On the External Forces in Consideration for a Stability and Buoyancy Criteria of a Drilling Rig

by

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Abstract

In order to establish a stability and buoyancy criteria of a floating vessel, the geometrical property as well as external forces and moments be dealt with. This paper discusses in general terms hidden but more salient factors of forces and moments of both natural and artificial origin, particularly wind, with regard to vessels of more general type such as oil drilling rigs.

A. Introduction

A vessel whether moving or at station performs or wants to perform certain functions in an environment. Therefore, the problem of establishing buoyancy and stability criteria is taken up in three parts. One of the parts deals with the vessel itself—its buoyancy, its righting moment, its operating characteristics, its countermeasures against flooding, list, capsizing, etc. The second part deals with the consideration of environment—forces and moments due to wind, waves, towline, thrusters, etc. The remainder is to establish certain criteria, of terminology, of design and of classification which is in fact allowances for safety, for accepted operational characteristics and for certain risks to which the vessel is to be classified.

For naval ships, Sarchin and Goldberg [1] have dealt with the problem of stability and buoyancy criteria in excellent detail. A number of quite useful, simple criteria have been accepted by various nations [2,3]. Although these require further syntheses to be of an "accepted criteria" as such, recently an interest on the problem has risen for more general type of vessels such as drilling rigs.

For a moe general type of vessel and for the part dealing with drilling rigs specifically, the righting arm concept, the floadable length and subdivision have been introduced [4,5]. A sketch of establishing criteria has also been introduced [6], although this will have to be expanded further in the future.

This paper deals in general terms with hidden but more salient factors of forces and moments from environment in the above three parts, specifically with regards to wind forces for vessels of more general types such as oil drilling rigs.

B. Estimates of Forces and Moments

a) General Considerations

External forces and moments on a vessel can be divided into two groups, (1) those due to the natural origin and (2) those due to the artificial origin. We shall refer to these as natural forces and artificial forces, respectively, for the lack of better names. Natural forces are in general distributed throughtout a part or parts of a vessel and the artificial forces are usually concentrated and hence simpler to treat. All forces and moments are inherently unsteady and particularly natural forces are. Not only the magnitudes of natural forces change but their distributions change in time thus causing variations in moments arm as well. In most cases, time varying forces can be taken to be periodic but not always. They may be aperiodic as well as random, latter being describable at best in some statistical sense. Also due to complex response motions of the vessel, the problem is non-linear and thus does not permit a superposi-

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tion of solutions.

What is done, then, is to treat the problem initially static and the dynamic component is taken into consideration either by a factor of safety or marginal allowances on the stability, allowable inclination and so on. Normally these allowances are included partly in the stability criteria that the owner or regulatory agencies establish in conjunction with the probability of risks involved.

This type of procedure has worked very satisfactorily in ships, but the same unfortunately can not be said of a more general type of vessel such as a drilling rig. This is because (1) experience with drilling rigs is rather short, (2) the dynamic component of force may be very large compared to the static component[1], and (3) a small dynamic force does not necessarily produce a small motion[2], the case being much more so than in a ship and particularly for unmoored rigs. The latter requires an explanation.

For a body floating on the free surface, say, in a heaving mode, the forces are:

$$\text{Natural Exciting Force} = -\begin{pmatrix}\text{inertia force}\\ \text{due to the added}\\ \text{mass only}\end{pmatrix} + \begin{pmatrix}\text{buoyancy}\\ \text{due to change}\\ \text{in elevation}\end{pmatrix} + \begin{pmatrix}\text{damping}\\ \text{force}\end{pmatrix} \quad (1)$$

Usually damping force is small and can be left out in this discussion. In a ship, the inertia term is small compared to the buoyancy and an exciting force on the left would balance out the buoyancy force. In a drilling rig, however, the inertia force is comparatively large and because of the negative sign in front almost cancells out the buoyancy term. The consequence of this is that a small exciting force can create a large amplitude motion although in a drilling rig the exciting force is rather small. This discussion is for a heave motion referring only at a given frequency. But, such a condition can indeed occur in an ocean.

