15th Australasian Fluid Mechanics Conference
The University of Sydney, Sydney, Australia
13-17 December 2004

Some hydrodynamic characteristics of an air-cushion supported concrete gravity structure

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Abstract

The tow out of a concrete gravity structure (CGS) through shallow water is assisted by employing an air-cushion for draft reduction purposes. This requires an understanding of the effect of the air-cushion on the stability and dynamics of the CGS. In this present work, experiments were performed on 1:100 scale models of typical concrete gravity substructure configurations at the University of Western Australia. Three models of dimensions 0.5m length x 0.5m width x 0.1m draft were considered. The experimental campaign focused on determining the effect of the air-cushion on the metacentric height and, coupled with the water depth, on the added mass and natural frequency in heave and pitch of each model. The experimental results illustrate that the air cushion reduces the stability of the vessel and influences both the natural frequency and added mass in heave and pitch. Compartmentalising the air-cushion and varying the water depth affects the hydrodynamic characteristics of the floating structure.

Introduction

The use of air-cushions to support floating bodies is well known. These bodies range from high speed surface effect ships to very large floating structures such as the mobile offshore base (MOB) used in military logistic applications. A floating body, supported by an air-cushion, comprises rigid - or flexible for surface effect ships - vertical side walls that penetrate below the main structure and exterior free-surface thus trapping a column of air. These vertical side walls must penetrate the free-surface to a sufficient depth to maintain an excess air pressure in the interior chamber. For surface effect ships, the air cushion typically supports 80% of the structures weight with the remainder supported by buoyancy. This weight balance is described by

$$M = \rho\left(V_0 + \frac{p_0}{\rho g}A_i\right), \qquad (1)$$

where M is the structure mass, ρ is the density of water, V_0 is the displaced volume, A_i is the air-cushion surface area, and p_0 is the excess air pressure contained within the cushion. The excess pressure contained within the air-cushion determines the static water plug height h_w - measured from the keel to the interior free-surface - through the hydrostatic relation $p_0 = \rho g(T - h_w)$ where T is the draft (see Figure 1).

The tow out of a concrete gravity structure (CGS) through shallow water is another application of an air-cushion support. In this context, the primary use of the air-cushion is to elevate the structure to avoid seabed contact during tow out operations. However, a consequence of this approach is a reduced hydrodynamic stability due to a destabilising moment produced by the depressed interior free-surface. Moreover, the reduced stiffness in angular motions can shift the natural frequency into the frequency space of significant wave energy. This is particularly important when the CGS is towed through shallow channels open to long period swells.

Early work on the use of air-cushion support for floating structures predominately concentrates on surface effect ships with

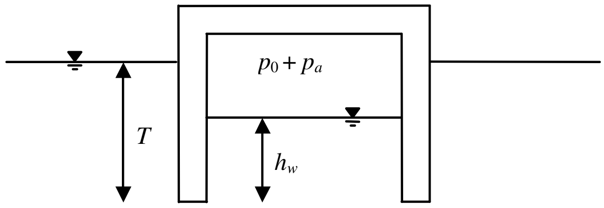

Figure 1: Schematic of an air-cushion supported floating body.

and without forward speed (see Kaplan et al. [3], and for a good literature review, Graham and Sullivan [1]). An examination of the added mass of a surface effect ship was considered by Kim and Tsakonas [4] where the authors describe the entrained air as a pulsating pressure distribution on the free-surface. In 2-dimensions, this approach was considered by Malenica and Zalar [6] to study the heave added mass and radiation damping of an air-cushion supported floating body with rigid side walls. Using a boundary integral equation method Guret and Hermans [2] extended the work of Malenica and Zalar to investigate transfer functions for the heave and the interior vertical free-surface displacement of an air-cushion supported body in regular waves. A 3-dimensional approach is given by Lee and Newman [5] and Pinkster [7] using the boundary integral equation method. The work of Pinkster [7] is particularly notable as the author considered an air-cushion structure with various compartment configurations. It is thought that compartmentalising the air-cushion 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. [11], and Pinkster and associates [8, 9]. The studies performed by [10] demonstrate that an air-cushion supported box exhibits a higher pitch response when compared to a closed bottom box model of similar geometry.

In this present work we experimentally study the effect of water plug height and compartmentalisation of an air-cushion on the metacentric height, heave and pitch natural frequency and added mass of an air-cushion supported box model. Moreover, we also consider the influence of water depth on the heave and pitch natural frequency added mass values.

