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THE INFLUENCE OF BUOYANCY PARAMETERS ON THE DYNAMIC BEHAVIOR OF ARTICULATED TOWER

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ABSTRACT

A study to develop a better understanding towards the dynamic behavior of articulated tower is considered necessary in view of anticipating the growth of its demand in the South East Asian region. This paper describes such study emphasizing on the effects of buoyancy parameter variations for both regular and random wave behaviors. Results of the study shows that +/- 20% changes in the outside diameter could affect the natural frequency as much as +/- 27.3% and the exciting moment energy by as much as 28.2% for increasing outside diameter and -22.4% for decreasing outside diameter. It seems to be significant, but in term of its value the change is fairly small. Variations at the buoyancy chamber length give the same effect, but it is smaller than varying the outside diameter. The variation of position gives much smaller effect from both study above, the only notable effect of position variation is on the extreme pitch response at medium range significant wave height (Hs). From overall study results, it could be concluded that AT is very feasible to be operate at extreme wave condition because of the natural frequency and maximum Response Amplitude Operator (RAO) is relatively small. This condition make the AT much suitable for the South East Asia region.

Keywords: *Articulated Tower, buoyancy parameter, dynamic behavior, natural frequency, exciting moment energy, extreme pitch response, RAO*

1.0 INTRODUCTION

Articulated tower (AT) is a type of compliant offshore structure may be utilized as an efficient means of tanker mooring and oil loading as well as production riser and control tower located in harsh and remote environment. Other terminologies are used to identify an AT, namely articulated loading platform, buoyant tower, and articulated loading column. AT technology was developed in the early of 1970s, and the first articulated tower ever been built was operated in Argyll Field of the North Sea in 1975. This structure was operated as a single point mooring to a shuttle tanker in conjunction with a semi-submersible as the production unit and a flexible riser. Since then a substantial number of AT has been constructed and put in operation as the supporting system for offshore hydrocarbon production facility, for instance the double articulated riser designed for the Hondo Field in Santa Barbara Channel of California in 1985. Although initially AT was projected for operation in water depth of approximately 100 – 200 m, but as the technology matures the operation in much deeper water was considered possible. An analysis by Sebastiani [1] on the dynamics of a single point-mooring tower at 1000 m water depth in the Mediterranean Sea eventually was an example that shows such a trend. With regards to the application of AT in deeper water Helvacioglu and Incecik [2] has further suggested employing the concept of double AT in order to minimize the overall deflection of the system.

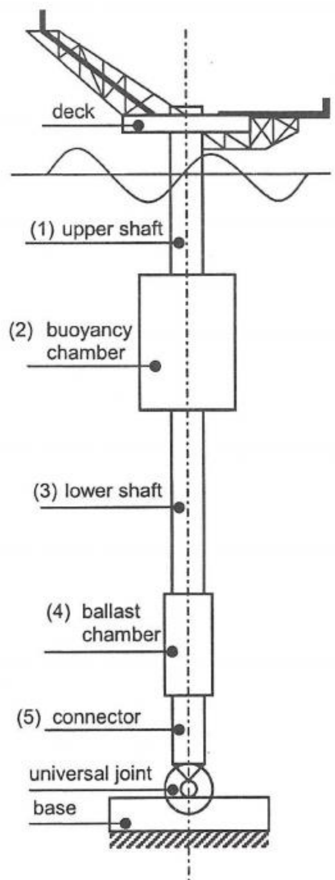

Figure 1: Basic configuration of an articulated tower

The basic configuration of an AT, as shown in Figure 1, comprises of five cylindrical subsections erected consecutively in vertical plane, namely the connector at the lower part, ballast chamber, lower shaft, buoyancy chamber, and upper shaft. The connector is joined to the base at the sea bottom by a universal joint, whilst the upper shaft supports a deck structure where necessary topsides facilities are accommodated. AT are considered economically attractive for deep waters application due to their reduced structural weight and simplicity in fabrication if compared to other conventional platforms [3, 4]. Unlike fixed structures, which are designed to withstand, environmental forces without any substantial displacement, compliant structures like AT are designed to allow small but not negligible deformation and deflection.

For an AT, the overall system deflection in angular rotational mode is made possible by the presence of the universal joint that connects the lower part of the structure to the base. The utilization of the universal joint will also relieve the foundation from resisting any lateral force developed by environmental action.