Stopping short of a dynamic analysis, this leads us to conclude that a ***much more stringent stability criteria must be required of a drilling rig compared to a ship.***

b. Natural Forces and Moments

Natural forces and moments may be considered separately in three categories: wind forces, current forces and wave forces, although in many cases winds and waves exist together. Perhaps, a better approach is to specify the design condition by "sea state," "hurricane," etc. In our case, ***an assumption is made here that the superposition is possible.*** Two things must be borne in mind for this assumption. First, ***allowances should be made for the non-linearity*** and second, the ***degree of sophistication in calculations should be weighed against the assumption.***

To understand the non-linearity problem better, consider a simple drilling rig-like object subjected to wind. Due to the wind pressure on the upper portion of the vessel, the vessel heels to a certain angle until its buoyancy moment counterbalances the wind heeling moment. As soon as heeling occurs, not only the lateral wind force gets bigger, but an additional wind lift normal to the flat deck is generated. Both of these effects heels the vessel further and still greater forces and heeling moments will be generated, and so on. In actual conditions, winds, currents, and waves exist together and the compound effect is indeed difficult to predict precisely.

What this amounts to is that today there are a great deal of leeways exercised in estimating natural forces and moments.

(i) Wind forces.

Lateral wind force on the superstructure in the past has been given in an aggregate form:

$$F_{WD} = C_{WD} \cdot A \cdot V_K^2 \quad (2)$$

where C_{WD} : the wind force coefficient,

F_{WD} : the wind force in the direction of the wind in Lbs.,

A : projected area of the superstructure on a plane normal to the wind in square feet,

V_K : wind velocity in knots.

We will look closely at C_{WD}, A, and V_K, respectively. Ocean engineers in the past have used $C_{WD}=0.004$, but recently reduced it to 0.0025. For regular ships,

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1) S. G. Gibbs and T.E. Schellin, *EPR*(Shell Exploration and Production Research) 17·66–P, p. 11. The ratio of the maximum surge force to its mean is about 10.0, a high number.

2) S. Motora and T. Koyama, "On Wave-Excitation Free Ship Forms," *Japan Society of Naval Architects Transactions*, vol 117, 1965 (Text in Japanese.)

U. S. Navy has been using $C_{WD}=0.004$ and may reduce to 0.0035 [1].

In order to look at the figure better, rewrite (2) as

$$F_{WD}=C_D\frac{\rho_{medium}}{2}\cdot Av^2 \tag{3}$$

where C_D : drag coefficient as defined,
ρ_{medium} : density of medium, Lbs-sec/ft^4
v : wind speed, ft/sec.

The following table is made up for discussion purposes.

Table 1. Variation of C_D for Various Air-Water Mixture
ρ for water$=1.99$ Lbs-sec/ft^4
ρ for air$=0.00377$ Lbs-sec/ft^4.

Water content in Weight, %	Density of Medium (Air-Water Mixture) Lbs-sec/ft^4	For $C_{WD}=0.004$, C_D
0	0.0024	9.48
$\frac{1}{2}$	.0123	1.85
1	.0223	1.02
2	.0422	.540
3	.0621	.366

This table tells us that the force coefficient C_{WD} is not a realistic means of obtaining forces on a structure, for C_D must be an independent number irrespective of the density of the medium. The second point is that the force is heavily dependent on the moisture content, and therefore, the moisture content must be known to a rather high degree of accuracy[3]. Such data are not available.

