On the Stability of Air Cushion Supported Structures

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ABSTRACT

This paper presents a set of calculations to evaluate the restoring moment of structures supported by an air cushion. The air cushion is assumed to be enclosed within a number of compartments that are open to sea. The height of the water plug within the compartments is thus an important parameter. Calculations are verified against experimental data performed on three scaled model structures:

- a closed rectangular box barge
- a single chamber air cushion supported structure
- a nine-compartment air cushion supported structure.

It is found that the single chamber structure suffers from serious loss of stability, while the nine-compartment structure is more stable than the closed box barge itself. This is explained in terms of the additional stabilizing effect of the individual air cushions.

Keywords: *air cushion structures, metacentric height, static stability.*

1. INTRODUCTION

Air cushions are used in offshore applications to temporarily lighten a structure such as the case of a concrete gravity sub-structure while being towed in shallow waters. The base of the structure may have several skirted compartments open to the sea. The air cushions are located within the compartments, and sealed by a “water plug” so as to prevent air egress into the open water.

The effects of air-cushion support on the dynamics of Surface Effect Ships (SES) with and without forward speed were studied by Kaplan et al. (1975). A good literature review on this topic may be found in e.g. Graham and Sullivan (2002).

A three-dimensional numerical approach to evaluating the dynamics of an air cushion structure using the boundary integral equation method is given by Lee and Newman (2000) and Pinkster (1997). Pinkster (1997) in particular, considered an air-cushion structure with various compartment configurations and concluded that compartmentalizing the air-cushion chamber reduces its effect on the hydrodynamic stability of the body. An air-cushion supported floating body has been studied experimentally in regular waves by both Thiagarajan et al. (2000) and Pinkster and Meevers-Scholte (2001).

Chenu et al. (2004) presented the results of a series of experiments on 1:100 scaled models of a box and air cushion supported structures. The authors conclude that the presence of air cushion in general reduces the stability of the structure. Increasing the water plug height and compartmentalization stabilize the vessel. In particular it was noted that a compartmented air cushion structure had better stability than the corresponding closed box structure. This was an interesting observation from the experiments.

On first intuition, one may be led to believe that the presence of internal free surfaces results in a significant loss of stability. However, it is shown through detailed calculations that loss of stability occurs only in the case of large air cushion chambers. Upon compartmentalization of the base structure, individual cushion chambers provide a pumping effect which restores stability. Our calculations are verified by comparison with the results from the inclining experiments of Chenu et al. (2004).

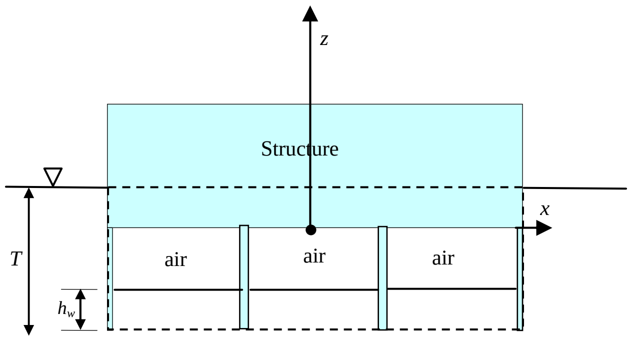

Figure 1. Structure geometry.

2. THEORETICAL DEVELOPMENT

We consider an air cushion structure and an equivalent box of same plan area and draft, Figure 1. It is acknowledged that these structures have different weight and centers of gravity. However, from a control volume approach, we can see that the air cushion structure + entrapped water may be statically and dynamically compared with the equivalent box. One can also contend that the restoring moments acting on the two control volumes must do work to restore the same displacement. We are interested in seeing if the restoring effects are different between the two cases. The control volume method (similar to added weight method of damaged stability, e.g. Lewis et al. 1988) is mathematically attractive because it enables us to develop a correction to the equivalent stability of a box.