2.0 ARTICULATED TOWER DYNAMICS

The primary physical features of an AT is on its ability to displace from its initial position when subjected to environmental loads, either wind, current, or especially waves, and hence reducing the maximum internal response on its structural elements. Under the environmental loads an AT displaces in rotational mode by the virtue of the universal joint located on the base. In order to revert into its equilibrium after being displaced under the environmental loads, an AT necessitates being equipped with a buoyancy chamber. The buoyancy chamber is considered as one of the most the important element since it will provide essential stiffness to the system through the buoyancy restoring forces. The use of buoyancy chamber replacing guylines or tethers is required to restrain any possible excessive motions, thus simplifying the system even further. An AT should also be designed to avoid as much as possible any resonance with most commonly occurring waves. Besides from its peculiar configuration, an adjustment of the AT natural frequency could be assisted by the set up of a ballast water chamber positioned above the connector.

The dynamic behavior of AT presented in this paper has been identified under the assumption of rigid body motion in single-degree of freedom using a certain analytical approach. A particular emphasize is then given on the effect of variations in size and position of the buoyancy chamber towards the maximum response in random waves. The case study has been performed with a reference to an AT operated in the North Sea [5]. The current study is expected to form a sensible basis for a further development of sophisticated non-linear model in two-degree of freedom [6, 7] as well as for the investigation of dynamic behavior on integrated tower and tanker system [8].

2.1 Analytical Formulations

The motion for an AT fixed by a universal joint having a single-degree of freedom could be explained in Figure 2.

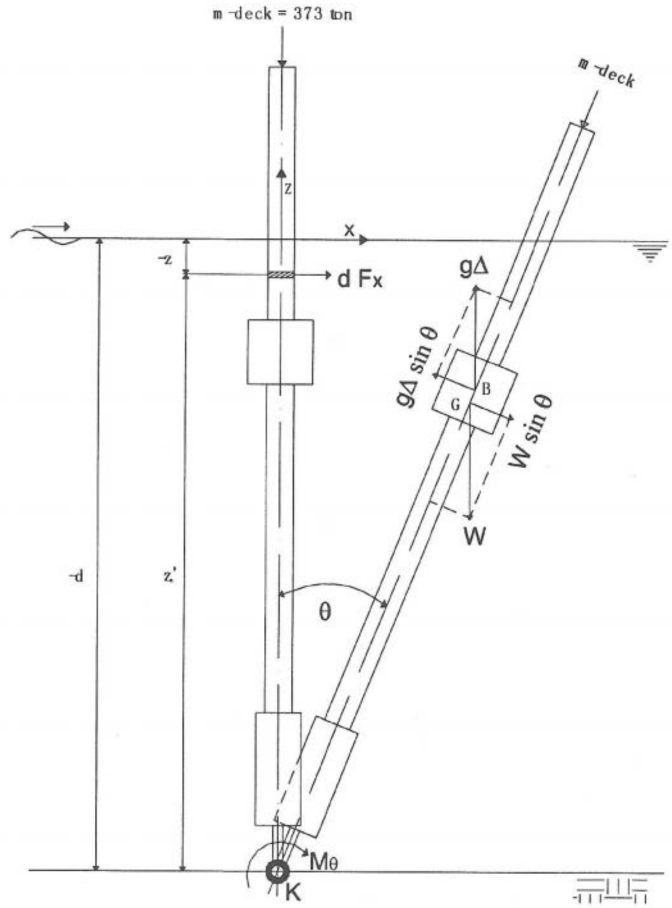

Figure 2: Analytical model of an articulated tower

Assuming that the waves is linear, small perturbations about an equilibrium position, and a linear drag force, the analytical formulation of AT motion can be expressed in the following general form:

$$\left(I_\theta + I_{\theta A}\right)\ddot{\theta} + C\,\dot{\theta} + R\,\theta = M_0 \cos \omega t \tag{1}$$

where: I_θ = mass moment of inertia of the structure about the centre of rotation

$I_{\theta A}$ = added mass moment of inertia of the structure about the centre of rotation