Experimental Campaign

Experiments were conducted in a circular tank of height 1m and diameter 1.65m. During testing, the models were positioned in the centre of the tank using a rigidly mounted linear voltage displacement transducer (LVDT). Three models were used in the experimental campaign: a simple closed bottom box configuration with no air-cushion; a one compartment air-cushion supported open bottom box model (see Figure 2, denoted 1-C); and a nine compartment air-cushion supported open bottom model (see Figure 3, denoted 9-C). For each model, the water plane area measured 0.5m $\times$ 0.5m and the draft was held constant at 10cm. For the two air-cushion supported structures, the height of the air-cushion was varied such that the water plug height consisted of the following values h_w=3cm, 4cm, 5cm and 6cm. These heights were controlled by adjusting valves located on

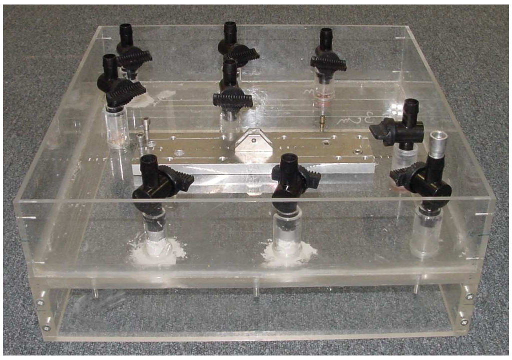

Figure 2: The one compartment air-cushion box model, 1-C.

Figure 3: The nine compartment air-cushion box model, 9-C.

the deck of the cushion models (see Figures 2 and 3). Moreover, through these valves, the pressure inside the air-cushion was monitored using pressure transducers. The main particulars of each model, including the vertical centre of gravity z_G relative to the quiescent free-surface position and the pitch radius of gyration r_{22}, are given in Table 1.

The metacentric height, denoted $\overline{\mathrm{GM}}$, of each model and water plug configuration was determined using a standard inclining experiment whereby a known ballast mass was displaced along the model's centreline. The inclination was recorded using a tilt sensor and the metacentric height determined by the following relation:

$$\overline{\mathrm{GM}} = md/\tan\vartheta, \tag{2}$$

where m is a known mass, d is the known mass displacement from its initial position and ϑ is the inclination induced by the mass displacement. The maximum induced inclination for all tests was $\vartheta = \pm 5$-degrees.

The natural frequency of each model in heave and pitch was determined by free oscillation experiment. Whereby, in the mode of interest, the model was given a small initial displacement or rotation and allowed to return to its initial position. Initial displacements of 2.5cm and 5-degrees were used in heave and pitch respectively. Vertical displacements were recorded by an LVDT and pitch rotations by a tilt sensor. The displacement time traces were digitised at 30Hz and logged by a personal computer for data analysis. In addition to the natural frequencies in heave and pitch, the added mass and damping of each model at the natural frequency was determined. Only the added mass values are presented here. The water plug height was varied to investigate its influence on the added mass and natural frequency of the 1-C and 9-C models. It was found that the recorded air pressure (cf. Table 1) inside the chamber follows (1) to within 5% error.

The natural frequencies in heave and pitch are given by the following expressions:

$$\omega_{0,3} = \sqrt{\frac{k_{33}}{M+\mu_{33}}}, \qquad \omega_{0,5} = \sqrt{\frac{Mg\overline{\mathrm{GM}}}{Mr_{22}^2+\mu_{55}}}, \tag{3}$$

where k_{33} denotes the the heave restoring stiffness and μ_{33} and μ_{55} are the added mass values in heave and pitch respectively. The heave restoring stiffness includes both hydrostatic and acoustic - arising from the compressibility of the air-cushion - contributions. The stiffness of each model in heave was experimentally determined and found to be $k_{33} = 2.43$kN/m, 2.18kN/m and 3.07kN/m for the closed bottom box, 1-C and 9-C models respectively. The closed bottom box stiffness is very close to the theoretical value of $\rho g A_0 = 2.45$kN/m. The natural frequency added mass values were determined from (3).

