Cross Wind Loads on Ships and Complex Structures

Max van Hilten†, Dick Engelbracht & Paul Wolkenfelt

In memory of Max van Hilten, former registered Rotterdam maritime pilot and guest lecturer at NLDA, who we lost to cancer in March 2007

Introduction

A few years ago the Maritime Pilots Institute Netherlands (MPIN) was asked to carry out practical research aimed at developing a simple method to predict wind loads on huge constructions. For practical reasons the method should not be time consuming. Some reasons for the initiative were the following.

Quite frequently large vessels and huge complex constructions, varying from offshore constructions to container cranes, enter or leave Dutch ports. Wind has given rise to dangerous situations during manoeuvres with barges or ships carrying high and/or complex structures several times in the past, despite the fact that usually both master and pilot make at least rough calculations as to the wind loads. With the present size of the port of Den Helder and with the increasing size of the lateral area of naval ships such as the landing platform docks (LPD) and the joint logistic support ships (JSS), see Figure 1, these dangerous situations may also arise with ships of the Royal Netherlands Navy.

The second reason was the substantial difference in the results of calculations used by a major shipping company and the approach used by Netherlands pilots. Finally, during this study MPIN was asked to co-operate in a research program concerning the nautical consequences of the development of a new extension to the port of Rotterdam: 'Maasvlakte-2'.

For this research MARIN (Maritime Research Institute Netherlands) and MSR (Maritime Simulation Institute Rotterdam) developed mathematical ship models of container vessels up to 385 m in length and of considerable height. A very important issue for these vessels was the calculation of the wind loads. This was a reason for MPIN to extend the study to wind loads on these large vessels as well.

Figure 1: Artist's impression of the Navy's new joint logistic support ship (JSS).

The most critical part of a passage often is the moment of the manoeuvre when the speed is nearly zero and the largest lateral area of the object concerned is exposed to the wind. At this moment enough propulsion power, either own ship's propulsion, tugboat's propulsion, or a combination of these, has to be available to, at least, stand the wind. Mostly the problem becomes less serious once the ship or barge increases speed. In this case a change of heading in order to correct for the set caused by the wind solves the problem as long as the fairway allows the required swept path. In this scenario low ship speeds should be taken into account: although increase of speed leads to hydrodynamical and rudder forces opposing the forces being exerted by wind, it also results in less effect from side thrusters and assisting tugs. These effects, amongst others, have to be taken into due consideration in daily practice. This article however focuses on the calculation of forces being exerted by the wind. The total power required to handle the ship safely will always be more than the calculated crosswind loads but may be based on these values.

For most floating objects however, as far as the authors know, the influence of air temperature and atmospheric pressure is not usually taken into account. Regarding normal ships the same goes for the use of a correct shape coefficient as well as a vertical wind profile. Variation of one of these parameters has its own specific influence (linear or quadratic). A combination of differences from standard values used may lead to results differing substantially from the wind loads being exerted on the object in reality. Especially the shape coefficient, the height of the object concerned and the air temperature play an important role. As stated above, several data are important in calculating the wind loads. The fact that not all of these parameters are used correctly in practice, if used at all, may result in unexpected wind loads, in some cases to a lesser and in some cases to a greater extent. Especially the latter, a greater load, might result in accidents. Some of the parameters are not easy to estimate, for instance the shape coefficient for the object concerned. For some of the others this is easier, the air temperature for instance. Even though a wrong assumption of the shape coefficient may contribute to wrong results for the most part, it is preferable (in the authors' opinion) to work as accurately as possible with regard to the other data. At least this avoids a wrong calculation result caused by the accumulation of a number of wrong assumptions.

Up until recently a lot of research has been carried out into wind loads on structures and ships. The scientists who carried out research in this area were, to name but a few, Davenport, Isherwood, Aage, Blendermann and Kareem. A lot of research was carried out regarding wind loads on offshore constructions as well, including wind tunnel tests. Furthermore, Engineering Sciences Data Unit (ESDU UK) supplies computer programs to calculate wind loads on structures. However, to use these programs one needs a sound theoretical background in engineering and also a lot of time to enter the necessary input.

Problem Definition and Basic Formulae

In trying to develop an approach to calculate the wind loads being exerted on ships or complex structures by cross winds the result should fulfil the following criteria:

1. Take into account, wherever possible, relevant parameters;

2. Easy to use on board for masters, navigation officers and pilots in daily practice;

3. Not be time consuming.

Fulfilling these preconditions requires analysis of the relevant components in determining wind loads and is only possible by the introduction of some tailor made software.

