The wave influence on wind pressure fluctuation of drifting rescue units

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Abstract

In the article the stochastic model of wave influence on wind loading fluctuation of drifting rescue units is presented. Wind speed is the single most important factor when trying to determine basic wind pressure. Wind motion is turbulent, and it is difficult to give a concise mathematical definition of turbulence. However, it is known that wind turbulence exists due to the lower viscosity of air in comparison with water. Any air motion faster than 4 km/h is turbulent; i.e., air particles move erratically in all directions. Basic wind pressure is affected by the uncertainty effect caused by the likelihood of the wind hitting the drifting rescue unit from any given direction. This parameter is known as the directionality effect.

The pressure exerted by strong winds on the life raft is a function of the dynamic part of Bernoulli's equation, known as basic pressure, which is modified by the following factors: wind direction according to a life raft axis system, wind speed, the life raft height, wave height, wave slope angle. Two random factors were considered. The first one is the drifting rescue unit heeling angle to the horizontal plane. The second one is connected with the position of drifting rescue unit on wave slope. The results obtained during laboratory tests in wind tunnel were used to model wind pressure on a life raft. The measurements of a life raft movement on waves obtained during sea experiments were used to estimate the distribution of pitch and roll angle. The position of drifting rescue unit on a wave slope has uniform distribution. The wind load coefficients for life rafts presented in this paper are derived from wind tunnel tests in uniform flow obtained at the Aviation Institute in Warsaw. Data of life raft movements on waves have been collected during full size experiments at sea. Data from wind tunnel test are the basis of knowledge of wind loads on drifting rescue units.

Keywords: *Drifting rescue units, wind pressure, wind pressure stochastic model*

INTRODUCTION

The power in the wind is a function of air density, the area intercepting the wind, and the instantaneous wind velocity [4]. Changing any one of these factors influence the power available from the wind.

In the case of variable wind the wind pressure Fw on a life raft should be treated as spatial - time stochastic process, stationary and ergodic with respect to time. Wind pressure depends on a moment speed of wind and it should be presented as amount of static load Fs and the random fluctuation of load dynamic Fd. For example a wind pressure on perpendicular surface in direction of undisturbed air flow is given by formula:

$$F_w = F_s + F_d \tag{1}$$

Wind intercepting area is a variable depending on the place on wave of a drifting rescue unit (DRU). In the case of random place of DRU the wind intercepting area should be treated as a realization of random function dependent on pitch angle, roll angle and location on a wave slope.

THE WIND FORCE

In the wind tunnel the apparent wind velocity Vw and angle are measured in the horizontal plane. The drive force and side force are measured in a horizontal plane, where the drive force is parallel to the centerline of the drifting rescue unit and the side force perpendicular to it, [7]. The vertical force is positive upwards.

The effect of a DRU heeling can be incorporated in the apparent wind angle to form an effective angle where the effective angle is the apparent angle in a plane normal to the z-axis.

The effective wind velocity (V_{eff}) is defined as the component of Vw in a plane normal to the z axis and calculated from

$$V_{eff} = V_w \cdot \cos(\phi) \cdot \cos(\psi) \tag{2}$$

where
ϕ - roll angle,
ψ - pitch angle.

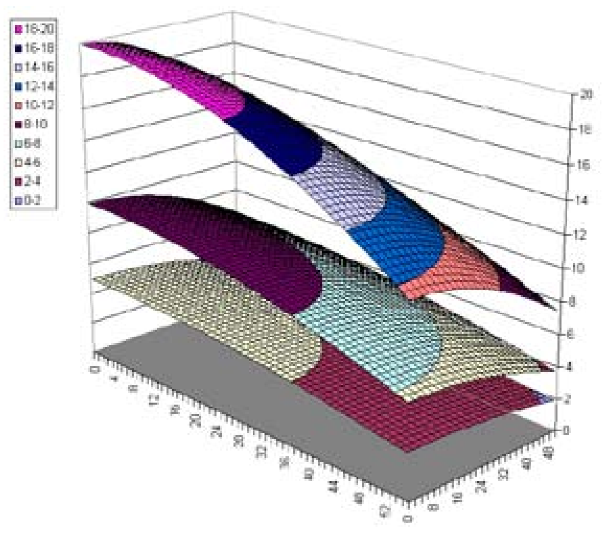


Figure 1 *Example of an effective wind velocity as a function of roll and pitch angles for wind speed 10, 20 and 40 knots.*

We will assume that the marginal distribution of the mean wind speed at 10 m can be described by the 2-parameter Weibull distribution:

$$F_w(x) = 1 - \exp\left\{-\left(\frac{x}{\beta}\right)^{\alpha}\right\} \tag{3}$$

where α and β are the shape and scale parameters, respectively.