Result and Discussion

The experimental results are now discussed with particular regard to: the influence of the water plug height and air-cushion compartmentalisation on the metacentric height; and the influence of the water plug height, air-cushion compartmentalisation and water depth on the natural frequency of oscillation and added mass in heave and pitch. The water plug height and water depth are normalised by the draft T. To incorporate the effect of the air-cushion (1), the added mass values are normalised according to $\mu_{33}^* = \mu_{33}/M$ and $\mu_{55}^* = \mu_{55}/Mr_{22}^2$ for heave and pitch respectively.

Metacentric Height

For each model configuration, the inclining experiment results are provided in Table 1 for the $\overline{\mathrm{GM}}$ and hydrostatic resorting coefficient $Mg\overline{\mathrm{GM}}$. It is immediately evident that the addition of a single compartment air-cushion reduces the $\overline{\mathrm{GM}}$ and thus destabilises the model. Compartmentalising the cushion, as in the 9-C model, reduces the destabilising effect of the air-cushion. However, we note that we cannot directly compare the $\overline{\mathrm{GM}}$ values of the two cushion models and the box model due to the large difference in their body masses. This was unavoidable since we required the under water geometry of the models to be similar for added mass and natural frequency comparisons. To circumvent this, the hydrostatic restoring coefficients $Mg\overline{\mathrm{GM}}$ provides insight. Subsequently, we notice that $Mg\overline{\mathrm{GM}}$ is of the same order of magnitude for both the box and 9-C models. Furthermore, in general the restoring moment is larger for the 9-C model than that of the box. This could be caused by each individual compartment behaving as it it were in heave when the structure is tilted, thus providing an additional restoring moment. However, it is thought that if one were to construct a nine compartment and box model of equal mass, then one would expect the $\overline{\mathrm{GM}}$ of the box model to be a little larger than the nine compartment model. In contrast, the similar masses of the single and nine compartment cushion models allows direct comparison of the $\overline{\mathrm{GM}}$ values.

The water plug height demonstrates a positive effect on the metacentric height of the cushion models. For instance, increasing h_w by a factor of 2 approximately doubles the $\overline{\mathrm{GM}}$ of the cushion models. This is physically caused by a reduced destabilising couple acting on the side walls for increasing h_w due to the reduced air pressure inside the air-cushion. It should be pointed out that the standard free-surface correction formula for internal fluid tanks (see Pinskter and Meevers Scholte [9] for instance) for the $\overline{\mathrm{GM}}$ does not take such effects into account and cannot be used for air-cushion supported structures.

Table 1: The characteristic of each model and water plug configuration.

Model	h_w (cm)	Mass (kg)	r_{22}	V_0 (m^3)	z_G	p_0 (kPa)	$\overline{GM}$ (m)	Mg$\overline{GM}$ (Nm)
Box	-	24.25	0.152	0.0250	-0.010	0	0.172	40.8
1-C	3	16.38	0.142	0.0062	0.014	0.526	0.013	2.06
	4	14.48	0.152	0.0062	0.011	0.456	0.036	5.10
	5	13.78	0.150	0.0062	0.007	0.342	0.045	6.06
	6	11.98	0.160	0.0062	0.011	0.251	0.063	7.42
9-C	3	16.94	0.144	0.0066	0.006	0.477	0.241	40.0
	4	14.99	0.152	0.0066	0.002	0.446	0.305	44.9
	5	13.29	0.157	0.0066	-0.005	0.354	0.373	48.6
	6	11.44	0.170	0.0066	-0.009	0.264	0.466	52.3

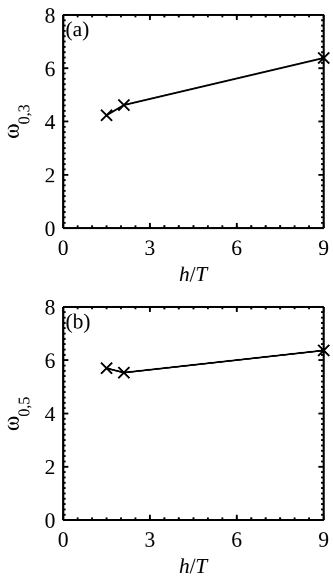

Figure 4: The natural frequency ω_0 of the closed bottom box model in heave (a) and pitch (b) versus the normalised water depth h/T.