The forces and moments of force required in an equation of motion can be determined as a function of relative wind velocity, relative wind direction and 3-dimensional shape of the ship. However, the calculation models used are not always the same. For the components in the equation of motion representing the forces and moments of force caused by wind, X_{wind}, Y_{wind} and N_{wind}, we can use the basic form of the formula for forces being exerted on an object by a flow

$$Xwind = C_x \rho V^2 A_F/2, \quad (1)$$
$$Ywind = C_y \rho V^2 A_L/2, \quad (2)$$
$$Nwind = C_N \rho V^2 A_L L_{oa}/2, \quad (3)$$

with C the shape coefficients, ρ the air density, V the wind velocity, $A_{F,L}$ frontal and lateral projected areas and L_{oa} the length over all. The values of the shape coefficients depend on the three dimensional shape of the ship and the angle of attack of the relative wind. Since the calculation models used are not always the same, the values of shape coefficients for different calculation models may differ substantially. Therefore indiscriminate comparison of coefficient values from tests or research may result in wrong conclusions. A difference of calculation models comes to light at comparison of the theoretical approaches by Isherwood [1] and Blendermann [2,3]. The starting point of both Isherwood and Blendermann is the use of wind tunnel tests with a uniform flow. They take into account a boundary layer, but neglect fluctuations in speed and/or direction.

Most practical approaches are based on a simple form of the formula for dynamic pressure. The following examples of formulas often used in daily practice are of particular interest:

$$Y_{wind} = F_t = 0.075V^2 \cdot A_L/1000 \text{ [ton force]},$$
$$Y_{wind} = F_t = 0.052V^2 \cdot A_L/1000 \text{ [ton force]}.$$

For practical use in the offshore business most manuals advise calculating the loads for separate characteristic parts of the construction, followed by addition of the loads on these separate parts. They advise using height coefficients: factors for separate height intervals. This means they take into account the effect of a vertical wind profile for the most part. Shape coefficients for several 3-dimensional shapes of separate parts of the construction are given. Usually the air mass density is considered to be constant. A disadvantage of this method is that separate calculations have to be made for a number of height intervals for high parts of the construction. Most manuals advise adding to the load a certain percentage for small parts of the construction not included in the calculations (e.g. 20%).

A more Detailed Discussion on Parameters of the Basic Formula

The most elementary form of the formula for loads caused by wind was shown in (1) and (2). Here we will discuss parameters of the formula in more detail. For each of the parameters we will

- consider the theoretical background for determination of its value,
- refer to existing theoretical and practical approaches and,
- refer to the implementation in the computer program.

Wind velocity

Since the wind velocity varies with the height, a vertical wind profile has to be determined. Once this profile is laid down it is possible to calculate the wind velocities for any height above sea level. This is required for the determination of the variation (with the height) of the dynamic pressure. In this context it is important to be aware of the fact that wind velocities observed on board ships usually are those measured at the height of the sensor. The heights of wind sensors may differ considerably.

Meteorologists [4] usually lay down the vertical wind profile by means of a logarithmic function

$$\frac{V_{h_1}}{V_{h_2}} = \frac{\ln(h_1/z_0)}{\ln(h_2/z_0)}, \tag{4}$$

with V_h the wind velocity at height h. Further, the difference of wind profiles above a certain terrain (e.g. sea or land) is determined by the choice of the roughness length (z_0). The value of z_0 usually varies from 0.0002 [m] (open sea, absolutely flat surface) to more than 2 [m] (city centre). For open sea with waves, PIANC mentions a value of 0.004 in [5].

The vertical wind profile is sometimes also given by the power law

$$V_{h_1} = V_{h_2} \cdot (h_1/h_2)^{\alpha}. \tag{5}$$

For this approach the difference of wind profiles above a certain terrain is determined by the choice of the coefficient α. In [4] the power law is justified during neutral stability of the atmosphere, when α is determined by $\alpha \approx 1/\ln(\sqrt{h_1 \cdot h_2}/z_0)$.

From the above it is obvious, that determining α or z_0 correctly is important for the computations. Also, when wind velocities observed from wind sensors are used, the height of the sensor has to be taken into account because the observed wind velocities may differ substantially from those at the standard height (10 m), for which weather forecasts give the expected wind velocity.

The difference in wind loads on a rectangular shape, between model with and without vertical wind profiles should not be underestimated. Here, we consider the rectangular shape with a vertical wind profile defined by a power law. It turns out that a critical height exists, for which, depending on α, velocities of vertical wind profile flows and height independent wind velocity flows are the same. Using a vertical wind profile objects higher than this critical height will be subject to higher wind loads than calculated without a vertical wind profile. The opposite is true for objects lower than this critical height. The critical height h_C can be computed by

$$h_C = h_1 \cdot (2\alpha + 1)^{1/2\alpha}.$$

For the construction of offshore plants different methods are used in practice for wind profiles. Det Norske Veritas (DNV) uses a logarithmic approach [6,7] for the vertical wind profile as a function of height in combination with the averaging time interval, given by

$$\overline{V}(t, z) = \overline{V}(t_r, z_r) \cdot (1 + 0.137 \ln(z/z_r) - 0.047 \ln(t/t_r)). \tag{6}$$

Here z_r represents the reference height (10 m), t_r the reference averaging time interval (600 s) and t, z are the variable time and heights. We observe that the roughness length is not included in this formula, which implies that this formula only applies to situations at sea. In the next section we will have another look at this approach, when the phenomenon gust factor is introduced.