For the case of the control volume in Fig. 1, the net external hydrostatic moment is balanced by the internal moment due to gravity. The hydrostatic and aerostatic pressures inside the compartments are internal forces cancelling one another in an inclined equilibrium state. Thus solving the problem reduces to finding the total mass and coordinates of center of gravity of the air cushion structure + entrained water in the compartments in the displaced condition (Fig. 2).

2.1 Preliminaries

We consider a compartmented structure similar to shown in Figure 1, with dimensions as shown in Table 1. The structure is given a set of static deflections $\zeta_k, k = 1 \cdots 6$, to obtain the configuration of Figure 2.

Table 1. Notations for dimensions

Length	L
Breadth	B
Still water draft	T
Compartment height	h_c
Compartment length	l
Compartment width	b
Number of compartments	$M \times N$
Initial height of water	h_w

Three coordinate systems are defined in Figure 2. These are:

- Global – (x, y, z)
- Body fixed – (x', y', z')
- Compartment fixed – (x^c, y^c, z^c)

As per convention, the global and body-fixed coordinate systems are coincident at the origin of time, and located at the intersection of the symmetry planes and the original water plane. The origin of the compartment fixed system is at the intersection of the symmetry planes within each compartment and located at the top of the compartment (Figure 2).

The configuration considered here always has a compartment centered at the origin of the body fixed coordinate system. Then the compartment indices range from (-*m*, -*n*) to (*m*, *n*) and

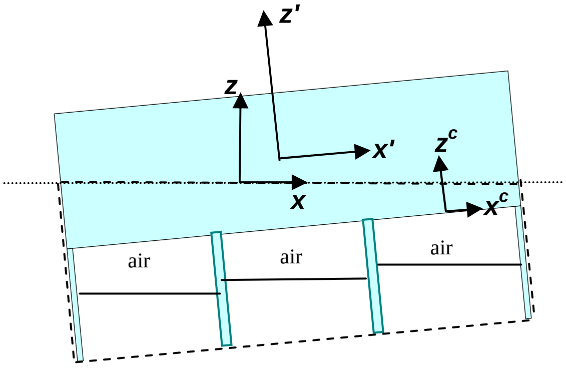

Figure 2. Coordinate systems definition

$$M = (2m+1);$$
$$N = (2n+1) \tag{1}$$

Then the position vector may be written in the coordinate systems as

$$\mathbf{r} = \mathbf{r}_0 + \mathbf{r}' + \boldsymbol{\omega} \times \mathbf{r} \tag{2}$$

$$\mathbf{r}' = \mathbf{r}_{ij}^{'} + \mathbf{r}^{c} \tag{3}$$

where subscripts (i, j) denote the indices of a compartment and

$$\mathbf{r}_0 = (\zeta_1, \zeta_2, \zeta_3)$$
$$\boldsymbol{\omega} = (\zeta_4, \zeta_5, \zeta_6) \tag{4}$$

2.2 Air Cushion Volume and Pressure

The initial pressure and volume of air within a compartment is given by

$$p_0 = p_a + \rho g (T - h_w)$$
$$v_0 = lb(h_c - h_w) \tag{5}$$

where p_a is the atmospheric pressure. When the structure is given a set of displacements ζ_k, the modified volume and pressure are given by

$$p = p_a - \rho g z_0^c$$
$$v = -lbz_0^c \tag{6}$$

where z_0^c denotes the vertical coordinate of the internal water surface at the center point $(x_0^c, y_0^c) = (0,0)$. As long as the displacements are small, one could reasonably assume that the position of the water surface z_0^c is incrementally different from the initial position of the water surface, i.e.,

$$z_0^c = -(h_c - h_w) + \Delta z_0^c \tag{7}$$

The change in pressure and volume is decided by the adiabatic gas law $pv^{\gamma} = \text{constant}$, where γ is the ratio of specific heats for air. Substituting for z_0^c into the adiabatic gas law and linearizing, we get

$$\frac{\Delta z_0^c}{h_c - h_w} = \frac{-\zeta_3 - y_{ij}^{'}\zeta_4 + x_{ij}^{'}\zeta_5}{\left(h_c - h_w + {p_0\gamma}/{\rho g}\right)} \tag{8}$$

For practical purposes, the above equation results in a very small displacement of the internal surface, because of the relatively large magnitude of the denominator arising from the effect of atmospheric pressure.This in turn indicates that the air cushion performs like a stiff spring ensuring that the water plug behaves like entrapped water and is displaced along with the structure.

