



equipped ship. Through a numerical example, the efficiency and effect of ART on the ship roll motion in irregular waves are evaluated.

## 2. SHIP MOTIONS IN REGULAR WAVES

The six rigid body motion of ship  $\xi_j$  in regular water waves are obtained by solving the linear system:

$$\sum_{j=1}^6 \left[ -\omega^2 (M_{ij} + m_{ij}(\omega) - m_{ij}^s(\omega)) + i\omega b_{ij}(\omega) + (c_{ij} + c_{ij}^s) \right] \xi_j = X_i(\omega), \quad \text{for } i, j = 1, 2, \dots, 6, \quad (1)$$

where,  $M_{ij}$  and  $m_{ij}(\omega)$  are ship's mass and added mass,  $b_{ij}(\omega)$  and  $c_{ij}$  are radiation damping and restoring matrix,  $X_j(\omega)$  is wave exciting force, and  $m_{ij}^s(\omega)$  and  $c_{ij}^s$  are added mass and restoring matrices of internal fluid inside the ARTs, respectively.

## 3. SPECTRAL ANALYSIS

In this section, the methodology of spectral analysis is addressed. For the extreme roll motion assessment, the roll RAO of ship  $A(\omega)$  in regular waves should be first found and the wave energy spectrums  $S_{\zeta}^{(p)}(\omega)$  should be defined. Then, the relation between wave energy spectrum  $S_{\zeta}^{(p)}(\omega)$  and the energy spectrum of ship motion  $S_x^{(p)}(\omega)$  can be defined:

$$S_x^{(p)}(\omega) = |A(\omega)|^2 S_{\zeta}^{(p)}(\omega), \quad (2)$$

where,  $\zeta$  is the wave amplitude and the  $p$  means the sea state number.

Then, the significant roll motion amplitude ( $A_{sig}^{(p)}$ ) is defined:

$$A_{sig}^{(p)} = 2\sqrt{m_0^{(p)}}, \quad (3)$$

in which the zero order moment  $m_0^{(p)}$  is calculated:

$$m_0^{(p)} = \int_0^{\infty} S_x^{(p)}(\omega) d\omega. \quad (4)$$

Finally, the extreme roll motion amplitude  $A_{ext}^{(p)}$  can be obtained:

$$A_{ext}^{(p)} = \sqrt{2m_0^{(p)} \log_e N}, \quad (5)$$

where,  $N$  is the number of observations and given as

$$N = \frac{1}{2\pi} \sqrt{\frac{m_2^{(p)}}{m_0^{(p)}}}, \quad (6)$$

in which the second order moment  $m_2^{(p)}$  is obtained:

$$m_2^{(p)} = \int_0^{\infty} \omega^2 S_x^{(p)}(\omega) d\omega. \quad (7)$$

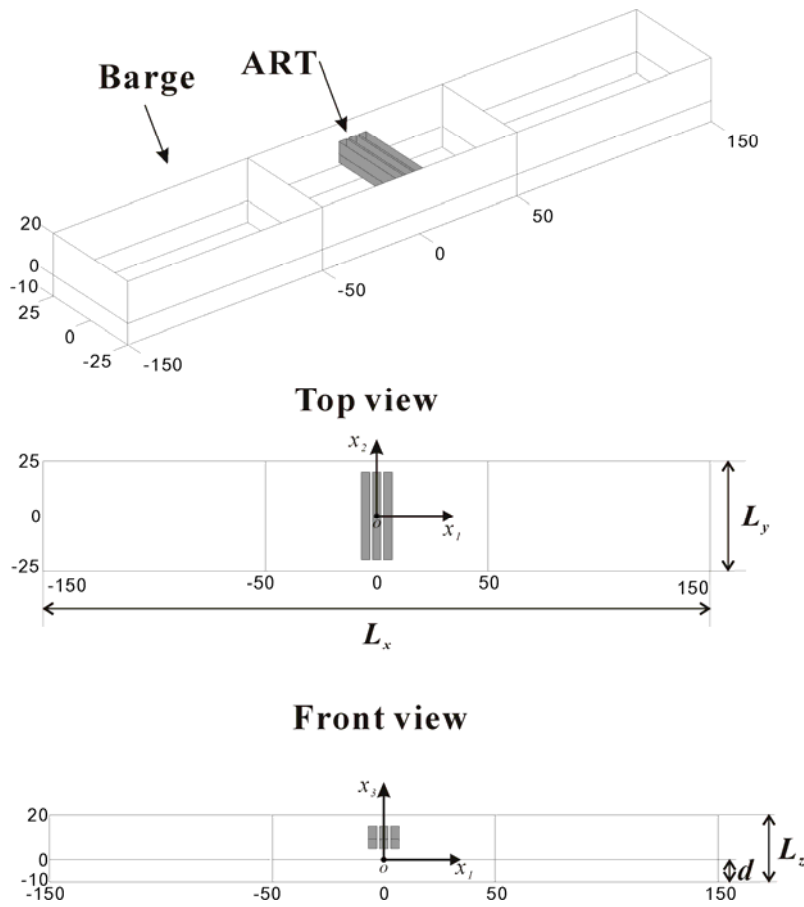
#### 4. NUMERICAL EXAMPLE

The box barge and three free surface ARTs depicted in Fig. 1 are considered and dimensions and analysis condition are summarized in table 1. The roll natural frequency of barge is 0.487 rad/sec and the tuned water depth of ARTs is the 4.105 m.