An approach by Hancox [8,9], used in practice in the offshore industry, is similar to the method mentioned above. There, the influence of the vertical wind profile is taken into account by the use of different height coefficients for separate height intervals. However, it seems that the effects of a vertical wind profile are not taken into account explicitly in formula used in daily practice for determination of wind loads on regular ships.

Our developed software takes into account the influence of height dependent wind velocities by including the defined vertical wind profile in the process of integration with respect to height, according to

$$Y_{wind} = C_y \rho/2 \sum_{n=1}^{N_s} L_n \int_0^{H_n} V^2(z)\, dz, \tag{7}$$

where N_s sections of a ship with lengths L_n and heights H_n are used. In the case of different heights over the ship's length separate length sections can be used. The validity of using one shape coefficient for separate length sections will be discussed later.

Furthermore, we use in our software a 1/10 power law profile for regular ships for situations at sea. For 'not exposed' harbour situations, a logarithmic profile (4) with a roughness length of 0.2 m was chosen. The reason for choosing this approach is the use of a height dependent gust factor which is especially applicable to a logarithmic profile. This will be explained in the next chapter.

For high (offshore) structures at sea, formula (6) has been implemented in the software used. This method combines the use of a logarithmic vertical wind profile with the use of a already mentioned gust factor. Following this procedure the introduction of an error due to the use of height intervals is avoided.

Gust factor (GF)

An important issue regarding the wind velocity is the phenomenon gust factor (GF): a factor to be applied to average wind velocities for longer periods of time to find the maximum average wind velocity for shorter periods of time. Introduction of a gust factor extends the basic formula to

$$F = C_y \rho A (GF \cdot V)^2/2.$$

The wind velocity at a defined height is not constant in time. Variations in velocity as well as the duration thereof depend, amongst other things, on the height. Close to the water level so-called wake effects of surrounding obstacles or a rough sea will cause these variations. In this scenario the roughness length (z_0) is important. At higher levels variations due to higher wind velocities usually last longer and are mainly caused by instability of the boundary layer. With respect to wind loads on ships, given a defined height and geographical situation, the question arises which wind velocity, or rather the mean wind velocity of which duration, should be used in determining these loads.

For wind forecasts the World Meteorological Organization (WMO) advises the use of durations from 10 to 30 minutes. Usually the wind velocities referred to in weather forecasts are 10-minute mean values. In order to determine a mean velocity for shorter durations the 10-minute mean value is multiplied by the gust factor. When using actual readings of a wind velocity sensor it depends on the time interval at which the readings were observed. For longer observations the observer can take the peak velocities into account. Then the necessity for using a gust factor decreases.

In [10] Kareem defined the phenomenon gust factor by

$$\begin{aligned} GF(t,z) &= \frac{\overline{V}(t,z)}{\overline{V}(1\text{hr},z)} \\ \overline{V}(t,z) &= \overline{V}(1\text{hr},z) + g(t)\cdot\sigma(z), \end{aligned} \tag{8}$$

with $\sigma(z)$ the standard deviation at height z and $g(t)$ a peak factor. We observe that in (8) a reference time interval of 1 hour is used. In some cases other intervals are used, e.g. 10 minutes.

The standard deviation is directly proportional to the turbulence intensity. Given a wind velocity registration, the geographical situation and the height, the values of both $g(t)$ and $\sigma(z)/\overline{V}(1\text{hr}, z)$ can be determined. The shorter the period of time, the higher the gust factor will be. A different interpretation of (8) with a reference time interval of 10 minutes yields

$$GF(10\text{min} \rightarrow 1\text{min}, z) = 1 + g(10\text{min} \rightarrow 1\text{min}, z) \cdot \frac{\sigma(z)}{\overline{V}(10\text{min}, z)}, \qquad (9)$$

where $g(10\text{min} \rightarrow 1\text{min}, z)$ and $I(z) = \sigma(z)/\overline{V}(10\text{min}, z)$ represent the peak factor and the turbulence intensity respectively.

According to Wieringa and Rijkoord [4] this turbulence intensity may be estimated by

$$I(z) = 1/\ln(z/z_0). \qquad (10)$$

Both, relations (9) and (10), clearly show the dependence of GF on the height z. From (10) the dependence of the roughness length z_0 can be seen. The value of the peak factor g depends on the height as well but that influence is of minor importance.