C = structural damping coefficients

R = structural stiffness coefficients

M_0 = amplitude of exciting moment due to wave actions

ω = incident wave frequency.
θ = pitch elevation

The mass moment of inertia of the structure can be simply calculated by the equation:

$$I_\theta = m_o\left(l_1 + l_2 + l_3 + l_4 + l_5\right)^2 + \frac{1}{12}m_1\left(6R_1^{\ 2} + l_1^{\ 2}\right)$$

$$+ m_1\left(\frac{l_1}{2} + l_2 + l_3 + l_4 + l_5\right)^2 + \frac{1}{12}m_2\left(6R_2^{\ 2} + l_2^{\ 2}\right)$$

$$+ m_2\left(\frac{l_2}{2} + l_3 + l_4 + l_5\right)^2 + \frac{1}{12}m_3\left(6R_3^{\ 2} + l_3^{\ 2}\right)^2$$

$$+ m_3\left(\frac{l_3}{2} + l_4 + l_5\right) + \frac{1}{12}m_4\left(6R_4^{\ 2} + l_4^{\ 2}\right) + m_4\left(\frac{l_4}{2} + l_5\right)^{2^2}$$

$$+ \frac{1}{12}m_5\left(6R_5^{\ 2} + l_5^{\ 2}\right) + m_5\left(\frac{l_5}{2}\right) \qquad (2)$$

where m_o is mass of the deck, l_n, R_n, m_n are, respectively, length, radius, and mass of the cylindrical components for n = 1,2,...,5; with a reference to Fig. 1, n = 1 is the upper shaft, n = 2 the buoyancy chamber, n = 3 the lower shaft, n = 4 ballast chamber, and n = 5 the connector.

The added mass moment of inertia of the structure is calculated by:

$$I_{\theta A} = m'_1\left(\frac{l'_1}{2} + l_2 + l_3 + l_4 + l_5\right)^2 + m_2\left(\frac{l_2}{2} + l_3 + l_4 + l_5\right)^2$$

$$+ m_3\left(\frac{l_3}{2} + l_4 + l_5\right)^2 + m_4\left(\frac{l_4}{2} + l_5\right)^2 + m_5\left(\frac{l_5}{2}\right)^2 \qquad (3)$$

where l'_1 and m'_1 are the length and mass volume of the upper shaft proportion submerged under the water surface.

The hydrodynamic damping applied to the structure may be obtained from [9]:

$$C = \pi . c_f . \left(\frac{M_o(\omega, \mu = 0)}{\zeta_0}\right)^2 \qquad (4)$$

where: $c_f = \dfrac{\omega^3 \cosh^2 kd}{4\pi\rho g^3 kd \tanh kd\left[1 + (\sin 2kd)/2kd\right]}$

μ = wave heading angle
ζ_0 = wave amplitude = $H_w/2$
H_w = wave height
ρ = sea water density
g = acceleration due to gravity
k = wave number = $2\pi/\lambda$
λ = wave length (for deep water $\lambda = g\,T^2/2\pi$)
d = water depth.

The structural stiffness is obtained as the hydrostatic restoring moment, which is the difference between the moment of buoyancy and the moment of structural weight about the centre of rotation, and written as:

$$R = \rho g \nabla \overline{KB} - W\,\overline{KG} \tag{5}$$

where: ∇ = displacement volume of the overall structure
W = weight of the structure
$\overline{KB}$ = height of the buoyancy point above centre of rotation K
$\overline{KG}$ = height of the structure centre of gravity point above centre of rotation K

Let dF_x be the horizontal component of wave exciting force acting on an element dz along the cylindrical member of an AT, then the contribution of this elemental exciting force onto the exciting moment is written by considering the lever arm $(z-d)$ as follows:

$$dM_0 = (z-d)\,dF_x \tag{6}$$

By assuming the cylindrical element be a slender body then Morisson equation may be applied to describe the horizontal force, consists of the inertia and drag force components:

$$dF_x = dF_{Ix} + dF_{Dx} \tag{7}$$

The elemental inertia force is given by:

$$\begin{aligned} dF_{Ix} &= -\frac{1}{4}\rho\pi D^2 C_m \dot{U}\,dz \\ &= -\frac{1}{4}\rho\pi D^2 C_m \frac{\pi H}{T}\omega e^{kz}\,sin\,(-\omega t)dz \\ &= A_1 C_m D^2 e^{kz}\,dz \quad \text{where } A_1 = -\frac{1}{4}\rho\frac{\pi^2 H}{T}\omega\,sin(-\omega t) \end{aligned} \tag{8}$$