Referring now to area A, the method of obtaining the resultant force is usually, (1) to subdivide the projected area of the vessel into one or several area elements, (2) to compute the force on each element, and (3) finally to sum up forces on all area elements, i.e.,

$$A=\sum_i A_i \tag{4}$$

$$F_{WD}=\sum_i(F_{WD})_i=\sum_i\left(\frac{\rho_{medium}}{2}\right)(C_D)_i\cdot A_i\cdot v_i^2 \tag{5}$$

Note that the wind velocity, the density of the medium and the drag coefficient are individually given for an area element.

Everyone agrees with this method *per se*, but the difference lies in to what degree of sophistication the area should be subdivided or how it should be done. On one side of the extreme is a case where the vessel is looked at as an object in its entirety, and on the other side of the extreme lies the case where every and all individual structural members are considered separately[4].

Neither of these is too practical, *nor is there a reason to believe that the method of dividing into every structural members gives any more correct estimate of force*. It should be understood *that the degree of sophistication* should be and can be introduced, as more reliable data are accumulated.

At this time, therefore, it appears best to divide the total projected area into approximately four following area elements :

(1) Cranes, derricks, and other high-rise deck equipment
(2) deck houses
(3) deck platform
(4) cylindrical pillars.

It is further recommended that the projected area as given by the silhouette with modifications for solidity ratio be used. The solidity ratio is defined as the ratio of material area to the total outline area. Members 2nd and 3rd in line are to be ignored presently as they lie in the wake of the first members and thus are shielded by the frontal members considerably.

Next to bring about another important factor, the scale effect, a number of data on actual calculation and experiment will be cited.

(1) Hough [7] gives the following for Ship Shoal Block 139.

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[3] D.L. Hough, *Review of Wind Force Criteria For Offshore Structures*, New Orleans Area Production Department, Sept., 1962.
"Another factor affecting the air density in a hurricane is water entrainment in the air in the form of rain or spray."

[4] Hough's recommendations [7] are :
$F_{WD}=\frac{1}{2}\sum_i(\rho\cdot C_D\cdot A\cdot v^2)_i$,
where $C_D=1.2$ for cylindrical truss members, 1.5 for gussest plates, beams, decks sides of buildings, etc. 0.63–1.0 for cylindrical deck equipment
$\rho=0.0024$Lbs/ft^4.

Platform Component	Average % of Total Wind Load	C_D	Overall Drag Coefficient
Trusses	20.3	1.2	.964
Deck and Cap Beams	20.2	1.5	
Decks, Curbs, Nailers	4.7	1.5	
Deck Equipment	54.7	0.63	

This is to be compared with a similar rectangular block. It appears that for a rectangular block the drag coefficient is between 0.80−1.05 [8]. This is to be corrected for solidity ratio, and thus the above drag coefficient becomes about 1.2−1.6 for solidity ratio of 0.4 [8].

(2) A Numerical calculation on Bluewater Rig 2… $C_D=1.48$. Calculated for 2 ft/sec current and 8 foot sea [9].

(3) Rig Model Test data $C_D=.65-1.0$ for Bluewater Rig No. 1, [10].

(4) Mohole Rig Experimental Data $C_D=9.5-0.75$ [11]. See Figs. 5 and 6 and Tables 3 and 4.

(5) Full Scale Experimental data on Bluewater Rig No. 2, $C_D=\sim 0.5$[12]

This short survey indicates that there has in fact been a rather poor agreement among calculated, experiemental and full scale data. It is rather difficult to asses the validity of any of these individually but with all fairness it must be stated that, as far as any paper study is concerned, the drag coefficient appears to be about twice the magnitude of full scale data. This review has pointed out the difficulties arising in using data on C_D, the main cause being the reason of scale effect due to the Reynolds number difference.

Referring to the heeling arm, similar difficulties exist.

Sarchin and Geldberg suggest the following for the heeling arm due to the wind force.

$$\text{Heeling arm in feet}=\frac{F_{WD}\cdot l\cdot\cos^2\theta}{\text{displacement in Lbs}} \tag{6}$$

where θ: heel angle

l: lever arm from half draft to the centroid of sail area, ft.