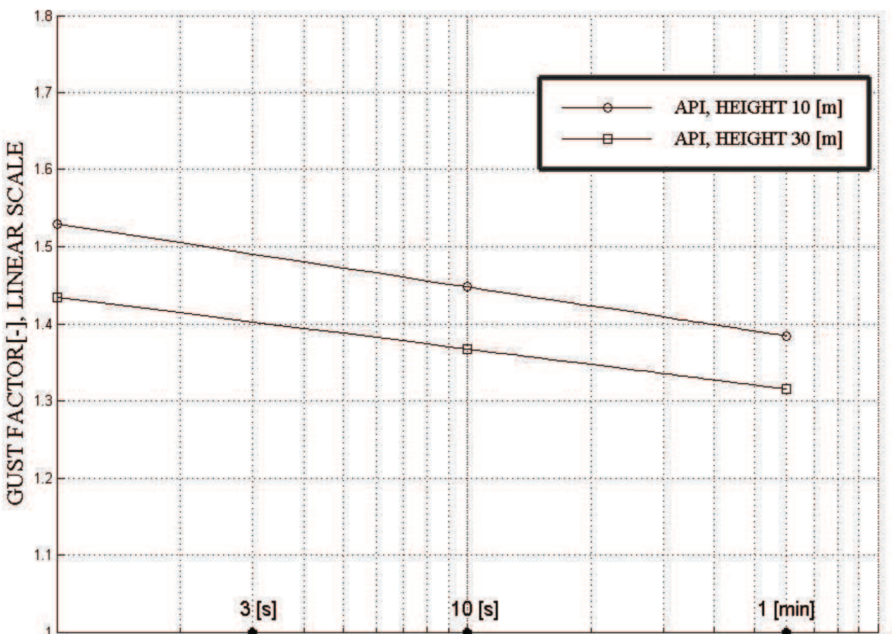

Figure 2: Comparing gust factor values of API for heights of 10 m and 30 m

As stated above, the value of a gust factor depends, amongst other things, on the height. This is shown clearly in Figure 2: the values used by the American Petroleum Institute (API) are shown for two different heights. Values of gust factors as well as calculation methods mentioned in literature are not exactly the same, as most of these values are valid for the defined wind profile coefficients or logarithmic relationships used. Therefore gust factor values of e.g. API, DNV and PIANC should not be compared reciprocally!

Another important issue in the use of a gust factor is the response of a vessel to gusts. In particular the gust duration, which is relevant for the vessel and manoeuvre concerned, are of great importance. PIANC [5] states that intervals of more than 1 minute may be considered relevant for large vessels. This is an arbitrary value, since two vessels with exactly the same lateral area (for instance a car carrier and a loaded tanker), will not respond in the same way to the same gust because of their different displacement and added mass.

The gust wavelength is the product of the duration of the gust and the mean wind velocity in that gust [4]. In this way gusts have physical dimensions. This is important since it means that objects are often not completely exposed to the gust concerned.

There are several ways to take the influence of gustiness into account. The most uncomplicated approach is the multiplication of the wind velocity with a constant that only depends on the averaging time. This method was proposed by PIANC [5]. Table 1 gives an overview of the proposed GF values.

Table 1: Gust factors depending on averaging time durations [5].

Duration	GF
3 seconds mean	1.56
10 seconds mean	1.48
1 minute mean	1.28
10 minutes mean	1.12
30 minutes mean	1.05
1 hour mean	1.00

In many circumstances these values can be of great help. However, in reality the value of a gust factor depends on the height above sea level or a landmass as well as on the local roughness of the terrain. An example of an existing approach used in the offshore industry is the method of Det Norske Veritas (DNV) [6,7], based on formula (6).

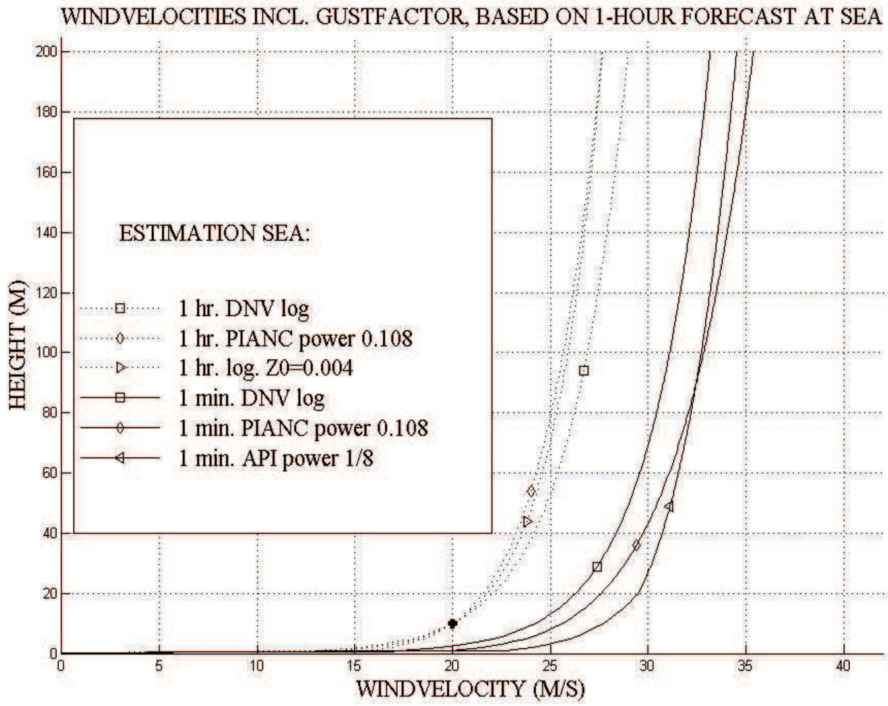

Figure 3: Comparison of some mean wind velocities at sea: 1-hour mean and 1-minute mean values.

