Hydrodynamic Analysis and Optimization of Oscillating Water Column Wave Energy Converters

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THE HYDRODYNAMICS OF WAVE ENERGY CONVERTORS 2 (Hywec 2)

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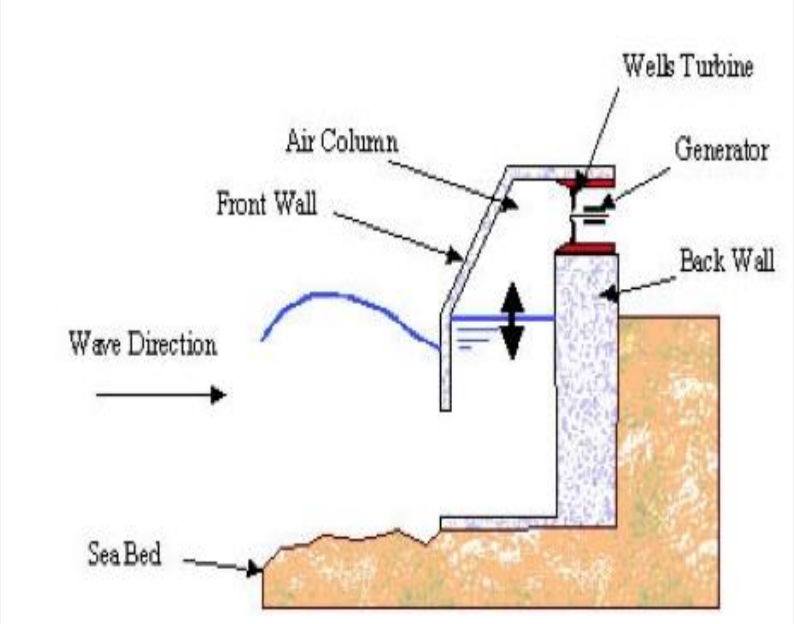
Contents

Introduction

Oscillating water column (OWC) – submerged closed chamber with an opening below the free surface towards the incident wave

- Due to the wave effect, water column acts like a piston on the air trapped above the internal surface
- Pressurized air runs a turbine that is attached to the generator



Advantages

- Very few moving parts
- Easy maintenance
- No machine components in water
- Can be onshore, near shore or offshore as a floating structure
- Use of an air turbine eliminates the need for gearboxes
- No underwater cables are needed for coastal and near shore devices
- Efficiently uses the sea space and it is environment friendly

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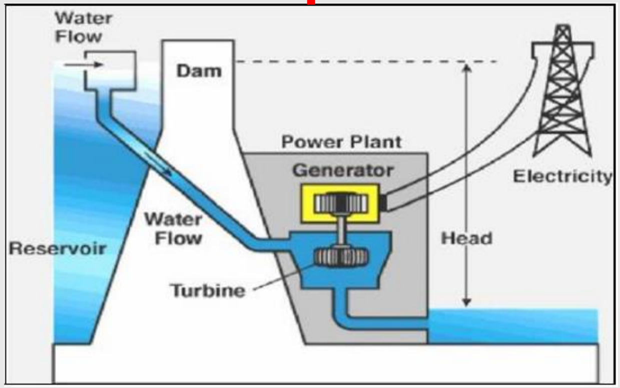
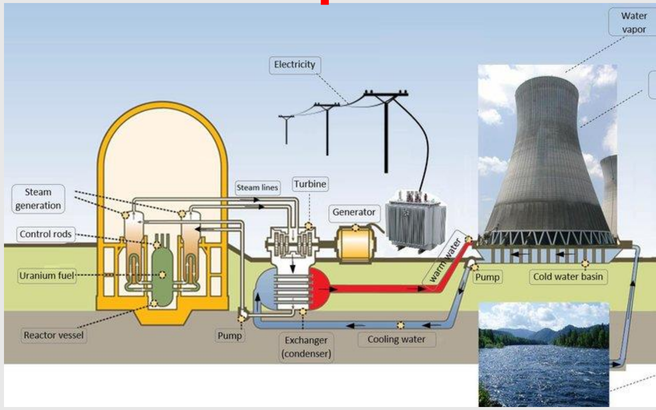
- Introduction
- **Motivation**
- Simplified 1-DOF model of WEC
- Enhancing the Efficiency (Dual-Mass System Application)
- OWC Device in Stepped Sea Bottom Condition
- Floating Dual-Chamber OWC Device
- Conclusions

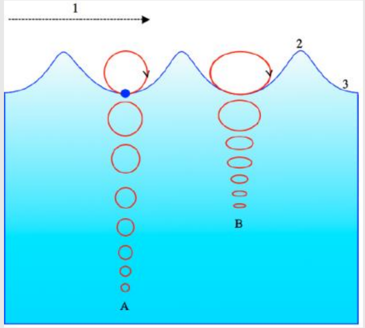
Motivation

- Capturing efficiently the energy of sea waves is challenging
- Almost in the all types of energy resources (except solar power and wave energy) the conventional turbines have been widely used to generate electricity.