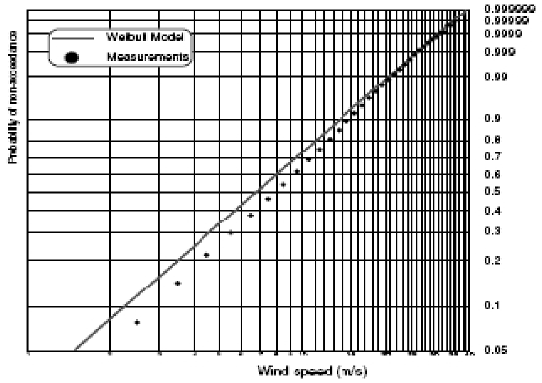


Figure 2 *Cumulative frequency distribution of 1-h mean wind speed for Northern North Sea, [1].*

The following equation is to be used to calculate the wind heeling force to be assumed acting on structure at a given height above the mean waterline:

$$F_w = \frac{0,5}{g} \cdot \rho_a \cdot A_d \cdot C_d \cdot \left(v_w^2 + v_w \cdot v(t)\right) \tag{4}$$

where:

F_w - is the wind force,
ρ - air density,
C_d - shape factor (drag coefficient),
A_d - the wind intercepting area,
v_w - average wind speed,
$v(t)$ - random fluctuation of wind velocity.
g - is acceleration due to gravity.

The wave influence

The location of a drifting rescue unit on a wave (crest or slope) can cause changes in wind pressure affecting a DRU, significantly changing the wind intercepting area and wind's basic pressure. Other conditions, such as a DRU trim and a wave slope angle are very important too. The pressure exerted by strong winds on the DRU is a function of the dynamic part of Bernoulli's equation, [5], known as basic pressure, which is modified by the following factors: wind direction in relation to a DRU axis system, wind speed, the DRU height, wave height, wave slope angle. A trochoid is the locus of a point at a distance R from the centre of a circle of radius r rolling on a fixed line. A trochoid has parametric equations. One of the simple mathematical methods used to describe a sea wave motion is the trochoid formula, [3], [6]:

$$\begin{aligned} x &= R \cdot \Theta + r \cdot \sin\Theta \\ z &= R + r \cdot \cos\Theta \end{aligned} \tag{5}$$

where:

R - distance from the centre ,
r - radius of the inner circle, $2 \cdot r = h_w$ - wave height.
Θ - parameter of the position.

Approximating the sea waves with trochoid allows to show influence of the wave height on wind forces. If the reference plane „0" is a wave though then the formula for DRU vertical position on a wave is:

$$z = r - r \cdot \cos\Theta \tag{6}$$

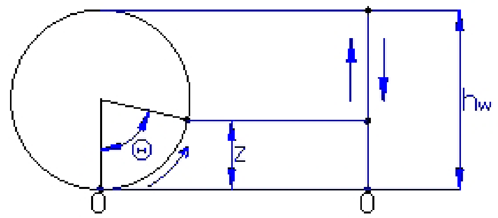


Figure 4 *Position of the search object on the trochoid, [9].*

Let's assume that random variable Θ has a continuous uniform distribution from 0 to 2π, which is described by the density function:

$$f(\theta) = \begin{cases} \frac{1}{2\pi} & \text{for} \quad \theta \in <0, 2\pi) \\ 0 & \text{for} \quad \theta \notin <0, 2\pi) \end{cases} \tag{7}$$

Accordingly, the cdf is

$$F(x) = \begin{cases} 0 & \text{for} \quad \theta \le 0 \\ \frac{x}{2\pi} & \text{for} \quad 0 < \theta \le 2\pi \\ 1 & \text{for} \quad \theta > 2\pi \end{cases} \tag{8}$$

The expectation of this distribution is

$$E(\theta) = \pi \tag{9}$$

According to (5) and [1] we can assume that random variable r has a Weibull distribution, with parameters dependent on sea region, which is described by the density function:

$$f_X(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} e^{-\left(\frac{x}{b}\right)^c} \qquad x \ge 0, c > 0, b > 0 \tag{10}$$

where

b- scale parameter,
c- shape parameter.

