CHAPTER 5

THE SEA & WAVES

5.1 Introduction

The sea and climate are the external enviroment which mainly affect the ship as a whole and all exposed equipment. The ship performance can also be influenced by the depth or width of water present.

It should be noted that the internal environment can affect the personnel and internal equipment as well. To some extent, this kind of environment is controllable, eg. The temperature and humidity can be controlled by means of an air conditioning system.

The human element is covered by what is termed Human Factors (HF) ; a full study of which involves multi-discipline terms of physiologists; psychologists, engineers and scientists.

Chearly there is an interaction between external and internal environment above in that the initial study must allow for the likely in-service environment.

5.2 The sea

Certain physical properties of the sea are of considerable importance to the study. They are : -

a) Density : The density effects the ship's draught and trim and depends mainly upon the temperature and salinity. The standard values of density of fresh and salt water at various temperatures are given in Table (5.1) and (5.2). which are reproduced from [69].

b) Kinematic Viscousity : This is particularly relevant to the frictional resistance experienced by a ship as it defines the Reynolds number. The standard values of the kinematic viscousity of fresh and salt water at various temperatures are also reproduced from [69] and shown in Table (5.3) and (5.4)

c) Salinity : Salinity is defined as the ratio of solid dissolved in one unit mass of sea water. Values for actual samples of sea water will vary from area to area. Standard calculation assumes 3.5% of salinity to be used.

TABLE (5.1) Mass densities for fresh water

(last decimal figure is doubtful)

°C	ρ	°C	ρ	°C	ρ
0	999.79	10	999.59	20	998.12
1	999.79	11	999.49	21	997.92
2	999.89	12	999.40	22	997.72
3	999.89	13	999.30	23	997.43
4	999.89	14	999.10	24	997.24
5	999.89	15	999.00	25	996.94
6	999.89	16	998.91	26	996.75
7	999.79	17	998.71	27	996.45
8	999.79	18	998.51	28	996.16
9	999.69	19	998.32	29	995.87
				30	995.57

Metric units; ρ in kg/m^3

TABLE (5.2) Mass densities for salt water (salinity 3.5 percent)
(last decimal figure is doubtful)

°C	ρ	°C	ρ	°C	ρ
0	1028.03	10	1026.85	20	1024-70
1	1027.93	11	1026.66	21	1024.40
2	1027.83	12	1026.56	22	1024.11
3	1027.83	13	1026.27	23	1023.81
4	1027.74	14	1026.07	24	1023.52
5	1027.64	15	1025.87	25	1023.23
6	1027.44	16	1025.68	26	1022.93
7	1027.34	17	1025.38	27	1022.64
8	1027.15	18	1025.19	28	1022.25
9	1027.05	19	1024.99	29	1021.95
				30	1021.66

Metric units; ρ in kg/m^3.

TABLE (5.3) Values of kinematic viscosity for fresh water, v, in metric units of $(m^2s^{-1}) \times 10^6$. Temp. in degrees Celsius

Deg. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1.78667	1.78056	1.77450	1.76846	1.76246	1.75648	1.75054	1.74461	1.73871	1.73285
1	1.72701	1.72121	1.71545	1.70972	1.70403	1.69836	1.69272	1.68710	1.68151	1.67594
2	1.67040	1.66489	1.65940	1.65396	1.64855	1.64316	1.63780	1.63247	1.62717	1.62190
3	1.61665	1.61142	1.60622	1.60105	1.59591	1.59079	1.58570	1.58063	1.57558	1.57057
4	1.56557	1.56060	1.55566	1.55074	1.54585	1.54098	1.53613	1.53131	1.52651	1.52173
5	1.51698	1.51225	1.50754	1.50286	1.49820	1.49356	1.48894	1.48435	1.47978	1.47523
6	1.47070	1.46619	1.46172	1.45727	1.45285	1.44844	1.44405	1.43968	1.43533	1.43099
7	1.42667	1.42238	1.41810	1.41386	1.40964	1.40543	1.40125	1.39709	1.39294	1.38882
8	1.38471	1.38063	1.37656	1.37251	1.36848	1.36445	1.36045	1.35646	1.35249	1.34855
9	1.34463	1.34073	1.33684	1.33298	1.32913	1.32530	1.32149	1.31769	1.31391	1.31015
10	1.30641	1.30268	1.29897	1.29528	1.29160	1.28794	1.28430	1.28067	1.27706	1.27346
11	1.26988	1.26632	1.26277	1.25924	1.25573	1.25223	1.24874	1.24537	1.24182	1.23838
12	1.23495	1.23154	1.22815	1.22478	1.22143	1.21849	1.21477	1.21146	1.20816	1.20487
13	1.20159	1.19832	1.19580	1.19184	1.18863	1.18543	1.18225	1.17908	1.17592	1.17228
14	1.16964	1.16651	1.16340	1.16030	1.15721	1.15414	1.15109	1.14806	1.14503	1.14202
15	1.13902	1.13603	1.13304	1.13007	1.12711	1.12417	1.12124	1.11832	1.11542	1.11254
16	1.10966	1.10680	1.10395	1.10110	1.09828	1.09546	1.09265	1.08986	1.08708	1.08431
17	1.08155	1.07880	1.07606	1.07334	1.07062	1.06792	1.06523	1.06254	1.05987	1.05721
18	1.05456	1.05193	1.04930	1.04668	1.04407	1.04148	1.03889	1.03631	1.03375	1.03119
19	1.02865	1.02611	1.02359	1.02107	1.01857	1.01607	1.01359	1.01111	1.00865	1.00619
20	1.00374	1.00131	0.99888	0.99646	0.99405	0.99165	0.98927	0.98690	0.98454	0.98218
21	0.97984	0.97750	0.97517	0.97285	0.97053	0.96822	0.96592	0.96363	0.96135	0.95908
22	0.95682	0.95456	0.95231	0.95008	0.94786	0.94565	0.94345	0.94125	0.93906	0.93688
23	0.93471	0.93255	0.93040	0.92825	0.92611	0.92397	0.92184	0.91971	0.91760	0.91549
24	0.91340	0.91132	0.90924	0.90718	0.90512	0.90306	0.90102	0.89898	0.89695	0.89493
25	0.89292	0.89090	0.88889	0.88689	0.88490	0.88291	0.88094	0.87897	0.87702	0.87507
26	0.87313	0.87119	0.86926	0.86724	0.86543	0.86352	0.86162	0.85973	0.85784	0.85596
27	0.85409	0.85222	0.85036	0.84851	0.84666	0.84482	0.84298	0.84116	0.83934	0.83752
28	0.83572	0.83391	0.83212	0.83033	0.82855	0.82677	0.82500	0.82324	0.82148	0.81973
29	0.81798	0.81625	0.81451	0.81279	0.81106	0.80935	0.80765	0.80596	0.80427	0.80258
30	0.80091	0.79923	0.79755	0.79588	0.79422	0.79256	0.79090	0.78924	0.78757	0.78592