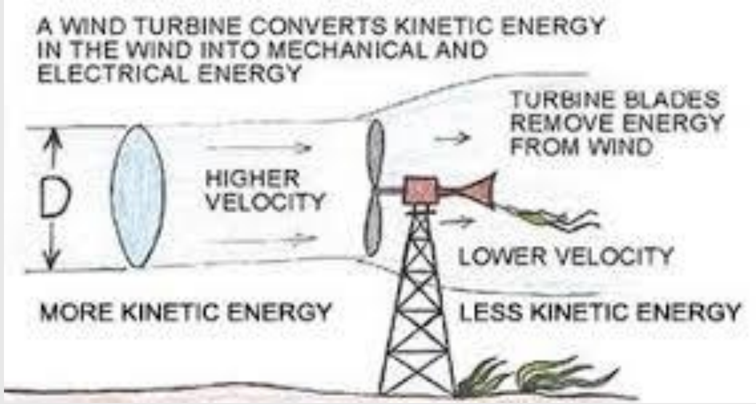


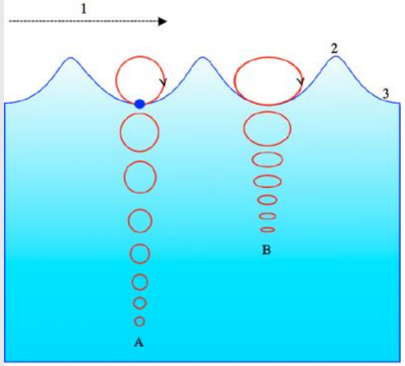
- The conventional methods which use the turbines cannot be utilized to harness power from the waves as the water particles do not follow a uniform streamline.



Motivation

- Capturing efficiently the energy of sea waves is challenging.
- The conventional methods which use the turbines cannot be utilized to harness power from the waves as the water particles do not follow a uniform streamline.
- On the other hand, apart from the conventional energy production systems which use turbines, it could be possible to theoretically capture 100% energy of the resource using WEC devices as there is no net mass flow in the linear waves.





Hence, we should substantially recognize the principle aspects of power absorption from sea waves. So, the proper approach to reap the energy of waves can be devised... .

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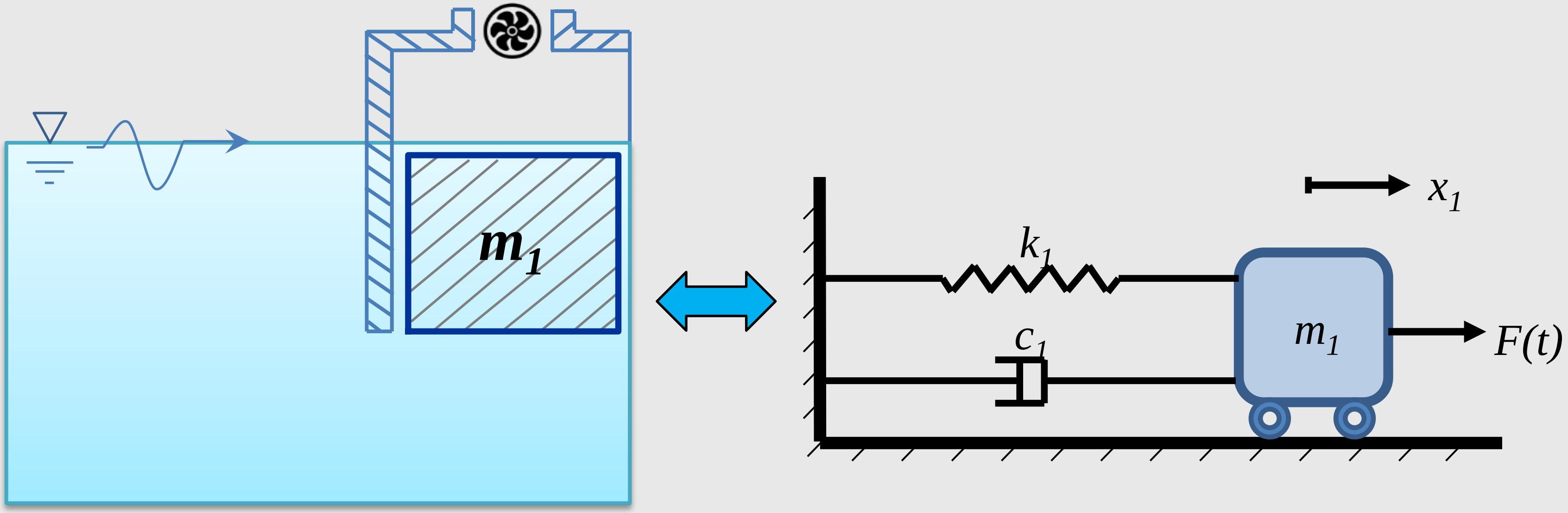
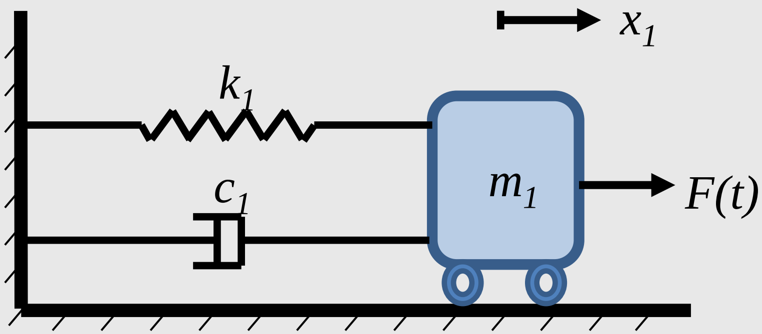
Simplified 1-DOF model of WEC

