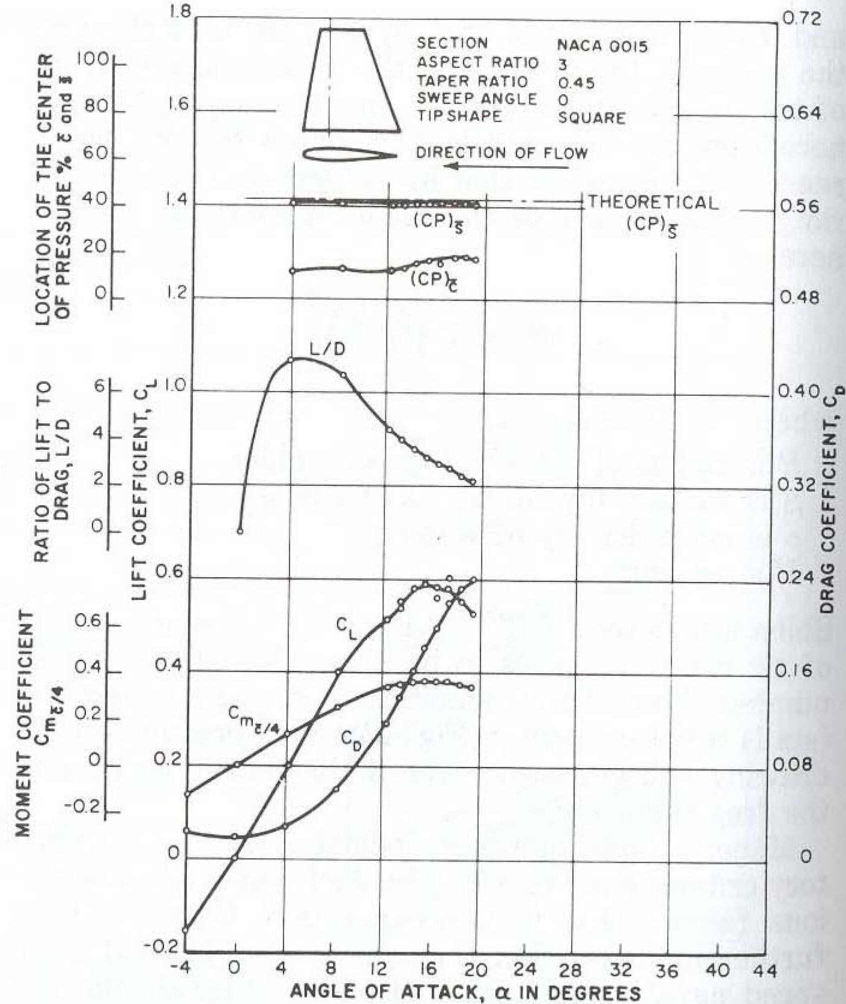


Fig. 133 Free-stream characteristics of an NACA 0015 section in astern condition at a Reynolds number of 3.00 × 10^6 (Whicker and Fehlner, 1958)

Figures from PNA

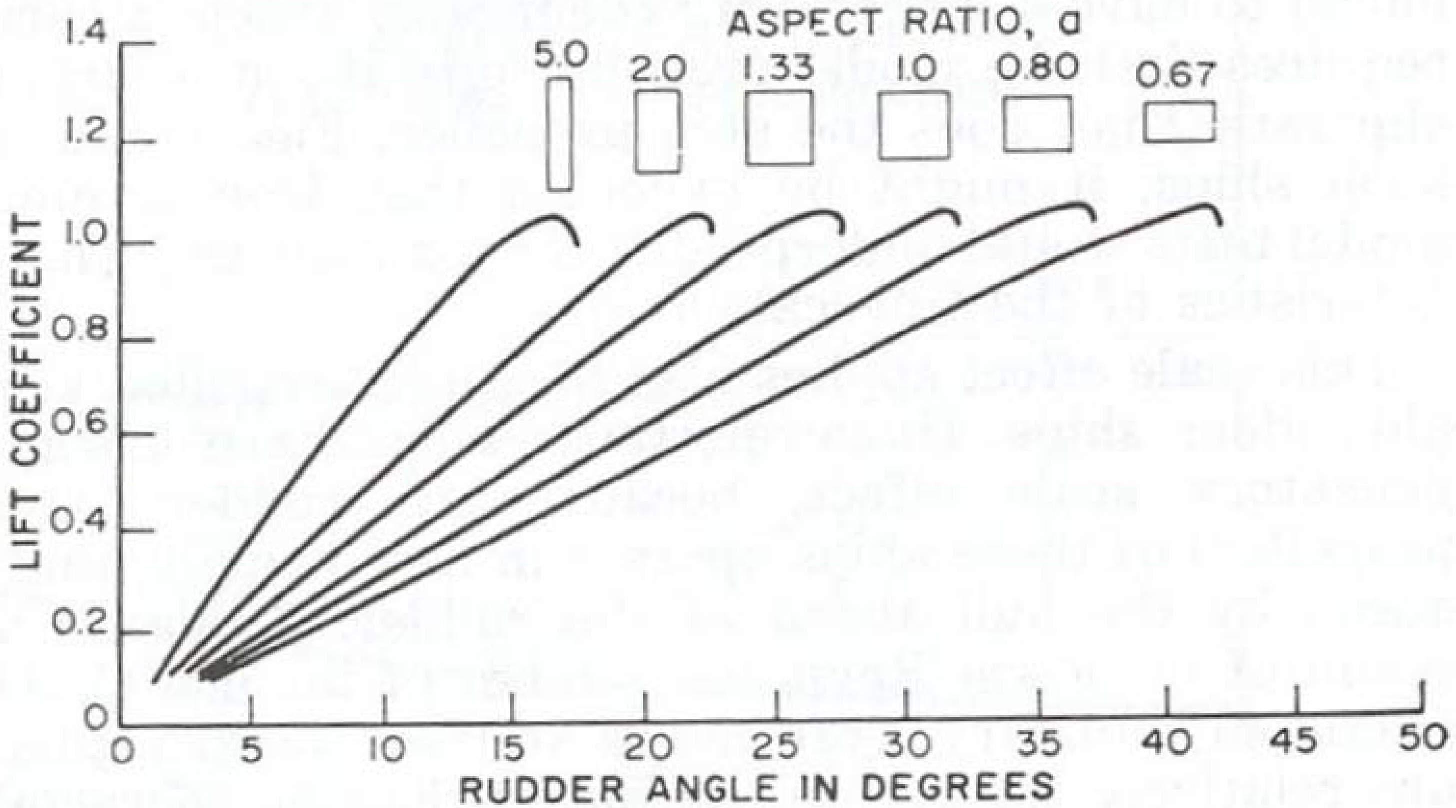


Fig. 131 Effect of rudder aspect ratio on lift coefficient (VanLammeren, Troost, and Koning, 1948)

Figure from PNA

Recommended References

- Fluid-Dynamic Lift. S.F. Hoerner, 1975, Hoerner Fluid Dynamics, Bakersfield, CA.
- Principles of Naval Architecture, Volume III (Motions in Waves and Controllability), E.V. Lewis, ed., 1989, SNAME, Jersey City, NJ.
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2.017J Design of Electromechanical Robotic Systems
Fall 2009