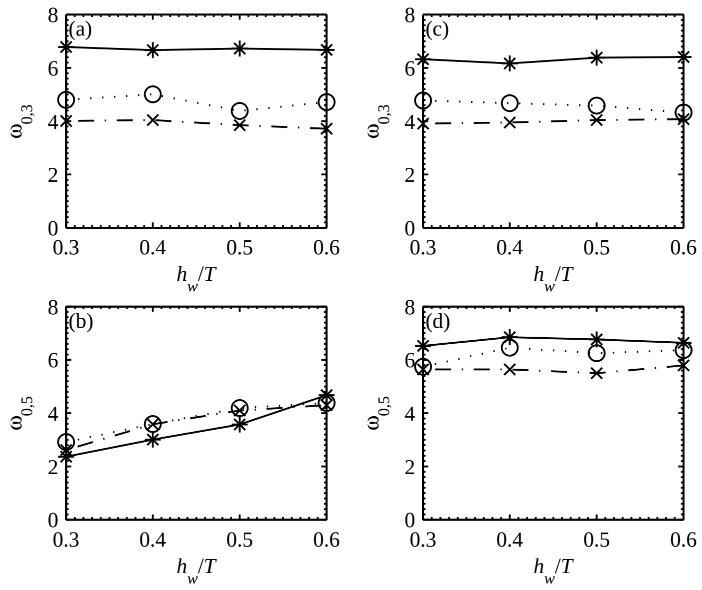

Figure 5: The natural frequency in heave and pitch of the 1-C and 9-C models versus the normalised water plug height h_w/T: (a), 1-C heave; (b), 1-C pitch; (c), 9-C heave; (d), 9-C pitch. Three water depth conditions are considered: $h/T = 1.5$, ($-\cdot-\times-\cdot-$); $h/T = 2.1$, ($\cdots\circ\cdots$); and deep water, (—$*$—).

Free Oscillation

Measured results, from the free oscillation experiments, of the heave and pitch natural frequencies are illustrated in Figure 4 for the closed bottom box model and Figure 5 for the two air-cushion models. Three normalised water depths are considered whereby h/T = 1.5, 2.1 and 9. For $h/T > 9$, we assume that the seabed does not affect the surrounding fluid pressures induced by the free oscillation of the body. Consequently, $h/T = 9$ is considered a deep water condition.

The experimental results in heave demonstrate that $\omega_{0,3}$ is susceptible to the water depth parameter h/T and reasonably insensitive to the water plug height parameter h_w/T (cf. Figures 5a and 5c). For instance, in deep water both the 1-C and 9-C cushion models exhibit a heave natural frequency of $\omega_{0,3} \approx 6.3$rad/s across the range of h_w/T values examined. Furthermore, the fact that $\omega_{0,3}$ is similar for both the 1-C and 9-C models suggests that compartmentalisation has little influence on $\omega_{0,3}$. The experimental values of $\omega_{0,3}$ versus h/T demonstrates that $\omega_{0,3}$ is remarkably similar for each model regardless of air-cushion configuration.

For the 1-C model in pitch, whilst the water depth does not appear to significantly influence $\omega_{0,5}$, h_w/T appears to be a far more important parameter. For instance, Figure 5b shows that $\omega_{0,5}$ linearly increases by approximately 2rad/s between h_w/T =0.3 and 0.6. Presumably, this is caused by an increased $\overline{GM}$ for increasing h_w/T (cf. Table 1). In contrast, the 9-C model behaves in a similar fashion to the heave results whereby $\omega_{0,5}$ is relatively insensitive to h_w/T. This suggests that compartmentalising the air-cushion reduces the effect of h_w on $\omega_{0,5}$. Moreover, compartmentalising the air-cushion almost trebles the magnitude of $\omega_{0,5}$ for small h_w/T. This significant change in $\omega_{0,5}$ would undoubtedly be an important air-cushion design consideration.

Measured results of the natural frequency added mass in heave and pitch for each model configuration are illustrated in Figures 6 and 7. Apart from μ^*_{55} for the 1-C model, the measured results indicate that both μ^*_{33} and μ^*_{55} consistently increases as h/T decreases. This is due to an increased surrounding fluid pressure when the model oscillates in the vicinity of the seabed - this is generally true regardless of body geometry (see Yeung [12]). For the 1-C model, it is interesting to note that μ^*_{55} exhibits very small and slightly negative μ^*_{55} for small h_w/T (cf. Figure 7b). Furthermore, the measured results suggest that the natural frequency pitch added mass, for the 1-C model, is relatively insensitive to water depth. At present, this result cannot be explained and is under continued investigation.