- Wave Energy Converter (WEC) devices are typically constituted from one or more oscillatory masses which interacts with waves to harvest their energy.
- The water mass confined inside the chamber of OWC devices can be considered as an oscillatory mass of the WEC system.



Simplified 1-DOF model of WEC

- Governing equation for the dynamic motion of the system:



$$\ddot{x}_1 + 2\zeta\omega\dot{x}_1 + \omega^2 x_1 = F/m_1,$$

$$\omega = \sqrt{\frac{k_1}{m_1}},\ \zeta = \frac{c_1}{2m_1\omega},\ F(t) = \mathrm{Re}\{F_0 \mathrm{e}^{-\mathrm{i}\Omega t}\}$$

- Energy absorbed by the system W_a during an oscillation:

$$W_a = \int_0^T F(t)\,\dot{x}_1(t)\,dt = \pi\mathrm{Re}\{-\mathrm{i}F_0^* x_{10}\} = \frac{|F_0|^2}{k_1}\frac{2\pi\zeta\beta}{(1-\beta^2)^2+(2\zeta\beta)^2}, \qquad \beta = \frac{\Omega}{\omega}.$$

- The primary efficiency η of the WEC device in regular waves: $\eta = \dfrac{W_a}{TP_w}$

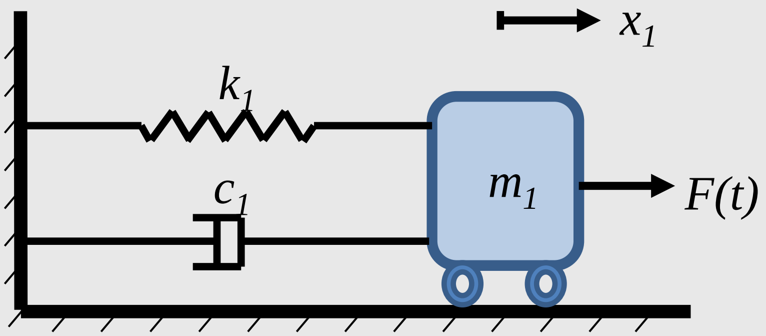
Assuming the device is operating in shallow waters