and the elemental drag force is given by:

$$
\begin{aligned}
dF_{D\,x} &= \frac{1}{2}\rho DC_d U|U|dz \\
&= \frac{1}{2}\rho DC_d \frac{\pi^2 H^2}{T^2} e^{2kz} \cos(-\omega t)|\cos(-\omega t)|dz \\
&= A_2 DC_d e^{2kz}\, dz \text{ where } A_2 = -\frac{1}{2}\rho\frac{\pi^2 H^2}{T^2}\cos(-\omega t)|\cos(-\omega t)|
\end{aligned}
\tag{9}
$$

where: D = the diameter of element dz of any AT's cylindical member
Cm = the inertia coefficient
Cd = the drag coefficient.
U = water particle velocity

An appropriate data of the inertia and drag coefficients such as that provided by Dahong and Qhihua [10] should be taken in order to attain more accurate computation results. In that reference the two coefficients are given as functions of the Keulegan-Carpenter number.

$$KC = U_0 T / D \tag{10}$$

where :
U_o = Water particle amplitude of velocity
T = Wave period
D = Cylinder diameter

Having accomplished the computation of elemental inertia and drag force component, the total exciting moment applied to the system is obtained by integration of the elemental exciting moment as:

$$M_0 = \int_{-z_n}^{-z_{n-1}} z\, dF_x - d\int_{-z_n}^{-z_{n-1}} dF_x \tag{11}$$

z_n and z_{n-1} denote the vertical position of any consequtive cylindrical member's bottom part. If the solution of the harmonically oscillating AT in angular mode, hereinafter referred to as the pitch motion, could be given by solving the differential eq. (1) in the form of:

$$\theta(t) = \theta_0 e^{-kz}\cos(kx - \omega t - \varphi) \tag{12}$$

and the moment of excitation by:

$$M(t) = M_0\, e^{-kz}\cos(kx - \omega t - \psi) \tag{13}$$

then by applying the general theory of forced vibration, the following correlation is obtained:

$$\theta_0 = \frac{M_0 / R}{\sqrt{\left(1-\Omega^2\right)^2 + (2\zeta\Omega)^2}} \tag{14}$$

where:
- $\theta(t)$ = pitch elevation as a function of time t
- $M(t)$ = pitch exciting moment as a function of time t
- θ_0 = pitch motion amplitude
- M_0 = pitch exciting moment amplitude
- φ = phase angle of pitch motion
- ψ = phase angle of exciting moment
- Ω = frquency ratio = ω/ω_n
- ω_n = natural frequency of the AT = $\sqrt{\frac{R}{I_\theta + I_{\theta A}}}$
- ζ = structural damping ratio = C/C_r
- C_r = critical damping = $2\left(I_\theta + I_{\theta A}\right)\omega_n$

Results of the computation utilizing eq. (14) will be used to describe the AT dynamic behavior in regular waves through the response amplitude operator, $RAO = \theta_0/\zeta_0$ as a function of the incremental incident wave frequency.

2.2 The Behavior of Articulated Tower in Random Waves

Results of evaluation as described previously have not entirely characterize the AT behavior in real seas. In order to cope with the problem of random waves a further analysis necessitate to be performed. This then known as spectral analysis, where initially introduced by Pierson and St. Denis in 1953 [11], which eventually a stochastic approach applied in evaluation of ocean structures. By the virtue of spectral analysis, the motion of AT in random waves could be computed by the transformation of wave spectrum into the motion response spectrum. The required data in this respect are the RAO and the wave spectral formulae, in which by employing the following transfer function the response spectrum is obtained:

$$S_{\theta\theta}(\omega) = RAO^2 S(\omega) \tag{14}$$

There are a large number of wave spectrum formulae available, hence it is very much up to the designer to choose which formula is more suitable for the case to be tackled.

An example of this is the well-known JONSWAP wave spectrum, which takes the form:

$$S(\omega) = \alpha g^2 \omega^{-5} \, exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right]\gamma^x \tag{15}$$

Where: $x = exp\left[-\frac{(\omega-\omega_0)^2}{2\tau\,\omega_0^2}\right]$

τ = *shape parameter*
τ = 0.07 for $\omega \leq \omega_o$
τ = 0.09 for $\omega \geq \omega_o$
α, γ *dan* ω_o are parameters which can be appropriately obtain from [12].