Nondimensional parameter C_{Ap} describing the proportion of a DRU wind intercepting area is given by formula

$$C_{Ap} = \left(1 - \frac{h_w(1 + \cos\Theta)}{2h_{SO}}\right) \qquad \text{for } h_w \le h_{SO} \tag{11}$$

where:

h_{SO} - height of drifting rescue unit, [m];
hw - height of wave, [m].

In this case equation describing the wind heeling force acting on DRU at a given position on a wave is given by formula:

$$F_w = \frac{0,5}{g} \cdot \rho_a \cdot C_{Ap} \cdot A_d \cdot C_d \cdot \left(v_{eff}^2 + v_{eff} \cdot v(t) \right) \tag{12}$$

where:

C_{Ap} - is the random variable;

Assuming that the h_{SO} is constant, the random variable C_{Ap} has the distribution function which is described by the density function:

$$\Pr\left(C_{Ap} < z\right) = \Pr\left(1 - \frac{h_w(1+\cos\Theta)}{2h_{SO}} < z\right) = \Pr\left(1 - z < \frac{h_w(1+\cos\Theta)}{2h_{SO}}\right) =$$
$$= \Pr\left(\left(1-z\right)\cdot 2h_{SO} < h_w(1+\cos\Theta)\right) = 1 - \Pr\left(h_w(1+\cos\Theta) \le \left(1-z\right)\cdot 2h_{SO}\right) \tag{13}$$

$$f_{C_{Ap}}(z) = -\frac{\partial \Pr\left(h_w(1+\cos\Theta) \le (1-z)\cdot 2h_{SO}\right)}{\partial z} =$$
$$\int_0^\infty \frac{\beta x^{\beta-1}}{\theta^\beta} \exp\left(\frac{x}{\theta}\right)^\beta \cdot f_{1+\cos\Theta}\left(\frac{(1-z)}{x}\cdot 2h_{SO}\right)\cdot\frac{2h_{SO}}{x}dx \tag{14}$$

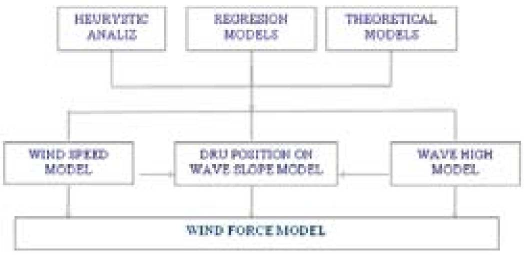


Figure 5. *Wind force model diagram.*

Application

Aerodynamic experiments of inflatable life rafts were performed in the Laboratory of Low Velocities in the Institute of Aviation, [7]. The aim of laboratory experiments was to determine the wind forces acting at a life raft. The research was carried out in the aerodynamic tunnel. The research concerned the range of speeds in the measurement space of the tunnel from 20 to 64 knots, Vw = 10-34 m/s. The results obtained from laboratory experiments allow to estimate life raft's real aerodynamic drag. This statement follows from lack of wind speed influence on flow character around raft.

Laboratory data were analyzed by the statistical program Statgraf. Regression models of relation between wind velocity and measured forces and moments were obtained.

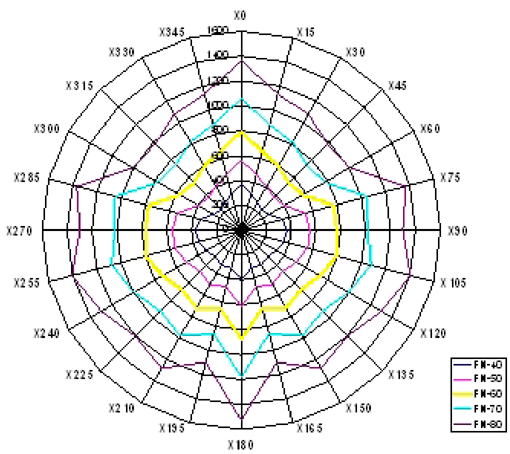


Figure 6. *The space distribution of wind heeling force, steady conditions- 40, 50, 60, 70, 80 kn wind speed, results from wind test tunnel for a ten-person life raft, [7].*

$$Y_\theta(\omega) = \frac{2\cdot\theta_a}{H_w}$$ - amplitude characteristic of pitching;

H_w - wave height, [m];