2.3 Moments Due to Weight

The total mass within the control volume of Fig. 2 is given by:

$$M = M_s + \sum_i \sum_j m_{ij} \tag{9}$$

where the mass of water within a compartment is given by

$$m_{ij} = \rho lb\left(h_w + \Delta z_0^c\right) \tag{10}$$

The coordinates of the center of gravity of the control volume in the global coordinate system is:

$$\mathbf{r}_G = \begin{pmatrix} x_g^{'} + \zeta_5 z_g^{'} - \zeta_6 y_g^{'} \\ y_g^{'} + \zeta_6 x_g^{'} - \zeta_4 z_g^{'} \\ z_g^{'} + \zeta_4 y_g^{'} - \zeta_5 x_g^{'} \end{pmatrix} \tag{11}$$

The gravitational moment acting about the origin of the body fixed coordinate system is

$$\begin{aligned} \mathbf{M}_g &= \mathbf{r_g} \times \left(0, 0, Mg\right) \\ &= Mg \begin{pmatrix} -y_g^{'} - \zeta_6 x_g^{'} + \zeta_4 z_g^{'} \\ x_g^{'} + \zeta_5 z_g^{'} - \zeta_6 y_g^{'} \\ 0 \end{pmatrix} \end{aligned} \tag{12}$$

To find the coordinates of Eq. (11), we can use the fact that the gravitational moment in the body fixed system is made up of the component structure mass and the individual water plug masses. Denoting the centroids by the subscript g, we get

$$\begin{aligned} Mx_g^{'} &= M_s x_{gs}^{'} + \sum_i \sum_j m_{ij}\left(x_{ij}^{'} + x_g^c\right) \\ My_g^{'} &= M_s y_{gs}^{'} + \sum_i \sum_j m_{ij}\left(y_{ij}^{'} + y_g^c\right) \\ Mz_g^{'} &= M_s z_{gs}^{'} + \sum_i \sum_j m_{ij}\left(h_c - T + z_g^c\right) \end{aligned} \tag{13}$$

The first term on the right side of Eq. (15) denotes the structural mass component. The second term denotes the moment due to the position of the water masses and their consequent moments about the origin of the compartment-fixed system. These moments are quite important, since the incompressibility of the air cushion results in the water plug moving with the structure. The last term denotes the moments due to the position of the center of gravity of the water masses with respect to the compartment coordinate system, and gives rise to the effects of the internal free surface. Upon evaluation of the centroid of the water plug in the displaced condition, we can find that

$$\begin{aligned} m_{ij} x_g^c &= -\rho \frac{l^3 b}{12} \zeta_5 \\ m_{ij} y_g^c &= \rho \frac{l b^3}{12} \zeta_4 \\ m_{ij} z_g^c &= \rho l b h_w \left(h_c - \frac{h_w}{2}\right) \end{aligned} \tag{14}$$

These are readily seen to be the terms due to internal free surface, and the last term is merely the linear term without any influence of the displacements.

Various terms may be substituted and the moments evaluated. The final results are shown in Eq. (15) and (16). Balance of forces between buoyancy and weight for the control volume provides the restoring moments in roll and pitch. Denoting the restoring coefficients as C_{44} and C_{55}, we get the expressions as shown in Eq. (17) and (18). D_r in the equations denotes the denominator of Eq. (8). S_{11} and S_{22} are the water plane moments about the x and y axes respectively.