A better method is to multiply the force on individual area element by each lever arm measured from the base line and to sum up for the total moment. Thus,

$$\text{Heeling arm in feet}=\frac{\cos^2\theta}{\Delta\text{in Lbs}}\times\frac{1}{2}\sum_i(C_D\cdot\rho\cdot A.lv^2)_i \tag{7}$$

where l: lever arm from the origin of the coordinate system to the centroid of each sail area, ft.

Δ: displacement

For the wind velocity distribution, Sarchin and Goldberg suggest the 1/6 power law distribution. This is consistent with other observations[10]. The relationship can be approximated by

$$v(h)\cong v_0\sqrt[6]{\frac{h}{h_0}} \tag{8}$$

where h: height above water

$v(h)$: velocity distribution

v_0: nominal wind velocity: $v_0=v(h_0)$

h_0: standard height 33 ft or 330 ft. Use 33 ft (10 meters) for consistency.

With a drilling rig high above the water, compared to a ship, the higher wind speed on the top for a given nominal wind speed becomes more apparent. Also note that if the area element is not small, F_{WD} must be obtained by integrating the dynamic pressure over the total rather than taking a descrete form as is done here.

The foregoing discussions were concerned with the drag forces, that is, forces in the direction of the wind. In addition, for a drilling rig lift forces and their moments due to the wind on the flat deck normal to the deck must be considered. Note that this component of forces does not appear to have been considered in the past.

Forces and moments on a flat deck of a drilling rig at an heeling condition may be schematically shown as in Fig. 1. With an initial heel, lift F_{WL} and drag F_{WD} are generated. Now suppose for the moment holding these constant, due to these forces a further heeling occurs with resultant true lift and drag components as pictorially shown.

F_{WD}: Eqn(5) on the deck initially.

F_{WL}: lift force due to the wind acting normal to the deck plane initially.

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[10] Hoener, *op. cit*, p4-1, fig 1.

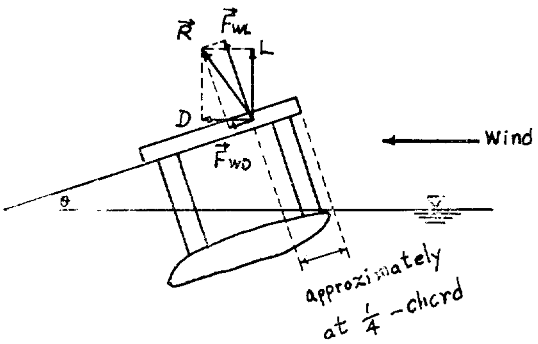

Fig. 1. Wind Forces on the Deck

R: resultant force $\vec{R}=\vec{F}_{WL}+\vec{F}_{WD}$

L: True lift component of $\vec{R}$ after further heeling.

D: True drag component of $\vec{R}$ after further heeling.

In the airfoil theory, the ratio F_{WL}/E_{DW} is known as lift-drag ratio, and it depends on the angle of attack, the aspect ratio of the foil, the shape of the foil, the trailing edge shape and the like, the numbers ranging between approximately 5.0-20.0. Note that F_{WL}/F_{WD} for a foil of aspect ratio 1 : 1 is between 4.0-6.0 [13, Fig. 172 on p.209].

Let us assume that the lift-drag ratio is about 2.5 for a drilling rig platform at an angle of attack, say, 3° in view of the heel due to rolling. To size up the magnitude of this moment against the windside force moment for the Mohole drilling rig, the following Table 2 is computed.