θ_α - pitching amplitude, [o]

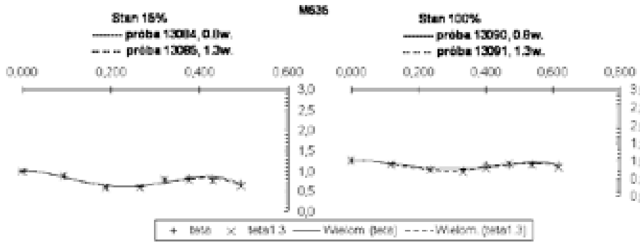
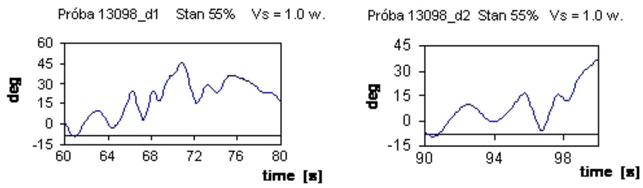


Figure 7. *Examples of pitching amplitude characteristic for the life raft.*



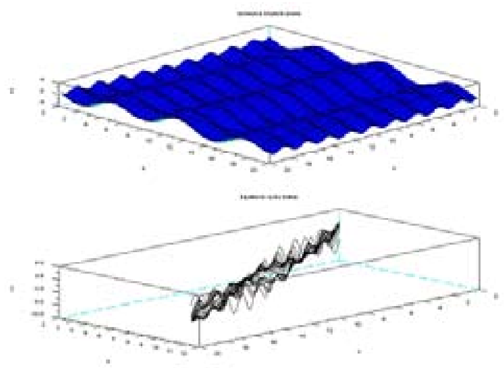


Figure 9. *Examples of drifting trajectory for the life raft obtained by the Monte Carlo method.*

Figure 10. *Checking the roll time for the life raft.*

Table 1 *Summary Statistics for roll and pitch*

Parameter	Roll	Pitch
Count	16383	16383
Average	-3,62876	-0,555882
Median	-3,65343	-0,55036
Variance	0,0214192	0,00721558
Standard deviation	0,146353	0,0849446
Minimum	-3,96105	-0,786566
Maximum	-3,13158	-0,270209
Range	0,829468	0,516357
Std. skewness	44,712	9,7818
Std. kurtosis	26,7091	4,51402

The table shows examples of summary statistics, measured for a 10-person life raft at sea tests. It includes measures of central tendency, measures of variability, and measures of shape. Of particular interest here are the standardized skewness and standardized kurtosis, which can be used to determine whether the sample comes from a normal distribution. Values of these statistics outside the range of -2 to +2 indicate significant departures from normality. The standardized skewness value is not within the range expected for data from a normal distribution. The standardized kurtosis value is not within the range expected for data from a normal distribution.

During tests the life raft had a trim according to the worst case of loading, asymmetry of 30% loading and drift velocity.

Conclusion

The excitation forces and moments in the DRU system are generated by wind and waves. Trim will play an important part in the stability of a DRU which is influenced by the wind, [8].

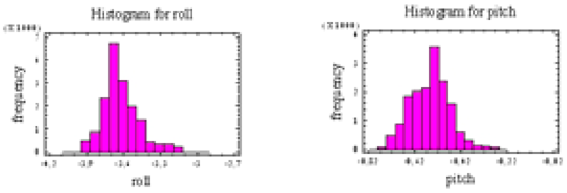


Figure 11 *Histogram for roll and pitch*

The mathematical model should be based on stochastic model and data from laboratory experiments.

Wind will play an important part in the response of any DRU that has a significant height above the waterline; the motions of DRU are influenced by the direction and characteristics of the wind. Application of wind forces and moments, estimated in the laboratory experiments for a particular drifting rescue unit type, will allow for more correct estimation of a DRU wind heeling arm and its stability. Dynamic models should be used to represent, or generate trends and patterns over time. They also could show averages per period, moving averages and comparative analysis. The dynamic wind force heeling model will be useful in estimation of a DRU safety.

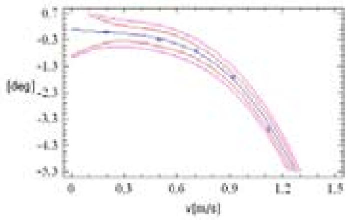


Figure 12 *The trim as a function of a life raft drift velocity, [1].*

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