$$M_{gx} = -M_s g y'_{gs} - \zeta_4 \left(\frac{\rho g L B b^2 (h_c - h_w) n(n+1)}{3D_r} + \rho g L B \frac{l^2}{12} + M_s g z'_{gs} - \rho g L B T h_w + \rho g L B \frac{h_w^2}{2} \right) - \zeta_6 M_s g x'_{gs} \tag{15}$$

$$M_{gy} = -M_s g x'_{gs} - \zeta_5 \left(\frac{\rho g L B l^2 (h_c - h_w) m(m+1)}{3D_r} - \rho g L B \frac{l^2}{12} - M_s g z'_{gs} + \rho g L B T h_w - \rho g L B \frac{h_w^2}{2} \right) - \zeta_6 M_s g y'_{gs} \tag{16}$$

$$C_{44} = \rho g S_{22} + \rho g V z'_B - M_s g z'_{gs} + \left(\frac{\rho g L B b^2 (h_c - h_w) n(n+1)}{3D_r} - \rho g L B \frac{l^2}{12} + \rho g L B T h_w - \rho g L B \frac{h_w^2}{2} \right) \tag{17}$$

$$C_{55} = \rho g S_{11} + \rho g V z'_B - M_s g z'_{gs} + \left(\frac{\rho g L B l^2 (h_c - h_w) m(m+1)}{3D_r} - \rho g L B \frac{b^2}{12} + \rho g L B T h_w - \rho g L B \frac{h_w^2}{2} \right) \tag{18}$$

3. COMPARISON WITH EXPERIMENTS

Chenu et al. (2004) reported a set of experiments on three models.

- Closed bottom box
- Box open to sea with one compartment
- Box open to sea with nine compartments.

All three models had common geometrical dimensions and draft, as shown in Table 2. Since the draft was kept constant, the structural weight was different. The ballast weight was altered to provide different water plug heights inside the compartments. Obtaining different water plug heights while maintaining a constant draft and even keel was a trial-and-error exercise requiring much caution. This was complicated for the one-compartment box because of its very marginal stability condition. For the nine-compartment box, the difficulty was in obtaining uniform air pressure in all the compartments. All these gave some element of uncertainty in the experiments.

Inclination tests were performed on the model to ascertain the restoring moments and from that the metacentric heights, as reported by Chenu et al. (2004). In this paper, we consider the restoring moments and compare them with the formulations derived in the previous section.

Table 2. Experimental particulars

Quantity	*Symbol*	*Value*
Length	*L*	0.5 m
Breadth	*B*	0.5 m
Draft	*T*	0.1 m
Box model		
Structure mass		24.25 kg
Vertical center of gravity		-0.01 m
One – compartment model		
Compartment height	h_c	0.085 m
Compartment length	*l*	0.47 m
Compartment width	*b*	0.47 m
9-compartment model		
Compartment height	h_c	0.085 m
Compartment length	*l*	0.154 m
Compartment width	*b*	0.154 m

Figures 3 and 4 show comparisons between experiments and theory for restoring moments in roll at four different values of water plug height. It is seen that the comparison is within 10% and the trends are captured by the theory. The margin of error in the figures is in line with the level of uncertainty in the experiments. Further, the comparison is limited to four data points and firm conclusions need more data. This deficiency will be redressed in the future.

For comparison purposes, the restoring moment for the equivalent box was evaluated as 40.8 N-m. Both models clearly show a monotonic increase of the restoring moments with the height of the water inside the compartments. This increase is also captured by the theoretical formulation.

Apart from experimental uncertainty, one is left to wonder if nonlinear terms ignored in the formulations may be of importance to bridge the gap. This aspect will be clarified with more experimental data.

For the one-compartment model, the internal free surface destabilizes the model and almost cancels the effect of the external free surface. The remaining terms of the water plug contribute to a marginal stabilizing effect, which is seen in Figure 3.

Thiagarajan and Morris-Thomas (2006) have postulated that the air cushion structure may be likened to an equivalent shallow box whose draft is adjusted to incorporate the effect of the water plug. Their dynamic analysis shows good correlations between simple theoretical formulation and experiments in heave and pitch. We can evaluate the restoring forces for a shallow box whose draft is (T-hw) and these are shown in Figure 5. The comparison is very interesting. The experimental data is encased between the two theoretical formulations. One could argue that the main difference in the theoretical formulations is the stiffness of the internal water surface. For the equivalent shallow box, the internal surfaces are solid, and hence provide maximum restoring moment.