Table 2. Magnitude of Moment due to the Lift Force on the Deck for Mohole Rig

Item	Wind speed, KTS			
	60	100	140	
Total force	180,000	500,000	982,000	Lbs
Total Drag on the Deck	36,000	100,000	196,000	Lbs
Platform drag, $\frac{1}{2}$ of above	18,000	50,000	98,000	Lbs
Lift on the deck $\frac{L}{D}=2.5$	54,000	150,000	295,000	Lbs
Moment (Arm $\frac{214}{4}=53.3$)	29×10^5	81×10^5	158×10^5	FT-Lbs
Heeling moment	116×10^5	323×10^5	635×10^5	FT-Lbs
Total Moment	145×10^5	404×10^5	793×10^5	FT-Lbs
% Lifting Moment of the total	—	20.0	—	

In this calculation, the deck area is taken to be the product of the length and the beam of the platform. The center of effort of the lifting force in all cases was taken to be at the $\frac{1}{4}$—chord point for this type of low aspect ratio platform.

Although this calculation includes some drastic assumptions, one can get some idea on the order of magnitude of the effect of the lift. It appears that the order of the magnitude of heeling moment due to the lift force is about 20% of the total based on this rough calculation, which is indeed not negligible.

To investigate the increase of lift and heeling moment as the heeling angle increases, we define the following similarly to (3) :

$$F_{WL}=C_{WL}\cdot\left(\frac{\rho}{2}A_p v^2\right)_{\text{deck}} \tag{9}$$

where C_{WL} the lift coefficient.

This may be rewritten in the following form

$$\delta F_{WL}\simeq\left(\frac{dc_{WL}}{d\theta}\right)\frac{\rho}{2}A_p v^2\delta\theta \tag{10}$$

where $\delta\theta$: increment of heeling angle in radians,

$\left(\frac{dc_{WL}}{d\theta}\right)$: Lift curve slope.

A_p: projected deck area on a plane parallel to the wind.

The lift curve slope $\left(\frac{dc_{WL}}{d\theta}\right)$ is exactly equal to 2π for an ideal two-dimensional foil. For a drilling rig, it appears that a reasonable number is about 2.75, which is for an airfoil of aspect ratio AR=1.0.

Questions have been raised on the measured lift at zero degree of heel. Apparently there is about 2.5 degrees effective heel angle when the platform is at a level. This is apparently caused by the depression of water surface under the platform. This margin must be allowed in all calculations of lift forces in heeling conditions.

The forces and moments can best be obtained from experimental data. Calculations as outlined in the above should be performed for the purpose of obtaining experimental correlation factors *in various degrees of precision.*

(ii) Current Forces

Forces and moments due to the current or towing can be analyzed in a manner similar to wind forces. The most severe situation would be encountered when the current runs in the opposite direction to the wind. For all practical cases the drag coefficient may be assumed to be between 0.7 and 1.0 using frontal area.

(iii) Wave Forces

Forces and moments due to waves can be considered in two components: drifting forces, and rolling or pitching moments.

"Drifting" forces are normally considered to be small, but not insignificant.

For a general discussion of rolling and pitching moments and how they should be obtained, consider the following in conjunction with Eqn. (1). This case approximates the Bluewater Rig No. 2.

The example is greatly simplified, probably to an unrealistic extent, just to show an approach. Use of more extensive computations and experiments found elsewhere as well is needed to arrive at the following conclusion[15].

For the present purposes the rig is assumed to be made up of two surface piercing cylinders as shown in Fig. 2.

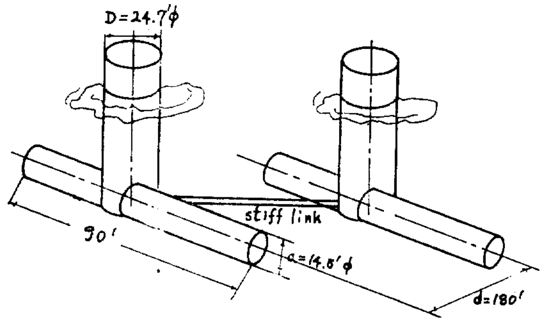

Fig. 2 Simplified Drilling Rig

When the left side cylinder alone is considered in a heaving mode, the buoyancy force and the inertia force induced by an incoming wave can be estimated or measured experimentally.