Figure 3 shows a comparison of wind velocities according to different approaches discussed in this article: some 1-hour mean values ($GF = 1$) and some 1-minute mean values for situations at sea. In this figure 'Log' means defined by a logarithmic function and 'power' means defined by a power law.

Usually a gust factor is not applied in daily practice, when determining wind loads for normal ships. The same goes for the offshore industry. It is not known by the authors whether or not effects of gusts are included, in a general way, in safety margins used in daily practice.

Based on this study we have implemented two possible choices for GF:

- no gust factor at all ($GF = 1$), (probably used in most circumstances),
- a gust factor for a 1-minute mean wind velocity (based on [5]).

When the use of a gust factor is chosen the calculation methods are different:

- for ‘normal’ ships at sea or in exposed harbours, as proposed in [5] by PIANC,
- for complex structures at sea or in exposed harbours, the use of a height dependent gust factor in combination with the corresponding wind profile as proposed by DNV [7],
- for ‘normal’ ships and complex structures in ’not exposed harbours’, the use of a height dependent gust factor as proposed by the Royal Netherlands Meteorological Institute (KNMI).

All of these calculations are based on weather forecasts providing a 10-minute mean wind velocity. Since the gust factor is height dependent, it is included in the process of numerical integration. As mentioned before the value of a gust factor depends, amongst others, on the roughness length (see formula (10)). Neither PIANC, nor DNV takes this into account. For this reason we searched for a method to determine a gust factor which can be used in ’not exposed’ harbours where a different vertical wind profile is valid. From KNMI as well as from [11] we received valuable information about the value of the so-called peak factor (9) applicable in these situations. This information is especially applicable to vertical wind profiles defined by logarithmic functions. For this reason the software uses this logarithmic function.

Figure 4 shows a comparison of wind velocities according to different approaches discussed in this article. As in Figure 3 we show a comparison of wind velocities with and without the use of a gust factor, above land with a roughness length of 0.2 m. This has been depicted in Figure 4. In order to be able to compare Figures 3 and 4, the wind velocity of 20 m/s at sea is translated into an estimated velocity for the geographical position concerned, which is not straightforward.

In [4] a formula is presented to estimate the velocity at geographical positions, given the velocity at another position. First the expected velocity at reference height z at sea is translated into a velocity at the so-called blending height (for the blending height 60 m is chosen). When the distance

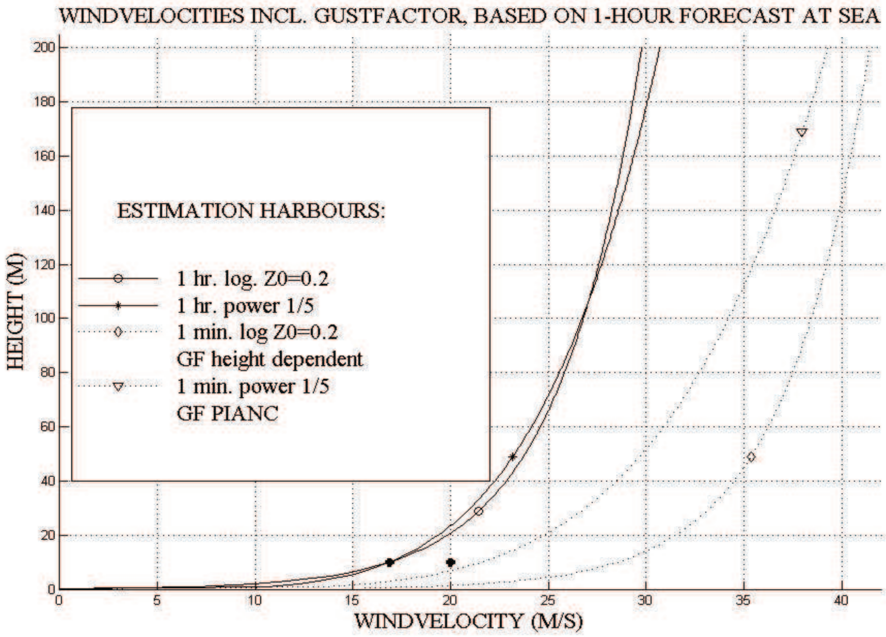

Figure 4: Comparison of some mean wind velocities ashore: 1-hour mean and 1-minute mean values.

between the two positions is not too long (about 5000 m), the wind velocity at blending height is supposed to be the same for both positions. Then the wind velocity at blending height above the 'not exposed' harbour is translated into a velocity at the local reference height according to the local vertical wind profile, see Equation (11):

$$V_{\text{land}} = V_{\text{sea}} \cdot \left(\frac{\ln(60/z_{0,\text{sea}}) \cdot \ln(z_{\text{land}}/z_{0,\text{land}})}{\ln(60/z_{0,\text{land}}) \cdot \ln(z_{\text{sea}}/z_{0,\text{sea}})} \right). \tag{11}$$

For a height of 10 m, with roughness lengths of 0.004 m (sea) and 0.2 m (land), this results into $V_{\text{land}} \approx 0.843 V_{\text{sea}}$. Formula (11) was used when compiling Figure 4, i.e., to estimate the wind velocities at 10 m height above land. For comparing Figures 3 and 4 two stars are plotted at 10 m height: one at velocity 20 m/s and one at about 16.9 m/s. The first one represents the wind velocity at sea at 10 [m], the second one the estimated wind velocity in a nearby 'not exposed' harbour. From a practical point of view the remarkable increase of wind velocity caused by the use of a gust factor for a vertical wind profile above land, especially at lower heights, is a very important conclusion.