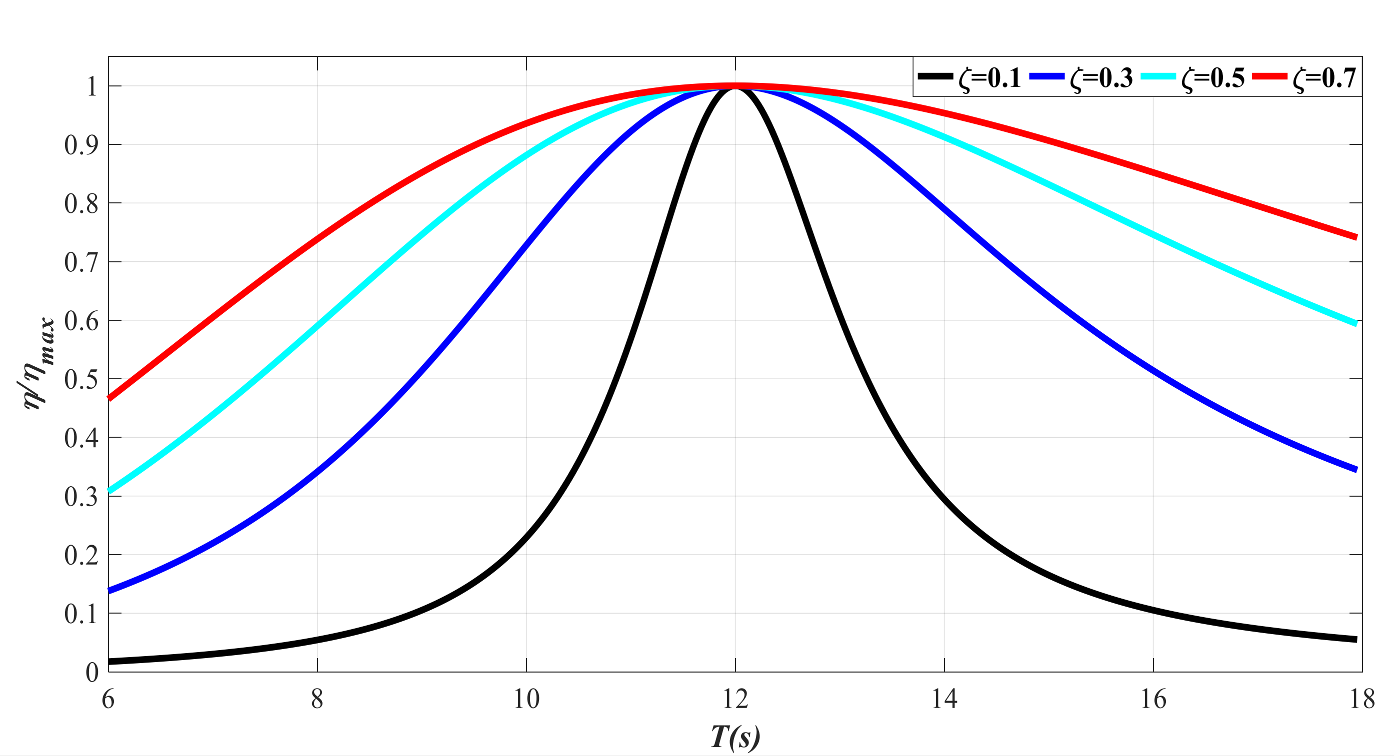
$$\frac{\eta}{\eta_{max}} = \frac{1}{1+\left(\frac{1-\beta^2}{2\zeta\beta}\right)^2}, \quad \eta_{max} = \frac{\frac{|F_0|^2}{k_1}}{0.5\rho g^{1.5} h_1^{0.5} L A^2}\frac{\omega}{4\zeta}.$$

Simplified 1-DOF model of WEC

$$\frac{\eta}{\eta_{max}} = \frac{1}{1 + \left(\frac{1-\beta^2}{2\zeta\beta}\right)^2}$$

$$\beta = \frac{\Omega}{\omega}, \quad \omega = \sqrt{\frac{k_1}{m_1}}, \quad \zeta = \frac{c_1}{2m_1\omega}$$