TABLE (5.4) Values of kinematic viscosity for salt water, v, in metric units of $(m^2 s^{-1}) \times 10^6$. (Salinity 3.5 per cent.) Temp. in degrees Celsius

Deg.C	00	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1.82844	1.82237	1.81633	1.81033	1.80436	1.79842	1.79251	1.78662	1.78077	1.77494
1	1.76915	1.76339	1.75767	1.75199	1.74634	1.74072	1.73513	1.72956	1.72403	1.71853
2	1.71306	1.70761	1.70220	1.69681	1.69145	1.68612	1.68028	1.67554	1.67030	1.66508
3	1.65988	1.65472	1.64958	1.64446	1.63938	1.63432	1.62928	1.62427	1.61929	1.61433
4	1.60940	1.60449	1.59961	1.59475	1.58992	1.58511	1.58032	1.57556	1.57082	1.56611
5	1.56142	1.55676	1.55213	1.54752	1.54294	1.53838	1.53383	1.52930	1.52497	1.52030
6	1.51584	1.51139	1.50698	1.50259	1.49823	1.49388	1.48956	1.48525	1.48095	1.47667
7	1.47242	1.46818	1.46397	1.45978	1.45562	1.45147	1.44735	1.44325	1.43916	1.43508
8	1.43102	1.42698	1.42296	1.41895	1.41498	1.41102	1.40709	1.40317	1.39927	1.39539
9	1.39152	1.38767	1.38385	1.38003	1.37624	1.37246	1.36870	1.36496	1.36123	1.35752
10	1.35383	1.35014	1.34647	1.34281	1.33917	1.33555	1.33195	1.32837	1.32481	1.32126
11	1.31773	1.31421	1.31071	1.30722	1.30375	1.30030	1.29685	1.29343	1.29002	1.28662
12	1.28324	1.27987	1.27652	1.27319	1.26988	1.26658	1.26330	1.26003	1.25677	1.25352
13	1.25028	1.24705	1.24384	1.24064	1.23745	1.23428	1.23112	1.22798	1.22484	1.22172
14	1.21862	1.21552	1.21244	1.20938	1.20632	1.20328	1.20027	1.19726	1.19426	1.19128
15	1.18831	1.18534	1.18239	1.17944	1.17651	1.17356	1.17068	1.16778	1.16490	1.16202
16	1.15916	1.15631	1.15348	1.15066	1.14786	1.14506	1.14228	1.13951	1.13674	1.13399
17	1.13125	1.12852	1.12581	1.12349	1.12038	1.11769	1.11500	1.11232	1.10966	1.10702
18	1.10438	1.10176	1.09914	1.09654	1.09393	1.09135	1.08876	1.08619	1.08363	1.08107
19	1.07854	1.07601	1.07350	1.07099	1.06850	1.06601	1.06353	1.06106	1.05861	1.05616
20	1.05372	1.05129	1.04886	1.04645	1.04405	1.04165	1.03927	1.03689	1.03452	1.03216
21	1.02981	1.02747	1.02514	1.02281	1.02050	1.01819	1.01589	1.01360	1.01132	1.00904
22	1.00678	1.00452	1.00227	1.00003	0.99780	0.99557	0.99336	0.99115	0.98895	0.98676
23	0.98457	0.98239	0.98023	0.97806	0.97591	0.97376	0.97163	0.96950	0.96737	0.96526
24	0.96315	0.96105	0.95896	0.95687	0.95479	0.95272	0.95067	0.94862	0.94658	0.94455
25	0.94252	0.94049	0.93847	0.93646	0.93445	0.93245	0.93046	0.92647	0.92649	0.92452
26	0.92255	0.92059	0.91865	0.91671	0.91478	0.91286	0.91094	0.90903	0.90711	0.90521
27	0.90331	0.90141	0.89953	0.89765	0.89579	0.89393	0.89207	0.89023	0.88838	0.88654
28	0.88470	0.88287	0.88105	0.87923	0.87742	0.87562	0.87383	0.87205	0.87027	0.86849
29	0.86671	0.86494	0.86318	0.86142	0.85966	0.85192	0.85619	0.85446	0.85274	0.85102
30	0.84931	0.84759	0.84588	0.84418	0.84248	0.84079	0.83910	0.83739	0.83570	0.83400