One may argue, that the gust factors used are arbitrary values, but at least they decrease the risk of calculating wind loads based on weather forecasts too low. The chosen values result in a considerable increase of load since the latter is determined by the square of the velocity. In most cases however, in practice the use of a gust factor will be omitted since wind velocities will be observed on local sensors and for a longer period of time.

Shape coefficient (C)

The value of the shape coefficient depends for the most part on the three dimensional shape of the object concerned and on the angle of attack of the relative wind approach. Since there is a great variety in three dimensional shapes of ships, the only realistic way to determine shape coefficients is by means of experiments like full-scale tests or wind tunnel tests using scale models. In this way the effect of mutual interference of nearby individual parts of the complete object is included in the coefficient. A disadvantage of full-scale tests is that laboratory-like circumstances are hard to create: disruptions of stable wind velocity situations are nearly always present. Gathering experimental data is time consuming and expensive, therefore these data are only available for a restricted number of ship types.

We will define the angle of attack for bow wind as 0°. In the context of this article we will use the value of the shape coefficient for relative crosswind for the most part: in that case the relative angle is ±90°. The value of the shape coefficient also depends on the computational model used. Therefore, the values of a shape coefficient for these methods may differ substantially.

In [5], PIANC proposes a rough estimate of the shape coefficient for 'normal' ships of 1.1 for cross wind for general use in combination with formula (2). Although not mentioned explicitly, we assume in this case the wind velocity at a height of 10m, where velocities at other heights can be derived by formula (5). For head wind an estimated value of 0.8 is mentioned.

The Oil Companies International Marine Forum (OCIMF) [12,13] has published coefficients for VLCCs and large liquefied gas carriers. The data for VLCCs is based on wind tunnel tests conducted at the University of Michigan in 1975. The data for LNG carriers are based upon tests carried out in the industry. Both publications suggest that the values mentioned therein might be rather conservative. The reason mentioned is that the coefficients must be applicable to a general range of vessel forms. Also their calculation method is based on formula (2) using the wind velocity at a height of 10m and a modification of the velocity by formula (5) using a height exponent $\alpha = 1/7$. The coefficients we obtained from there differ substantially from a study by Blendermann [2]. The difference in wind loads shows a ratio of about 1.4. It is difficult to indicate the reason for this but it should be kept in mind that, although LNG carriers with spherical tanks were used for both tests, the shapes of the vessels show significant differences in dimensionless ratios like e.g. L_{oa}/B (Length over all divided by Breadth).

In the offshore industry, it seems to be common practice to calculate the loads for separate characteristic parts of the complete construction followed by addition of the loads on these separate parts. Both, DNV [7] and Hancox [8,9], use different shape coefficients for these separate parts. Some values mentioned in [7] are given in Table 2.

Table 2: Shape and shape coefficient as in [7].

Shape	Shape coefficient (C)
Spherical	0.4
Cylindrical	0.5
Large flat surface (hull, deckhouse)	1.0
Clustered deckhouses	1.1
Wires	1.2
Drilling derrick	1.25
Isolated shapes (crane, beam)	1.5

Using a vertical wind profile which is defined by height (z) combined with a certain averaging time interval (t) and different shape coefficients for individual parts of the construction leads to:

$$F_{\text{wind}} = \sum_{n=1}^{N_s} C_{s,n}\, \rho\, L_n/2 \int_{h_{1,n}}^{h_{2,n}} V^2(t,z)\, dz. \qquad (12)$$

For ‘normal’ ships the derived software offers the user different levels of accuracy. Besides, it offers the use of one or more length sections: sections of different heights and reaching from sea level. Furthermore, the following methods of application of a shape coefficient are offered:

1. A method requiring a minimum of time for calculating wind loads makes use of different preset values of the components used in the calculations; in this case a value of 1.0 is used for the shape coefficient.

2. More advanced methods offer:
   a) A value of the shape coefficient of 1.1 ($\approx$ PIANC),
   b) A value of the shape coefficient based on a mean value of comparable types of ships [2], converted to values to be used in formula (7).
   c) Values of the shape coefficients (for different angles of wind approach) for specific ships mentioned in [2].