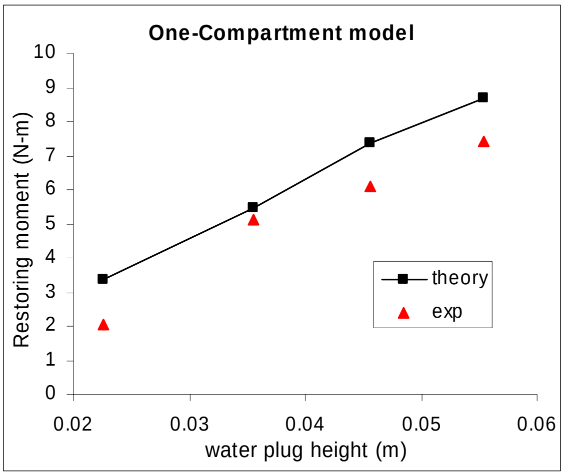

Figure 3. Restoring moment vs. water plug height for the one-compartment model

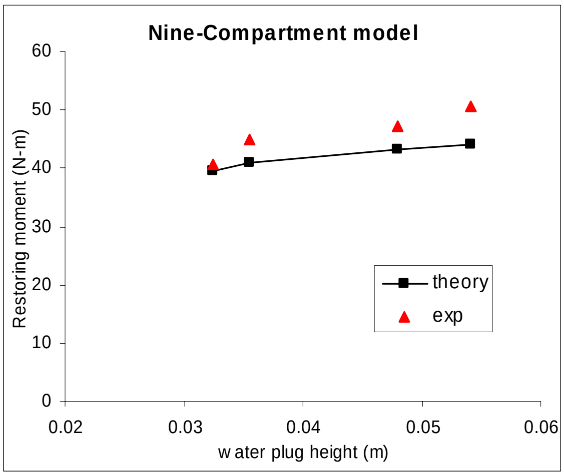

Figure 4. Restoring moment vs. water plug height for the nine-compartment model

The theoretical formulation that incorporates the internal effect shows that the destabilizing effect of the internal surface is offset by the physical displacement of the water plugs to balance the internal and external pressures. The actual experimental data seems to be somewhere in between. Further experimental data is needed to confirm the actual trends.

4. CONCLUSIONS

The theoretical formulations shown in the paper comprise the effect of various components that affect the stability of an air cushion platform. A control volume approach

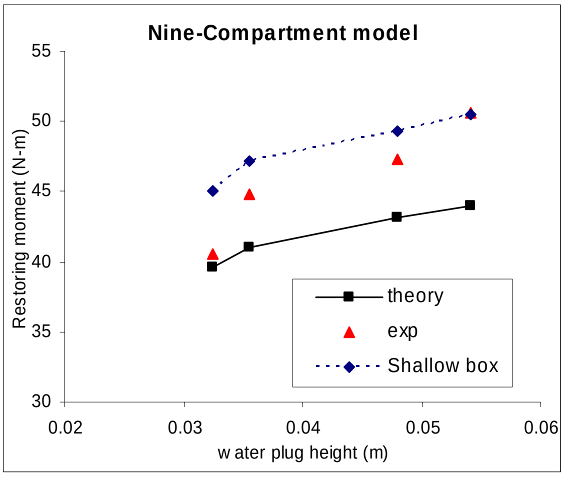

Figure 5. Comparison of stability of a nine-compartment model with a shallow box

is used where the water masses are treated as added weights. The resulting formulations are closed form expressions for the restoring moments in roll and pitch. The formulations are compared with experimental data and the comparisons are shown to be within 10%. It is shown that the destabilizing effect of the internal free surface is offset by the displacement of the water plugs with the structure. A nine-compartment structure thus has more stability than an equivalent box of the same draft. If the draft is altered to account for the height of the water plug, then the restoring moments are shown to be higher.

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