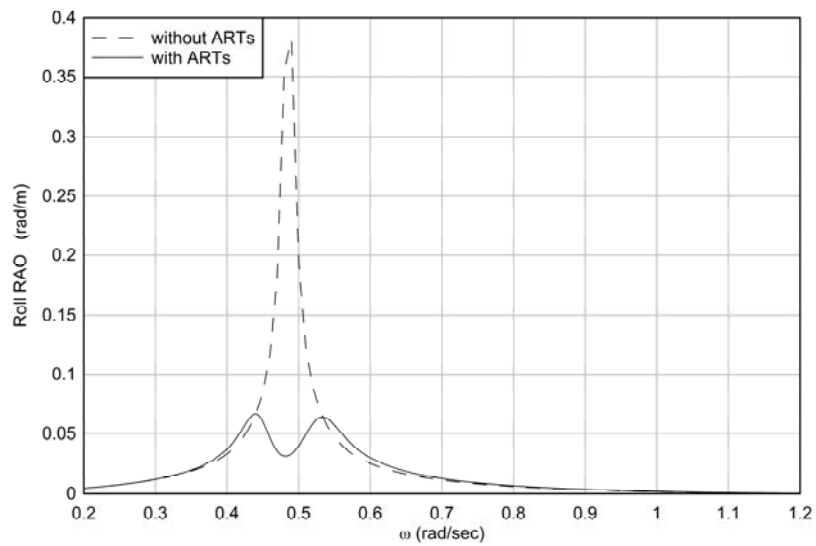
As mentioned, the RAO should be obtained in prior to the spectral analysis and that is obtained through the Eq. (1) and showed in Fig. 2. The hydrodynamic analysis code PADO (Kim 2013 and Lee 2014) was used for RAO computation.

**Table 1. Dimension of 3D box barge and 3 ARTs (filling ratio = 0.0 %) and analysis condition.**

3D box barge			
$L_x$ (m)	300	$I_{xx}$ ( $kg \cdot m^2$ )	7.60735E10
$L_y$ (m)	50	$I_{yy}$ ( $kg \cdot m^2$ )	1.28255E12
$L_z$ (m)	30	$I_{zz}$ ( $kg \cdot m^2$ )	1.32865E12
d (m)	10	LCG, TCG (m)	0
Displacement (ton)	150000	VCG (m)	-0.91538
3 ARTs		Sea spectrum	JONSWAP
$L_{t-x}$ (m)	4	Water depth (m) : $h_E$	infinite
$L_{t-y}$ (m)	40	Direction (deg) : $\theta$	90
$L_{t-z}$ (m)	10	Frequency (rad/sec) : $\omega$	0.2~1.2



**Fig. 1** Box barge and ARTs



**Fig. 2** Roll RAO of box barge

For the extreme roll motion assessment, the JONSWAP spectrum is generated by using the beaufort wind scale data. Then, the significant roll motion and the extreme roll motion are obtained through the Eq. (3) and Eq. (5) and the results are summarized in table 2.

**Table 2. Significant and extreme roll motion of barge**

Sea state (p)	$H_{1/3}$ (m)	$T_1$ (s)	$A_{sig}^{(p)}$ (deg)		$A_{ext}^{(p)}$ (deg)	
			Without ART	With ART	Without ART	With ART
3	0.80	4.20	0.222479	0.06749	0.44253	0.14234
4	1.10	4.60	0.609727	0.19324	0.99132	0.43423
5	1.65	5.10	1.995230	0.65507	4.38213	1.63442
6	2.50	5.70	6.366367	2.02212	13.33142	4.92314

## 5. CONCLUSIONS

In this study, the extreme roll motion analysis was performed for the evaluation of ART effect on ship roll motion in irregular waves. The spectral analysis is quite conventional method in ship industry and therefore the evaluation is very straightforward. In the numerical results, the significant roll motion is about reduced by 70% and the extreme roll motion is suppressed by 65%. In particular, as the peak frequency of sea spectrum and the ship roll natural frequency getting closed, the increment of extreme values is getting larger and larger. Therefore, the deep consideration is required on the design of ARTs in irregular waves.

## REFERENCES

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