d) The sea surface : The sea presents are ever changing face to the observer. In the long term, the surface may be in any condition form a flat calm to extreme roughness. In the short term, the surface may present the appearance of a fairly steady level of roughness but the actual surface shape will be continuously varying.

The sea surface presents a very confused picture which defined, for many years, any attempts at mathematical definition. Although Sir Isaac Newton had made some study of waves, it would appear that the generally accepted theory of waves in water was initiated in a work publishing during 1804 by Franz Gerstner, Professor of Mathematic in Prague from 1789 to 1823. In U.K. the theory was developed, practically, simultaneously and independently by Professor Macquorn Rankine and William Froude who were probably aware of Gerstner's work [59].

The surface, then, is disturbed by the wind, the extent of the disturbance depending upon the strength of the wind, the time for which it acts and the length of the water surface over which it acts. These three qualities are referred to as the strength, duration and fetch of the wind respectively [37; 38]. The disturbance also depends on tide, depth of water and local land contours. Wave characteristics become practically independent of fetch when the fetch is greater than about 300 miles.

Once a wave has been generated it will move away from the position at which it was generated until all its energy is spent. Waves generated by local winds are termed sea and those which have traveled out of their area of generation are termed swell [31]. Sea waves are characterised by relatively peaky crests and the crest length seldom exceeds some two or three times the wave-length. Swell waves are generally lower with more rounded tops. The crest length is typically six or seven times the wave-length. In a swell, the variation in height between successive waves is less then in the case for sea waves [7; 8; 30].

Two cases, which are of particular significance, are : -

a) The trochoidal wave

b) The sinusoidal wave

In the following section, two of them will be described in more detail.

5.3 Trochoidal waves

The trochoidal wave theory has been adopted for certain standard calculation, eg. that for longitudinal strength. By observation, the theory appears to reflect many actual ocean wave phenomena although it can be regarded as only an approximation to the complex wave form actually existing.

The section of the trochoidal wave surface is defined mathematically as the path traced by a point fixed within a circle when that circle is rolled along and below a straight line as shown in Fig (5.1).

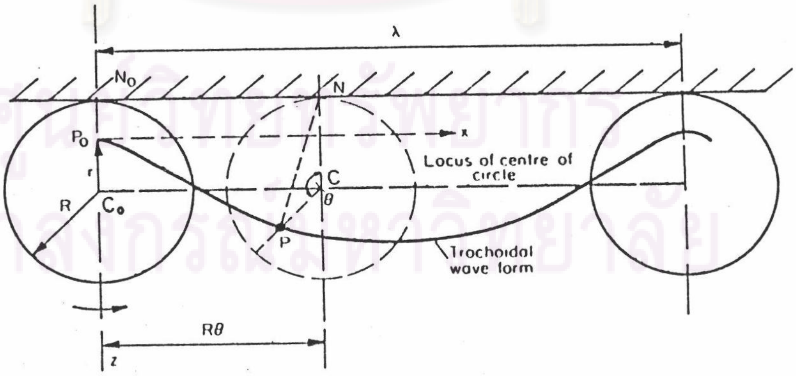

Fig. 5.1 Generation of trochoidal wave form

Suppose the height and length of the wave to be generated are h_w and λ respectively : then the radius of the generating circle is R, say, where

$$\lambda = 2\pi R$$

and the distance of the generating point from the centre of the circle is r, say where

$$h_w = 2r$$

Let the centre of the generating circle at position C_o and let it have turned through and angle 0 by the time it reaches C. Then

$$C_oC = N_oN = R\theta$$

Relative to the x-, z-axes shown in Fig. (5.1) the co-ordinates of p are

$$x = R\theta - r \sin \theta$$

$$= \frac{\lambda\theta}{2\pi} - \frac{hw}{2} \sin \theta$$

$$z = r - r \cos \theta = \frac{hw}{2}(1 - \cos\theta)$$

As the circle rolls it turns, instantaneously, about its point of contact, N, with the straight line. Hence NP is the normal to the trochoidal surface and the instantaneous velocity of p is

$$NP\frac{d\theta}{dt} \text{ normal to NP}$$

Surfaces of equal pressure below the water surface will also be trochoidal. Crests and troughs will lie vertically below those of the surface trochoid, i.e. the length of the trochoidal wave is the same in all case and they are all generated by a rolling circle of the same diameter. At great depths, any surface disturbance is not felt so that the radius of the point generating the trochoidal surface must reduce with increasing depth.

Consider two trochoidal sub-surfaces close to each other as shown in Fig. (5.2).