In method 2c the software uses the calculation method proposed by Blendermann. In this case the projected lateral area is represented by one rectangular reference area. A distribution of the cross wind load to forces on bow and stern is available for several angles of attack of the relative wind. The longitudinal wind load is shown as well. When the type of vessel concerned is not available in [2], the vessel may be divided into separate length sections followed by application of method 2a or 2b offering a distribution of forces on bow and stern as well.

We observe that the distribution of forces at bow and stern is impossible in case of use of only one rectangular section. When using an estimated coefficient for more than one length section, the same coefficient is used for all sections. This is not fully correct since separate length sections will usually not be subject to exactly the same shape coefficient. The sum of the forces will still be correct. The results of the calculation of the distribution of forces on bow and stern however, may be affected. A comparison of calculation results of methods 2b and 2c for some of the vessels available in [2] show promising results: differences in forces at bow and stern of at most 4%.

For complex (offshore-) structures the computer program uses the values of shape factors mentioned by DNV [7]. The outlines of the calculation method proposed by DNV are applied: calculation of loads for separate characteristic sections followed by addition of these separate loads. The selection of sections may be based on different heights, different shape factors and/or different contours of the projected lateral area. Since the effect of mutual interference of nearby individual parts of the complete object is neglected, this method gives a rough indication only.

Comparisons of results of full-scale measurements, wind tunnel tests and the method mentioned above show that wind loads found by this method would usually be too large [14]. For use in practice the availability of a safety margin is an advantage since it reduces the risks. A disadvantage is the extra charges for tugs. On the other hand these structures do not call at ports frequently.

Air mass density (ρ)

The density of the air flowing around the vessel is a function of the height and depends on the air temperature at sea level (T_0), the rate of change of temperature with respect to the height (a), the atmospheric pressure at sea level (P_0) and the humidity.

The humidity factor will not be addressed in this article since this item is beyond the original scope of this research. Using the standard atmosphere as a starting point, the effect of all of the other factors mentioned above is included in one single formula [15,16] given by

$$\rho(z) = \frac{P_0}{RT_0}\left(1 + az/T_0\right)^{-(1+g_0/aR)},$$

with R the gas constant (in dry air) and g_0 the gravity constant at mean sea level.

The rate of change of atmospheric pressure with the height plays a role too and depends on the temperature. It plays a minor role but greater than the role of the rate of change of temperature (with the height) itself.

Using a realistic temperature range and atmospheric pressure range as starting point, the possible differences of temperature have a far greater influence on the air mass density than the possible differences of atmospheric pressure. The influence of these factors is often neglected in daily practice. A constant value often used is 1.225 kg/m^3. Most classification societies neglect this influence, which is rather surprising, since the temperature factor especially may contribute to a relatively high percentage of wind loads.

All of these contributions are included in the computer program where $\rho(z)$ is included in the integrand. The necessary input data are the temperature at sea level, the atmospheric pressure at sea level and the height interval.

Projected lateral area (A_L)

In many cases, especially when constructions are considered as a combination of separate sections, each with its own contour and shape coefficient, it is useful to express the width of the lateral area concerned as a function of the height, i.e., $dA = L(z)\,dz$. In our software we only use this method for complex constructions, as for 'normal' ships a concatenation of rectangles can be used. A variety of contours of the projected lateral area is shown in the menu driven program, offering the user choices. In accordance with methods used in books on practical oil field seamanship 20% is added to the projected lateral areas concerned for small parts, which are not included in these areas. Since the addition of 20% is represented by a constant factor of 1.2, it does not influence the process of integration and is applied to the total of wind loads.

Resulting Formula and the Software

As explained in the previous subsections, ρ, GF, V and often also L, are functions of the height. The formula that combines all the previous considerations, taking (12) as a starting point, may now be written as

$$F = C_y/2 \int_{h_l}^{h_u} \rho(z)(GF(z) \cdot V(z))^2 L(z)\,dz.$$

In the derived computer program this force is computed by means of numerical integration.

In order to offer masters, navigation officers and pilots the possibility of estimating the wind loads of cross winds for a great variety of ships / complex objects in daily practice, MPIN and NLDA developed a menu supported computer program. One of the criteria was that the method should not be time consuming. The software offers the choice between calculation of wind loads on ships and the calculation of wind loads on complex constructions.

The effects of air density, a vertical wind profile and the possibility to use a gust factor (mostly height dependent) are included in both methods. Depending on the required accuracy different paths can be followed. Report [17] gives more background on the structure of the program and the computing methods used. The program is also used within the Royal Netherlands Navy [18].

Conclusions

The subject of determining wind loads on ships appears to be very complex. The most common used methods to determine wind loads in daily practice are often based on simplified models. By doing this too many risks may be taken: risks for damage, or worse, for human life and the environment. In most cases the formula used by the Dutch pilots shows reasonable results. For low or extra high objects however substantial differences may appear.

We observe, that there are only two ways to determine correct wind coefficients for objects like ships: full scale trials and wind tunnel tests. Furthermore, despite the existence of scientific approaches it remains very difficult to determine the actual forces being exerted by wind on a ship to a high level of accuracy. Taking account of the influence of air temperature, atmospheric pressure as well as the rate of change in both, on the air density, a higher level of accuracy is reached. Also, taking into account a realistic vertical wind profile instead of using no wind profile at all, leads to a higher level of accuracy.