Basically there are various statistical variables to describe the dynamic behaviour of ocean structures that could be derived from the spectral analysis, such as average values, significant values, etc. But for the current study it is considered adequate to evaluate the extreme value of the AT motion response. The peculiar equation for this case is:

$$\theta_{ext} = \left[2\,ln\left\{\frac{60^2\,T}{2\pi}\sqrt{\frac{m_2}{m_0}}\right\}\right]^{1/2}\sqrt{m_0} \qquad (16)$$

where: m_0 = zeroth moment of the response spectrum
m_2 = second moment of the response spectrum
T = storm duration (hour).

3.0 DISCUSSION OF THE RESULTS

This study has been conducted on an AT operated in the North Sea at the water depth of 141.5 m [5]. The lengths of the cylindrical member, respectively from the upper shaft to the connector, are 57.1 m, 15.0 m, 75.2 m, 25.5 m, and 7.7 m with the corresponding diameters of 6.0 m, 15.0 m, 6.3 m, 10.5 m, and 2.3 m. The structural weight of the cylindrical member consecutively from the upper shaft to the ballast chamber are, respectively, 455 tons, 721 tons, 2258 tons, and 4014 tons, and the corresponding buoyancy of 522 tons, 2717 tons, 2339 tons, and 2470 tons. Weight of the deck is assumed to be 373 tons. Six sets of study altogether have been conducted on the selected AT, covering both the evaluation of dynamic behaviors in regular and random waves. The parametric study is aimed to investigate effects of variations in the presumed primary parameter, namely the buoyancy chamber sizing and position, on the AT dynamic responses. The six sets of study, denotes as PS, so performed are summarized as follows:

a. PS1: reducing outside diameter of the buoyancy chamber
b. PS2: increasing outside diameter of the buoyancy chamber
c. PS3: reducing length of the buoyancy chamber
d. PS4: increasing length of the buoyancy chamber
e. PS5: lowering position of the buoyancy chamber, and
f. PS6: raising position of the buoyancy chamber.

For each case the conditions of constant structural weight and buoyancy are examined. The structural weight and buoyancy are kept constant by varying the size of the upper shaft, the lower shaft or the ballast chamber, or the combination of those three components. The buoyancy chamber sizing or position in all cases are varied by three intervals, namely 1.0 m, 2.0 m, and 3.0 m, which essentially represent some 6.7%, 13.3% and 20.0% changes with respect to its primary dimensions, i.e. 15.0 m. Results of the evaluations are represented by the values of natural frequencies, peak of RAO curves, maximum energy content of the exciting moment, and the extreme pitch responses.

For the latter, three values are derived to indicate the trends in low range, medium range, and high range of significant wave heights, that is H_s = 2.0 m, 5.0 m, and 10.0 m. Any computation performed for each study yields necessary numerical data which could then be plotted in the graphical forms. The overall results of the study are summarized in Table 1, and examples of graphical plots are as shown in Figures 2 to 4.

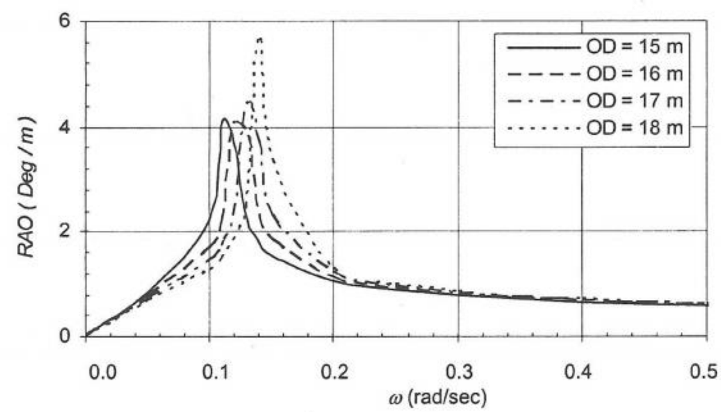

Figure 3: Pitch response amplitude due to change in buoyancy chamber diameter; constant buoyancy