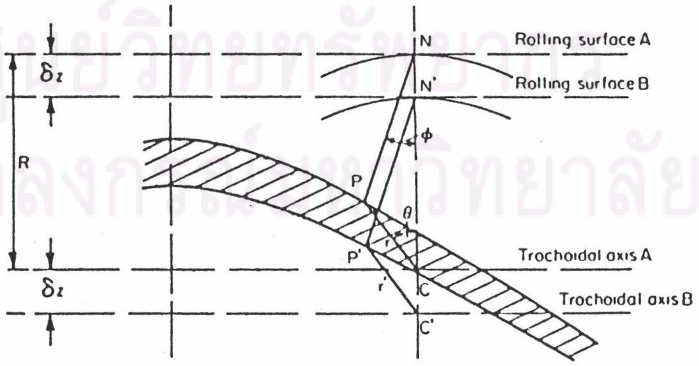

Fig. 5.2 Sub-surface trochoids

By definition, no particles of water pass through a trochoidal surface. Hence, for continuity the space shown shaded in Fig. (5.2) must remain filled by the same volume of water.

Let t = thickness of layer at P (measured normal to the trochoidal surface)

$$\text{Velocity at P} = PN\frac{d\theta}{dt}$$

Hence the condition of continuity implies

$$PN\frac{d\theta}{dt} = \text{constant for all values of } \theta$$

i.e.

$$tPN = \text{constant for all values of } \theta$$

Now CP and C'P' are parallel and, provided δz is small, PN and P'N' are very nearly parallel. Resolving along PN

$$P'N' + \delta z \cos\theta = PN + t$$

$$t = \delta z \cos\theta + \delta PN, \text{ where } \delta PN = P'N' - PN$$

$$= \delta z \left[\frac{R - r\cos\theta}{PN}\right] + \delta PN$$

$$tPN = \delta z\,(R - r\cos\theta) + PN \cdot \delta PN$$

Also

$$PN^2 = R^2 + r^2 - 2\,Rr\cos\theta$$

Differenctiating and remembering that R and θ are constant

$$2PN\ \delta PN = 2r\,\delta r - 2R\cos\theta\ \delta r$$

$$tPN = \delta z\,(R - r\cos\theta) + r\,\delta r - R\cos\theta\ r$$

$$= R\,\delta_z + r\,\delta_r - \cos\theta\,(r\,\delta z + R\,\delta r)$$

Since tPN is constant for all values of 0

$$r\,\delta z + R\,\delta r = 0$$

in the limit

$$\frac{1}{r}\,dr = -\frac{1}{R}dz$$

Integrating

$\log_e r = c - z$ where c = constant

If $r = r_0$ at $z = 0$, $c = \log_e r_o$

$$\log_e r = \log_e r_o - \frac{z}{R}$$

i.e.

$$r = r_o \exp\left(\frac{-z}{R}\right)$$

That is to say, the radius of the point tracing out the sub-surface trochoid decreases exponentially with increasing depth. This exponential decay is often met within natural phenomena.

Although it has been convenient to study the shape of the trochoidal wave using the artifice of a point within a rolling circle, a particle in the water surface itself does not trace out a trochoid. The absolute motion is circular and neglecting bodily movement of mases of water such as those due to tides, is obtained by superimposing on Fig. (5.1) an overall velocity of C from right to left such that

$$C = \frac{\lambda}{T}$$

This superposition of a constant velocity in no way invalidates the results obtained above or those which follow. The use of the stationary trochoid as in Fig. (5.1) is merely one of mathematical convenience.

The magnitude of C can be expressed in terms of λ by considering the forces acting on a particle at P in Fig. (5.1). Such a particle will suffer a downward force due to gravity and a centrifugal force in the line CP.

If the mass of the particle is m, the gravitational force is mg and the centrifugal force mrw^2 where $w = d\theta/dt$.

Since the surface is one of equal pressure, the resultant of these two forces must be normal to the surface, i.e. it must lie in the direction of NP

Referring to fig. (5.3)

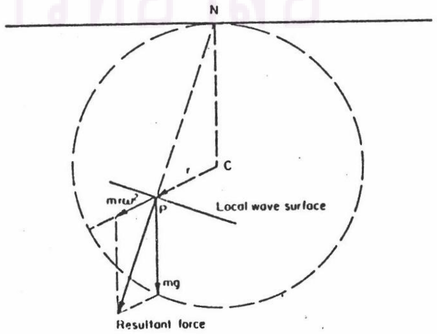

Fig. (5.3) Forces on particle in wave surface

$$\frac{mg}{NC} = \frac{mrw^2}{CP}$$

i.e.

$$\frac{mg}{R} = \frac{mrw^2}{r}$$

whence

$$w^2 = \frac{g}{R}$$

Now $C = \lambda/T$ Where T, the wave period = $2\pi/w$.

$$C = \lambda w/2\pi = wR$$

Hence

$$C^2 = w^2R^2 = gR = g\frac{\lambda}{2}$$

Relationship between line of orbit centres and the undisturbed surface

In Fig. (5.4) the trochoidal wave form is superimposed on the still water surface in a crest, as measured above the still water level, must be equal to the volume of a trough measured below this level. Put another way, the area Po; P'o ; P''o must equal the area of the rectangle PoP'oL'L or, for simplification of the integration