In daily practice the influence of gusts may cause serious problems: a good reason to take into account a value for the gust factor. Especially when wind loads are calculated based on wind forecasts. Gusts depend to a great extent on local circumstances and appear to be an extremely complex subject. Existing gust models require an extensive study for each particular geographical situation and wind direction. Within the derived software choices had to be made as to the application of these models. Since 'easy to use in daily practice' is one of the preconditions in this study, simplification of gust calculations could not be avoided. From a practical point of view the remarkable increase of wind velocity caused by the use of a height dependent gust factor for logarithmic profile with higher roughness lengths, especially at lower heights, is a very important conclusion.

Attention should be paid to the fact that values of wind loads depend to a certain extent on the actual vertical wind profile. This can be taken into account either in a way as proposed by Blendermann [2,3] or leading to the same result, by adjustment of the transverse force coefficient. As a result of this, indiscriminate comparison of coefficient values from tests or research may result into wrong conclusions.

Recommendations

In the authors' opinion further study should address the following aspects:

- Better insight into the effect of wind on large high-sided vessels, in particular the large container vessels expected to come. These vessels with their containers high-stacked on deck have such a height (and width) that the wind coefficients used now may not reflect reality. With respect to this aspect wind tunnel tests might be very useful.
- The same applies to other ships and floating structures, of which construction differs significantly from what has been seen as normal up until now. An example is the type of cruise vessels with cabins located in such a way that a rough 'indented' surface of shipsides is created with regard to wind.
- Better insight in appropriate wind spectra, in particular with respect to wind gusts, and their influence on ships and floating structures. A question to answer is what effect the gust wave length has on the forces being exerted by the wind on a ship, taking into account type, size, displacement and hydro dynamical characteristics of the vessel concerned.
- Extension of computer programs to calculate wind loads, based on the results of the previous recommendation, by offering the use of different gust durations.
- The possibility of implementation in the computer program of the probabilistic and spectral modelling approach as published by Blendermann [19].
- It might be useful to study whether the technique of computational fluid dynamics can be used to determine wind coefficients for ships and offshore structures.

References

[1] R.M. Isherwood, "Wind resistance of merchant ships," in *Proceedings RINA*, 1973.

[2] W. Blendermann, "Wind Loading of Ships - Collected Data from Wind Tunnel Tests in Uniform Flow," Hamburg University, Hamburg, Report Nr. 574, 1996.

[3] W. Blendermann, "Estimation of wind loads on ships in wind with a strong gradient," in *Proceedings OMAE 95*, Volume I-A (Offshore Technology), 1995.

[4] J. Wieringa and P.J. Rijkoort, *Windklimaat van Nederland.* Royal Netherlands Meteorological Institute, Staatsuitgeverij, 1983.

[5] PIANC, "Report of working group 1 (International Commission For The Reception Of Large Ships)," annex to Bulletin No. 32 Vol. I, PIANC, 1979.

[6] Det Norske Veritas, *Classification notes*, No. 30.5, 2000.

[7] Det Norske Veritas, *Offshore Standard DNV-OS-C301,* 2001.

[8] M. Hancox, *Towing. Oil Field Seamanship Vol. 4.* Oil field publications Ltd., 1994.

[9] M. Hancox, *Jackup Moving. Oil Field Seamanship Vol. 2.* Oil field publications Ltd., 1994.

[10] J.D. Riera and A.G. Davenport (eds.), *Wind Effects on Buildings and Structures.* Rotterdam: Balkema, 1998.

[11] J.W. Verkaik, "Evaluation of two gustiness models for exposure correction calculations," *Journal of Applied Meteorology*, vol. 39 no. 9, 2000.

[12] Oil Companies International Marine Forum, *Prediction of Wind and Current Loads on VLCC's,* 2nd. edition. Witherby & Co Ltd., 1994.

[13] Oil Companies International Marine Forum, *Prediction of Wind Loads on Large Liquefied Gas Carriers,* OCIMF and SIGTTO, 1985.

[14] H. Boonstra, "Wind tunnel tests on a model of a semi submersible platform and comparison of the results with full scale data," in *Proceedings Offshore Technology Conference*, Houston, 1982.

[15] F.M. White, *Fluid mechanics*, McGraw-Hill, 1999.

[16] De Jong, *Electromechanical instruments*, Dutch National Aviation Association.

[17] M.J. Hilten, "Rapportage orienterend onderzoek windbelasting op schepen en hoge transporten," Loodswezen, Hoek van Holland / Royal Netherlands Naval College, Den Helder, Technical Report, 2001.

[18] D.J. Engelbracht, "Windkracht uitgeoefend op het LCF," Report MHKC, Royal Netherlands Naval College, Den Helder, 2003.

[19] W. Blendermann, "Probabilistic and spectral modelling of the wind loads on ships," Hamburg University, Report Nr. 615, 2001.