By observing Table 1, it is obvious that the AT parent configuration is characterized by a very low natural frequency, i.e. in the order of around 0.11 rad/sec, or high natural period which is approaching 57.09 sec. Such values indicate that the resonance with most wave occurrence in the operational area was not possible. Typical response amplitude operator from regular wave analysis as presented in Figure 3 shows the gradual increase in the lower frequency range or sub-critical zone followed by a steep increase in the resonance frequency or critical zone, and finally a sudden decline at the higher frequency range or the super-critical zone. Results of the random wave spectral analysis are represented by the curves of energy content of moment excitation as functions of incident wave frequency in Figure 4 and the curves of extreme pitch response as functions of the variations in significant wave heights, H_s, in Figure 5. In general, the curves of energy content of moment excitation increase in line with the growth of incident wave frequency. A peculiar manner is demonstrated by the extreme pitch response curves deploying from the present case study, which is moderate at lower H_s, and then notably decline at intermediate range of H_s and followed by a steep increase at higher range of H_s. Other studies commonly show much lower response values in the lower range of H_s. Nonetheless such an occurrence as depicted in Figure 4 is possible due to the complex correlation between the modal period of the wave spectral curve and the resonance of the RAO; not mentioning as well the effects of other wave spectrum parameters.

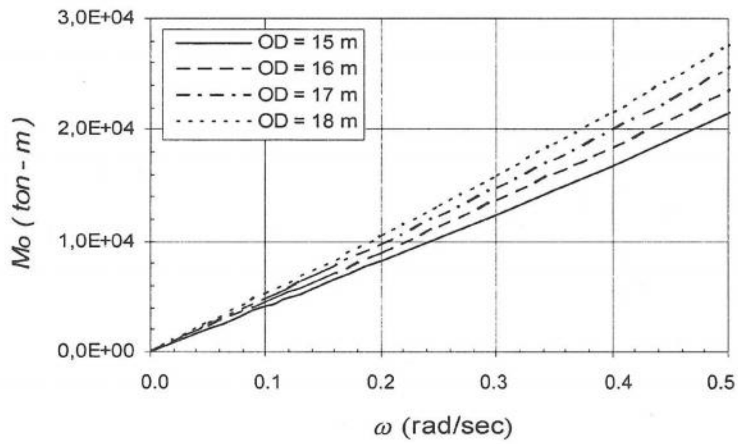

Figure 4: Moment excitation energy due to change in buoyancy chamber

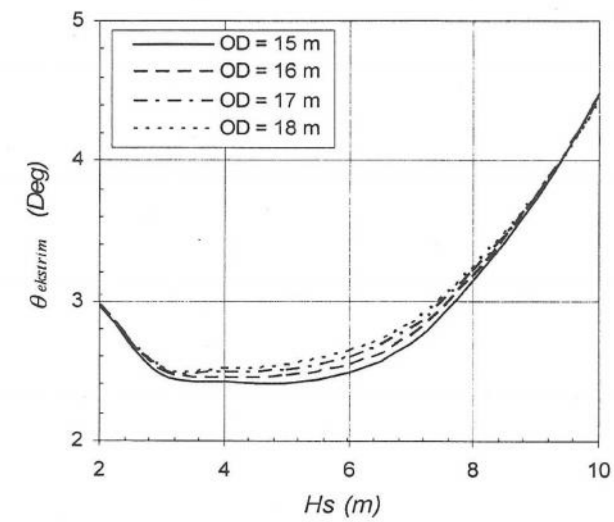

Figure 5: Extreme pitch due to change in buoyancy chamber

Effects of the AT main parameters about its dynamic behaviors could further be described concurrently with reference to Table 1.