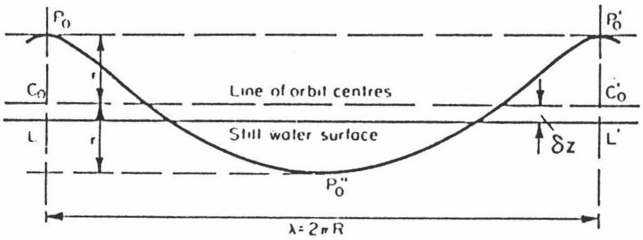

Fig.(5.4) Line of orbit centres in relation to the still water surface

$$\int_{0}^{x=\pi R} z \, dx = \pi R \, (r + \delta z)$$

Where δz = distance of still water surface below the line of orbit centres. Since $x = R\theta - r \sin \theta$ and $z = r - r \cos \theta$, we obtain

$$\int_{\theta=0}^{\theta=\pi} (r-r \cos \theta) \, (R-r \cos \theta) \, d\theta = \pi R(r + \delta z)$$

$$\int_{0}^{\pi} (rR - rR \cos \theta - r^2 \cos \theta + r^2 \cos^2 \theta) = \pi R(r + \delta z)$$

i.e.

$$\pi Rr + \frac{\pi r^2}{2} = \pi R(r + \delta z)$$

$$\delta z = \frac{r^2}{2R}$$

This property has been used in the past as a wave pressure correction [36; 54].

5.4 Sinusoidal Waves

Mathematically, the trochoidal wave is not easy to manipulate and the basic units from which an irregular sea is assumed to be built up are sinusoidal in profile.

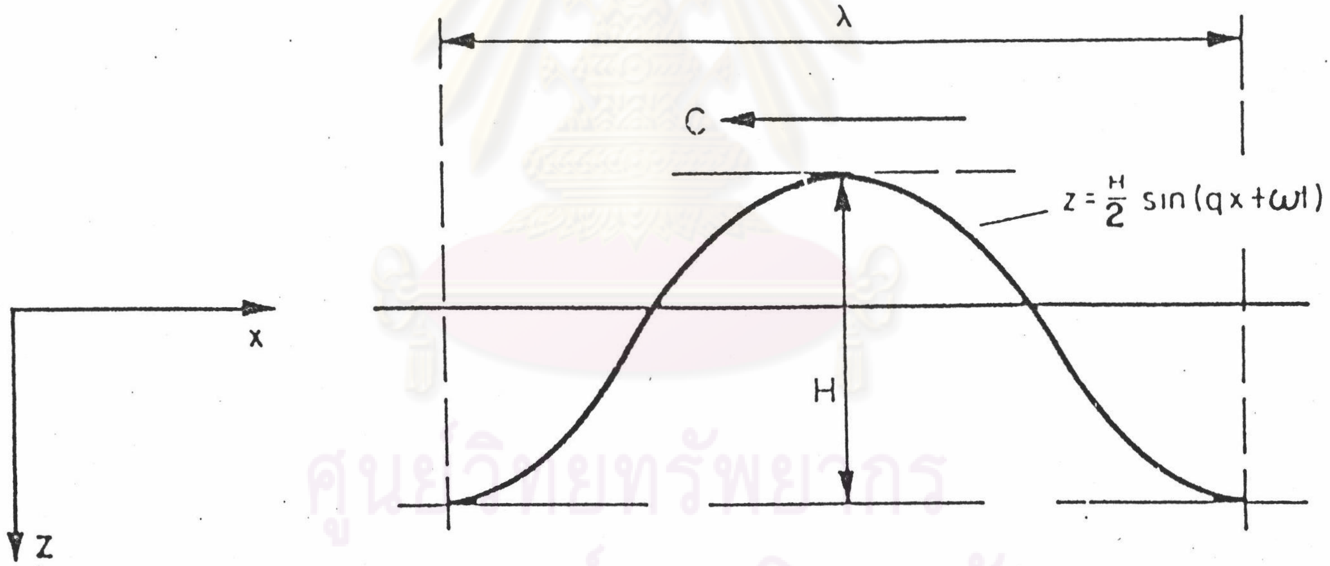

Fig. (5.5) Profile of sinusoidal wave

For a wave travelling with velocity C in the direction of decreasing x, Fig. (5.5) the profile of the wave can be represented by the equation

$$z = \frac{H}{2} \sin (qx + wt)$$

In this expression, $q = 2\pi/\lambda$ is known as the wave number and $w = 2\pi/T$ is known as the wave frequency. The wave velocity as in the case of the trochoidal wave, is given by

$$C = \frac{\lambda}{T} = \frac{w}{q}$$

Other significant features of the wave are

$$T^2 = \frac{2\pi\lambda}{g}$$

$$w^2 = \frac{2\pi g}{\lambda}$$

$$C^2 = \frac{g\lambda}{2\pi}$$

Water particles within the waves move in orbits which are circular, the radii of which decrease with depth in accordance with the expression

$$r = \frac{H}{2} \exp (-qz) \text{ for depth } z$$

From this it can be deduced that at a depth $z = +\lambda/2$, the orbit radius is only 0.02H so that for all intents and purposes motion is negligibly small at depths equal to or greater than half the wavelength. The proof of this relationship is similar to that adopted for the trochoidal wave.