The heaving force F_{zw} is given by

$$F_{zw}=-\gamma_1 k_z \rho V\omega^2 z_w+\gamma^3 \rho g\frac{\pi}{4}D^2 z_w+\gamma_2 N_z \dot{z}_w \qquad (11)$$

where V : underwater volume

z_w : wave elevation

ρ : density of fluid

ω : circular frequency of wave

k_z : added mass coefficient for the submerged part.

γ_1 : correction for added mass in waves.

Use $\gamma_1=e^{-kf}$ for the submerged cylinder

$\gamma_1=e^{-k(f-a)}$ for the surface piercing cylinder

($k=\dfrac{\omega^2}{g}a$, f : depth to the submerged cylinder,

a : diameter of submerged cylinder).

γ_3 : correction factor for Smith Effect

g : gravitational constant

D : diameter of the surface piercing cylinder

γ_2 : correction factor for damping in waves

N_z : damping coefficient

$\dot{z}_w$: heaving velocity.

Although these appear quite complicated, a reasonably good estimate can be made by the aid of data available in literature. Of course, the simpler way is to obtain the numbers experimentally. One expects certain discrepancy between theoratical predictions and experimental results, particularly at the higher frequency range.

When the buoyancy is greater than the inertia force, the motion is in-phase with the wave elevation, and when the buoyancy is less than the inertia force the motion is out-of phase.

It should become qualitatively apparent that, for the consideration of statical stability, the case of inertia force greater than buoyancy is to be regarded as being of greater severity.

The maximum rolling moment occurs when the length of the incoming wave is shorter than twice the spacing of columns of the vessel. This is primarily due to the out-of-phase motion of the vessel in shorter waves. This essentially agrees with the model test data reported in NSMB Test Report No. 195.

Since the rolling moment due to the wave is fairly independent of the draft, the heeling arm for a rolling moment of 36,000 ft-L.T. (80.7 million ft-Lbs) is computed and listed in Table 3 to give an indication of GZ requirement. These numbers are of the order twice as big as those due to the wind and shifting weights, if there is any, thus indicating the predominancy of wave forces.

Table 3. Order of Wave Heeling Moment Arm as a Function of draft.

Draft, ft	Displacement, L. T.	Heeling Moment Arm, ft
9.0	1,825	7.5
12.0	6,529	5.5
25.0	7,984	4.5
33.0	8,407	4.3
40.0	8,819	4.1

It should be pointed out that we have considered the maximum rolling to be about 4 degrees half amplitude. In a ship, the same ranges 6°—7° for pitching and 25°—30° for rolling. For the NRL Alternate 1 Stable Platform (FORDS) in a wave 500 ft long and 15—20 ft wave height, the result is about 2.5 degree half amplitude.

c. Artificial Forces and Moments

An artifical fore is a concentrated force, assumed to be known as to its magnitude and location. Six components are required to describe it completely.

$\vec{F}=(F_x,\ F_y,\ F_z)$: force vector

$\vec{r}=(r_x,\ r_y,\ r_z)$: location vector

The moment of F about the origin is given by

$\vec{M}=\vec{r}\times\vec{F}$.

When several forces are present, we have simply

$$\vec{F}=\sum_i \vec{F}_i$$

$$\vec{M}=\sum_i \vec{M}_i=\sum_i \vec{r}_i\times\vec{F}_i$$

The force due to the thrust of the propellers, that due to mooring lines and that due to towing lines can be taken care of in this manner. These forces are normally in equilibrium with the natural forces, and therefore can be found rather simply once the natural forces are known. Concentrated dynamic forces such as variable thrust for positioning are rather difficult to estimate[9]. For dynamic positioning of a SEDCO 135 rig in surging motion, the dynamic component is about 1.7 times the static one. A factor of safety of 2.0 seemes to be a reasonable number.

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