The experimental results show that the water plug height exhibits a significant influence on both the heave and pitch added mass. For the nine-compartment model in particular, μ^*_{55} increases from 2.6 at $h_w/T = 0.3$ up to 3.7 at $h_w/T = 0.6$ for $h/T = 1.5$ (see Figure 7d). Furthermore, compartmentalising the air-cushion significantly increases the magnitude of μ^*_{55} (cf.

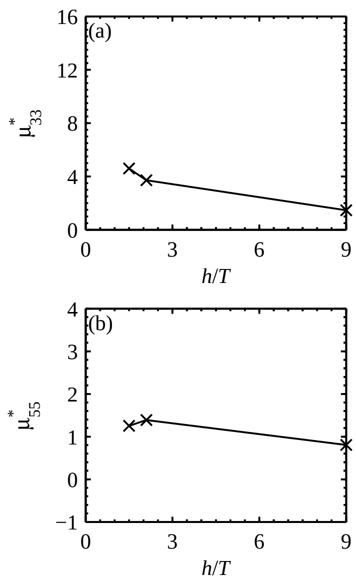

Figure 6: The normalised added mass of the closed bottom box model versus the normalised water depth h/T: (a), heave μ^*_{33}; and (b), pitch μ^*_{55}

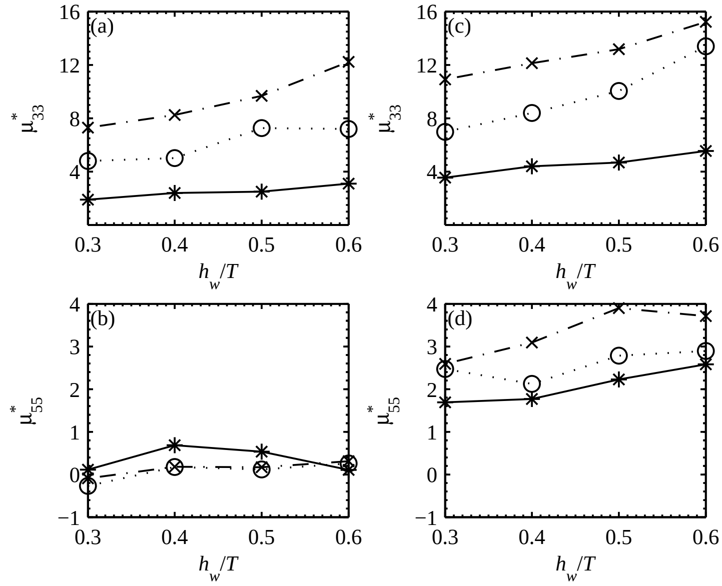

Figure 7: The added mass in heave and pitch of the 1-C and 9-C models versus the normalised water plug height h_w/T: (a), 1-C heave; (b), 1-C pitch; (c), 9-C heave; (d), 9-C pitch. Three water depth conditions are considered: $h/T = 1.5$, $(- \cdot - \times - \cdot -)$; $h/T = 2.1$, $(\cdots \circ \cdots)$; and deep water, $(— * —)$.

Figures 7b and 7d). It is reasonable to expect that this increase in μ^*_{55}, through compartmentalising the air-cushion, would offer important pitch motion reduction consequences.

Conclusions

The present work has experimentally examined the metacentric height, natural frequencies, and added mass of a closed bottom box model and two cushion models in heave and pitch. The two cushion models differ by the cushion compartmentalisation into one single compartment and one nine-compartment model. The results demonstrate that the inclusion of an air-cushion reduces the metacentric height. However, this can be circumvented by compartmentalising the air-cushion. Increasing the water plug height has a positive effect on the metacentric height. We find that the cushion compartmentalisation is mostly important to the pitch natural frequency and both heave and pitch added mass values. Generally, the water plug height was found to be an important parameter for both the heave and pitch natural frequency added mass. However, for the natural frequency in pitch, the water plug height seems only to influence the 1-compartment cushion model. The measured results indicate that the water depth influences the heave natural frequency and both heave and pitch added mass regardless of air cushion configuration.

Acknowledgements

The experiments were conducted as part of a research project supported by Minerals and Energy Research Institute of Western Australia (MERIWA), with financial support of Woodside Energy, Concrete Offshore Structures Industry Subgroup, and Ove Arup and Partners.

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