The hydrodynamic pressure at any point in the wave system is given by

$$p = \rho g \frac{H}{2} \exp(-qz) \sin(qx + wt)$$

The average potential and kinetic energies per unit area of the wave system are equal, and the average total energy per unit area is

$$\frac{\rho g H^2}{8}$$

The energy of the wave system is transmitted at half the velocity of advance of the waves. Thus, when a train of regular waves enters calm water, the front of the waves advances at the velocity of energy transmission, and the individual waves travel at twice this velocity and disappear through the front.

Two of the above relationships are presented graphically in Fig. (5.6) above, this wave form is assumed in building up irregular wave systems. It is also used in studying the response of a ship to regular waves [3; 9;10]. Differences in response to a trochoidal wave would be small if the waves are of the same height and length.

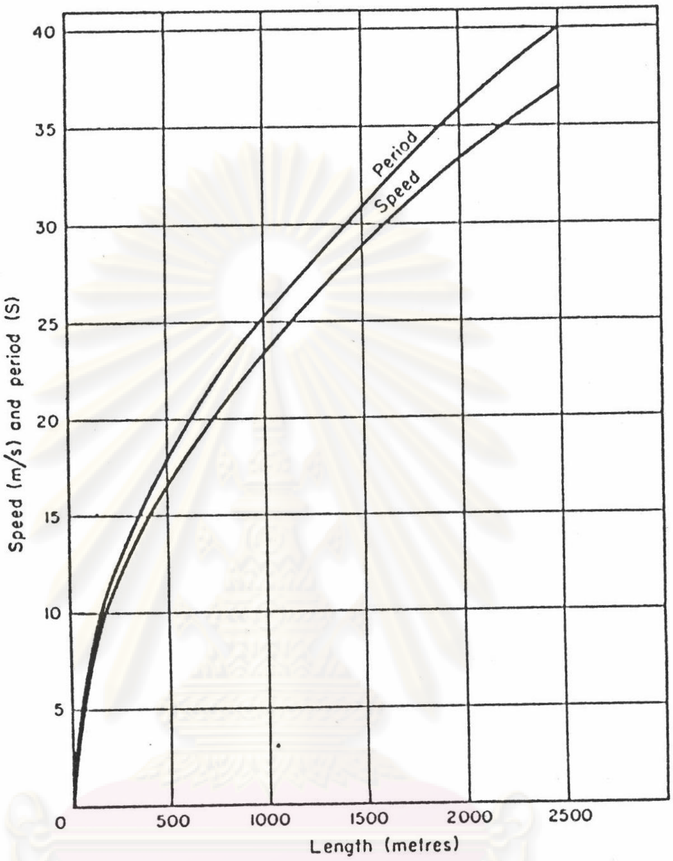

Fig. (5.6) Wave proportions

5.5 The wind [37; 38]

The main influence of the wind is felt indirectly through the waves it generates on the surface of the sea. As stated above, the severity of these waves will depend upon the strength (i.e. velocity) of the wind, the time it acts (i.e. its duration) and the distance over which it acts (i.e. the facts).

The strength of the wind is broadly classified by the Beaufort Scale. The numbers 0 to 12 were introduced by Admiral Sir Francis Beaufort in 1806. O referring to a calm and force 12 to a wind of hurricane force. Originally, there were no specific wind speeds associated with these numbers but in 1939 the values shown in Table (5.5) have more recently been adopted internationally. The figures relate to an anemometer at a height of 6 m. above the sea surface.

No fixed relation exists between the spectra of a sea and the speed of wind generating it. Figure (5.7) shows a relationship agreed by the ITTC but it applies only to fully developed seas where duration and fetch are large. Figure (5.8) shows the probability of exceeding a given wind speed in the North Atlantic.

The wind velocity varies with height. At the surface of the water, the relative velocity is zero dueto a boundary layer effect. Reference [64] defines a nominal wind at 33 ft above the waterline, and the

TABLE (5.5) The Beaufort Scale

	Limits of speed (Kts)	(m/s)	(ft/s)
0 Calm	1	0.3	2
1 Light air	1-3	0.3-1.5	2-5
2 Light breeze	4-6	1.6-3.3	6-11
3 Gentle breeze	7-10	3.4-5.4	12-18
4 Moderate breeze	11-16	5.5-7.9	19-27
5 Fresh breeze	17-21	8.0-10.7	28-36
6 Strong breeze	22-27	10.8-13.8	37-46
7 Near gale	28-33	13.9-17.1	47-56
8 Gale	34-40	17.2-20.7	57-68
9 Strong gale	41-47	20.8-24.4	69-80
10 Storm	48-55	24.5-28.4	81-93
11 Violent Storm	56-63	28.5-32.6	94-106
12 Hurricane	64 & Over	32.7 & Over	107 & Over

variation in wind velocity with height is assumed to be in accord with Fig. (5.9) which is based on that reference. It will be noted, that these nominal velocities will be about 6 per cent less than those defined by the Beaufort Scale at a height of 6 m. above the surface. Also given in Fig. (5.9) is a curve based on this nominal height.