Table 1: Parameter variations and results of the parametric studies

PS1: Reducing outside diameter of buoyancy chamber							
PS1a: Maintaining a constant structural weight by varying outside diameter of the lower shaft							
D-BC	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
					Hs=2m	Hs=5m	Hs=10m
15	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
14	6.424	0.10	4.170	86548.120	2.951	2.344	4.483
13	6.548	0.09	4.871	78835.970	2.935	2.278	4.490
12	6.673	0.08	11.496	71540.750	2.915	2.206	4.504
PS1b: Maintaining a constant buoyancy by varying outside diameter of the lower shaft							
D-BC	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
					Hs=2m	Hs=5m	Hs=10m
15	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
14	6.744	0.11	4.984	87162.090	2.941	2.336	4.414
13	7.132	0.10	23.829	80115.770	2.917	2.256	4.367
12	7.473	0.09	4.294	73474.380	2.889	2.193	4.339

PS2: Increasing outside diameter of buoyancy chamber							
PS2a: Maintaining a constant structural weight by varying outside diameter of the ballast chamber							
D-BC	D-BIC	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
					Hs=2m	Hs=5m	Hs=10m
15	10.500	0.11	4.111	94637.540	2.963	2.405	4.481
16	10.386	0.12	4.050	103257.900	2.968	2.456	4.456
17	10.273	0.13	4.448	112185.900	2.971	2.502	4.434
18	10.160	0.14	5.676	121404.100	2.971	2.542	4.414
PS2b: Maintaining a constant buoyancy by varying outside diameter of the ballast chamber							
D-BC	D-BIC	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
					Hs=2m	Hs=5m	Hs=10m
15	10.500	0.11	4.111	94637.540	2.963	2.405	4.481
16	9.592	0.12	4.006	103230.800	2.972	2.459	4.462
17	8.520	0.13	4.198	112129.900	2.978	2.508	4.446
18	7.212	0.14	4.652	121319.600	2.983	2.552	4.433

PS3: Reducing length of buoyancy chamber									
PS3a: Maintaining a constant structural weight by varying outside diameter of the lower shaft									
L-BC	L-US	L-LS	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
15	57.100	75.200	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
14	57.600	75.700	6.372	0.11	11.810	90864.270	2.944	2.369	4.508
13	58.100	76.200	6.444	0.11	4.507	87150.750	2.924	2.333	4.535
12	58.600	76.700	6.514	0.10	5.596	83490.340	2.905	2.296	4.562
PS3b: Maintaining a constant buoyancy by varying outside diameter of the lower shaft									
L-BC	L-US	L-LS	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
15	57.100	75.200	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
14	57.600	75.700	6.493	0.11	6.808	91081.700	2.940	2.366	4.481
13	58.100	76.200	6.679	0.11	7.417	87623.790	2.918	2.328	4.482
12	58.600	76.700	6.857	0.11	4.064	84253.810	2.896	2.289	4.485

PS4: Increasing length of buoyancy chamber									
PS4a: Maintaining a constant structural weight by varying outside diameter of the ballast chamber									
L-BC	L-US	L-LS	D-BIC	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
15	57.100	75.200	10.500	0.11	4.111	94637.540	2.963	2.405	4.481
16	56.600	74.700	10.433	0.12	7.007	98577.850	2.980	2.437	4.439
17	56.100	74.200	10.366	0.12	5.870	102570.500	2.997	2.469	4.398
18	55.600	73.700	10.300	0.13	4.432	106618.900	3.014	2.501	4.357
PS4b: Maintaining a constant buoyancy by varying outside diameter of the ballast chamber									
L-BC	L-US	L-LS	D-BIC	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
15	57.100	75.200	10.500	0.11	4.111	94637.540	2.963	2.405	4.481
16	56.600	74.700	10.144	0.12	7.040	98567.680	2.981	2.438	4.441
17	56.100	74.200	9.776	0.12	5.788	102550.100	3.000	1.471	4.402
18	55.600	73.700	9.393	0.13	4.524	106588.400	3.018	2.504	4.363

PS5: Lowering position of the buoyancy chamber

PS5a: Maintaining a constant structural weight by varying outside diameter of the lower shaft

BC-Ld	L-US	L-LS	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
0.000	57.100	75.200	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
1.000	58.100	74.200	6.361	0.12	3.857	91508.290	2.931	2.362	4.483
2.000	59.100	73.200	6.425	0.12	4.096	88561.200	2.900	2.322	4.484
3.000	60.100	72.200	6.491	0.12	4.413	85784.210	2.871	2.283	4.486

PS5b: Maintaining a constant buoyancy by varying outside diameter of the lower shaft