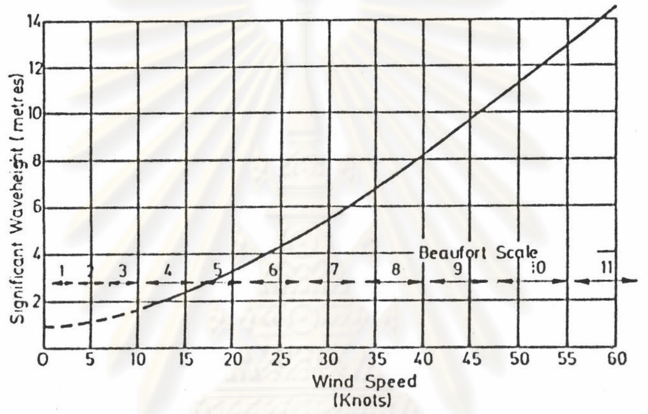

Fig. (5.7)

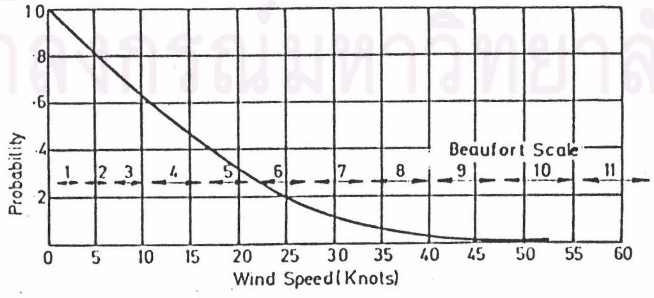

Fig. (5.8)

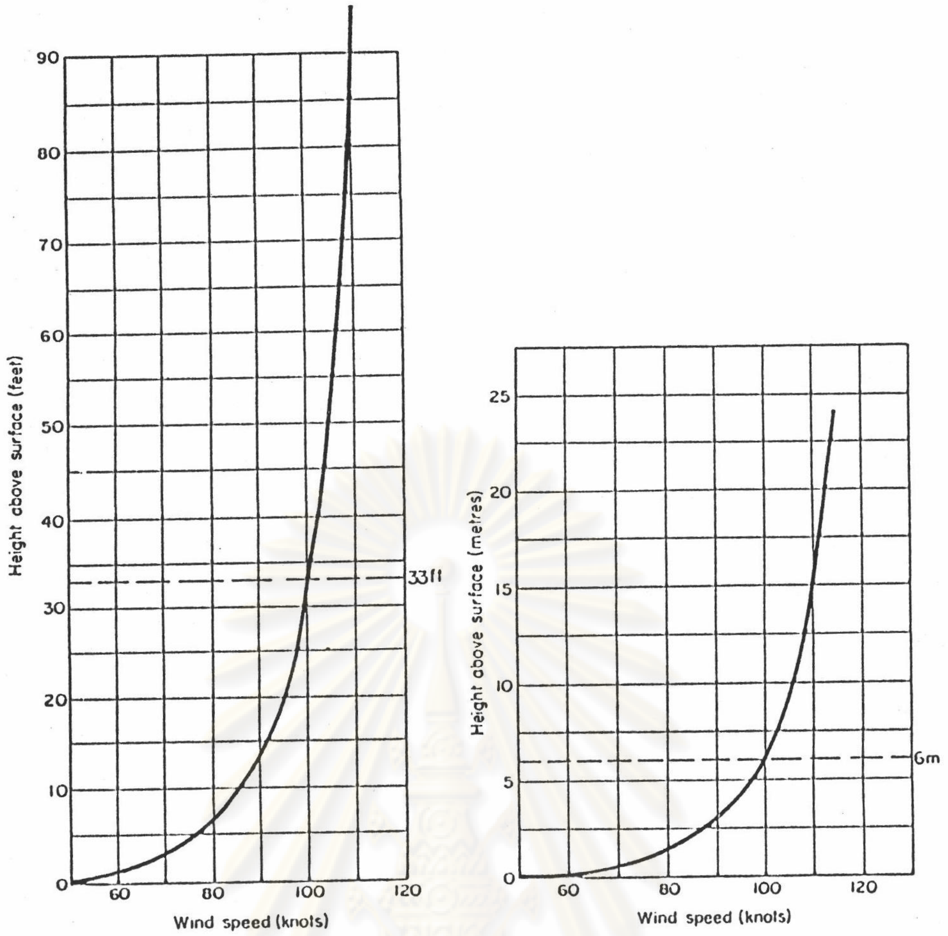

Fig. (5.9) Variation of wind speed with height above sea surface (nominal wind speed 100 knots)

For nominal velocities other than 100 knots, the true velocities can be scaled in direct proportion to the nominal velocities.

More direct influences of the wind are felt by the ship as forces acting on the above water portions of the hull and the superstructure. The fore and aft components of such forces will act either as a resistive or propulsive force. The lateral force will act as a heeling moment. Thus, standards of stability adopted in a given design must reflect the possible magnitude of this heeling moment, e.g. large windage area ships will require a greater stability standard.

Another direct influence of the wind, including the effect of the ship's own speed, is to cause local wind velocities past the superstructure which may entrain the funnel gases and bring them down on to the after decks, or which may produce high winds across decks to the discomfort of passengers. These effects are often studied by means of model experiments conducted in a wind tunnel, in order to obtain a suitable design of funnel and superstructure [69].

Table (5.6) shows the definitions of sea conditions including both Beaufort wind scale and the Sea State scale. This table has been reproduced from [9].

TABLE (5.6) DEFINITIONS OF SEA CONDITIONS : WAVE AND SEA FOR FULLY ARISEN SEA

Sea-General		Wind				Sea								
Sea Slate	Description	(Beaufort) Wind force	Description	Rang (knots)	Wind Velocity (knots)	Wave Height			Significant Range Periods sec	Periods of maximum Energy of Spectra $T_{mas}=T$	Average Period T	Average Wave-length L It unless otherwise indicated	Minimum Fecth (nautical) miles)	Minimum Duration hr unle otherwis indicated
						Average	Significant	Average of one-Tenth Highest						
	Sea like a mirror	U	Calm	1	0	0	0	0	–	–	–	–	–	–
0-	Ripples with the appearance of scales are formod, but without foam crests	1	Light airs	1–3	2	0.04	0.01 0.01	0.09	1.2	0.75	0.5	10in	5	18min
1	Small wavelets;short but pronounood crests have a glossy appearance, but do not break	2	Light breeze	4–6	5	0.3	0.5	0.6	0.4–28	1.9	–1.3	6.7ft	8	39min
	Large wavelets; crests brgin to break. Foam of glossy appearance. Perhaps scattlered with horses.	3	Gentle breeze	7–10	8.5 10	0.8 1.1	1.3 1.8	1.6 2.3	0.8–5.0 1.0–6.0	3.2 3.2	2.3 2.7	20 27	9.8 10	1.7 2.4
2 3	Small waves, becoming larger; fairly frequerx white horses	4	Moderate breeze	11–16	12 13.5 14 16	1.6 2.1 2.3 2.9	2.6 3.3 3.6 4.7	3.3 4.2 4.6 6.0	1.0–7.0 1.4–7.6 1.5–7.8 2.0–8.8	4.5 5.1 5.3 6.0	3.2 3.6 3.8 4.3	40 52 59 71	18 24 28 40	3.8 4.8 5.2 6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray)	5	Fresh breeze	17–21	18 19 20	3.7 4.1 4.6	5.9 6.6 7.3	7.5 8.4 9.3	2.5–10.0 2.8–10.6 3.0–11.1	6.8 7.2 7.5	4.8 5.1 5.4	90 99 111	55 65 75	8.3 9.2 10
5 6	Large waves begin to form; white crests are more extensive everywbere (probably some spary)	6	Strong breeze	22–27	22 24 24.5 26	5.5 6.6 6.8 7.7	8.8 10.5 10.9 12.3	11.2 13.3 13.8 15.6	3.4–12.2 3.7–13.5 3.8–13.6 4.0–14.5	8.3 9.0 9.2 9.8	5.9 6.4 6.6 7.0	134 160 164 188	100 130 140 180	12 14 15 17
7	Sea heaps up, and white foam from breaking waves being to be blown in streaks along the direction of the wind (Spindrift begins to be seen)	7	Moderate gale	28–33	28 30 30.5 32	8.9 10.3 10.6 11.6	14.3 16.4 16.9 18.6	18.2 20.8 21.5 23.6	4.5–15.5 4.7–16.7 4.8–17.0 5.0–17.5	10.6 11.3 11.5 12.1	7.5 8.0 8.2 8.6	212 250 258 285	230 280 290 340	20 23 24 27
7	Moderate high waves of greater length; edges of crests break into spindrift. The form is blown in well-marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh gale	34–40	34 36 37 38 40	13.1 14.8 15.6 16.4 18.2	21.0 23.6 24.9 26.3 29.1	26.7 30.0 31.6 33.4 37.0	5.5–18.5 5.8–19.7 6–20.5 6.2–20.8 6.5–21.7	12.8 13.6 13.9 14.3 15.1	9.1 9.6 9.9 10.2 10.7	322 363 376 392 444	420 500 530 600 710	30 34 37 38 42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong gale	41–37	42 44 46	20.1 22.0 24.1	32.1 35.2 38.5	40.8 44.7 48.9	7–23 7–24.2 7–25	15.8 16.6 17.3	11.3 11.8 12.3	492 534 590	830 960 1110	47 52 57
9	Very high waves with long over-hanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole, the surface of the sea takes on a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole gale	48–55	40 50 51.5 52 54	26.2 28.4 30.2 30.8 33.2	41.9 45.5 48.3 49.2 53.1	53.2 57.8 61.3 6.25 67.4	7–5–26 7–5.27 8–28.2 8–28.5 8–29.5	18.1 18.8 19.4 19.6 20.4	12.9 13.4 13.8 13.9 14.5	650 700 736 750 810	1250 1420 1560 1610 1800	63 69 73 75 81
	Exceptionally high waves. Sea completely covered with long white patches of foam lying in direction of wind. Everywhere edges of wave crestes are blown into froth. Visibility affected.	11	Storm	56–63	56 59.5	35.7 40.3	57.1 64.4	72.5 81.8	8.5–31 10–32	21.1 22.4	15 15.9	910 985	2100 2500	88 101
	Air filled with foam and spary. Sea white with driving spary. Visibility very seriously affected	12	Hurricane	> 64–71	>46.6	74.5	94.6		10–35	24.1	17.2	–	–	–