BC-Ld	L-US	L-LS	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
0.000	57.100	75.200	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
1.000	58.100	74.200	6.304	0.11	3.906	91421.410	2.932	2.364	4.495
2.000	59.100	73.200	6.308	0.11	3.747	88389.070	2.903	2.325	4.508
3.000	60.100	72.200	6.312	0.12	3.790	85530.130	2.876	2.287	4.520

PS6: Raising position of the buoyancy chamber

PS6a: Maintaining a constant structural weight by varying outside diameter of the lower shaft

BC-Rd	L-US	L-LS	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
0.000	57.100	75.200	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
1.000	56.100	76.200	6.239	0.11	4.611	97955.270	2.996	2.449	4.481
2.000	55.100	77.200	6.180	0.11	5.295	101476.400	3.031	2.495	4.481
3.000	54.100	78.200	6.122	0.11	6.331	105211.600	3.068	2.543	4.481

PS6b: Maintaining a constant buoyancy by varying outside diameter of the lower shaft

BC-Rd	L-US	L-LS	D-LS	ω_n	*RAOmax*	M_{en}	$\theta_{extreme}$		
							Hs=2m	Hs=5m	Hs=10m
0.000	57.100	75.200	6.300	0.11	4.111	94637.540	2.963	2.405	4.481
1.000	56.100	76.200	6.296	0.11	4.345	98048.410	2.955	2.447	4.467
2.000	55.100	77.200	6.292	0.11	4.614	101665.600	3.028	2.491	4.453
3.000	54.100	78.200	6.289	0.11	4.922	105503.300	3.063	2.537	4.437

Notes:

D-BC	= outside diameter of the buoyancy chamber (m)
D-LS	= outside diameter of the lower shaft (m)
D-BlC	= outside diameter of ballast chamber (m)
L-US	= length of upper shaft (m)
L-LS	= length of lower shaft (m)
BC-Ld	= buoyancy chamber lowered by z (m)
BC-Rd	= buoyancy chamber raised by z (m)
M_{en}	= maximum energy of the exciting moment (ton.m)
ω_n	= natural frequency (rad/sec)
RAOmax	= peak value of the RAO curve (deg/m)
θ_{extreme}	= extreme pitch response (deg)
H_s	= significant wave height (m)

The variation of the buoyancy chamber parameters eventually brings only slight change in the natural frequency, either for the case of constant weight or constant buoyancy condition. The greatest change as much as +/- 27.3% was obtained by varying outside diameter until +/- 20% (the "+" term for increase and "_" term for decrease). Although in term of percentage the natural frequency change seems to be significant, but in term of its value the change is fairly small, i.e. in order of only +/- 0.03 rad/sec.

The energy content of moment excitation greatest change is also obtained by varying the outside diameter until +/- 20% which give effect as much as 28.2% for outside diameter increase and -24.4% for outside diameter decrease. In the term of its value it seems quite significant, i.e. in order of 26766.56 ton.m for outside diameter increase and -23096.79 ton.m for outside diameter decrease, but the effect on the extreme response still small i.e. 0.152 deg (6.3%) for outside diameter increase and -0.217 deg (8.9%) for outside diameter decrease.

The extreme response greatest change is also obtained by varying the outside diameter until +/- 20% which give effect as much as 6.7% for outside diameter increase and -9.7% for outside diameter decrease.

From discussion above and Table 1, it can be seen that the variations of buoyancy chamber length give much less effect on the resonance frequency, the energy content or the extreme response. The effect becomes lesser for the variation of buoyancy chamber position, but the only notable effect is witnessed on the extreme response at medium range of significant wave height (5.0 – 6.0 m), it is higher than buoyancy chamber length variation, but still lesser than buoyancy chamber outside diameter variation.

Effect of parameter variation on the maximum value of RAO curve is rather uncertain, as indicated by the fluctuation in the resulting values.

4.0 CONCLUSIONS

A study has been performed aimed at exploring the effect of the AT main parameter variations, namely the sizing of diameter and length as well as positioning of the buoyancy chamber, on its dynamic behavior both in regular and random waves. From the above discussion it could be concluded that the effect of the buoyancy parameter variations are looking quite significant as percentage value, but we can see from Table 1, the effect is numerically almost the same. From overall study results, it could be concluded that AT is very feasible to be operated at extreme wave condition because of the natural frequency and maximum Response Amplitude Operator (RAO) is relatively small. This condition make the AT very much suitable for the South East Asia region.

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