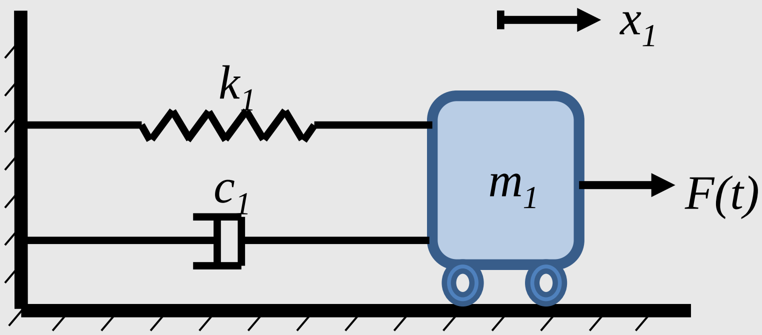


Contents

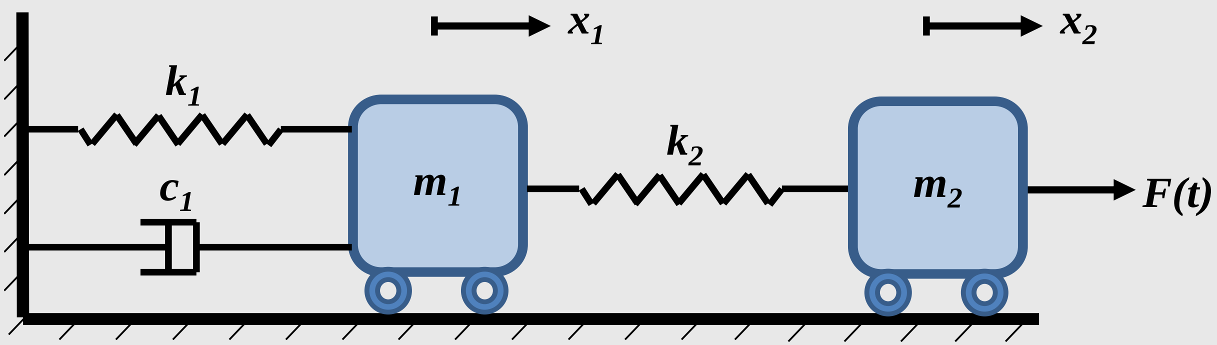
Enhancing the Efficiency (Dual-Mass System Application)

- Involving an additional mass in a single degree of freedom WEC system could improve the performance.

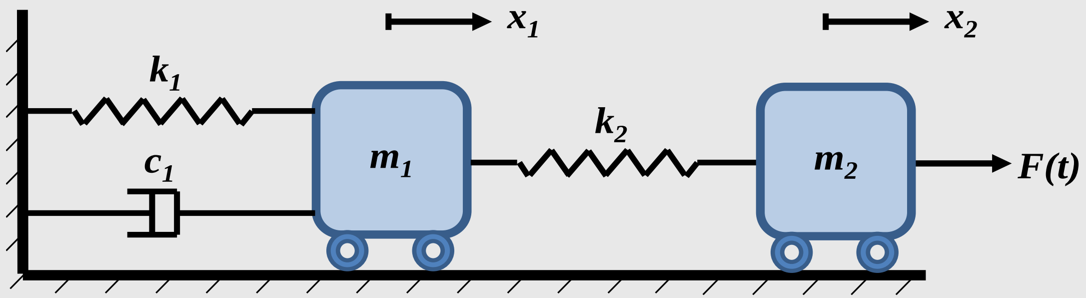
- Single degree of freedom WEC system



- Two degree of freedom WEC system (Dual-Mass system)



Enhancing the Efficiency (Dual-Mass System Application)



- Governing equation for the dynamic motion of the system:

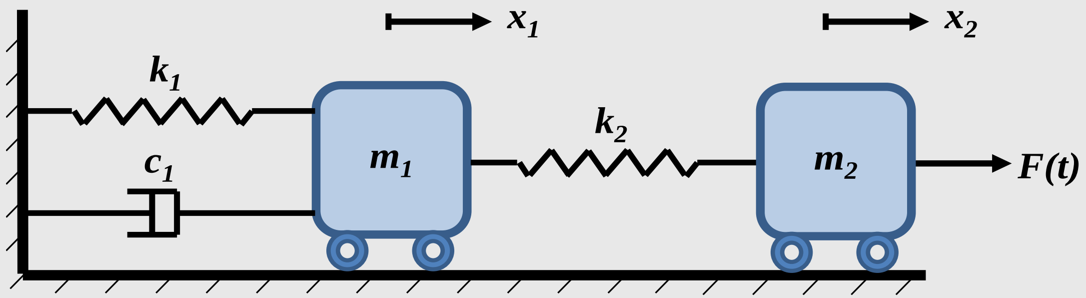
$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ F(t) \end{bmatrix}$$

$$x_1(t) = \mathrm{Re}\{x_{10} \mathrm{e}^{-\mathrm{i}\Omega t}\} \quad x_2(t) = \mathrm{Re}\{x_{20} \mathrm{e}^{-\mathrm{i}\Omega t}\} \quad F(t) = \mathrm{Re}\{F_0 \mathrm{e}^{-\mathrm{i}\Omega t}\}$$

- Energy absorbed by the system W_a in a complete cycle of oscillation:

$$W_a = \int_0^T c_1 \left(\dot{x}_1(t)\right)^2 dt = \pi c_1 \Omega |x_{10}|^2$$

Enhancing the Efficiency (Dual-Mass System Application)



- Primary efficiency of the dual-mass WEC system in shallow waters:

$$\eta = \frac{\frac{|F_0|^2}{k_1}}{0.5\rho g^{1.5} h_1^{0.5} L A^2} \frac{\zeta \beta_{i1} \Omega}{4\zeta^2 \beta_{i1}^2 \left(1-\beta_{i2}^2\right)^2 + (1-\beta_1^2)^2 (1-\beta_2^2)^2}$$

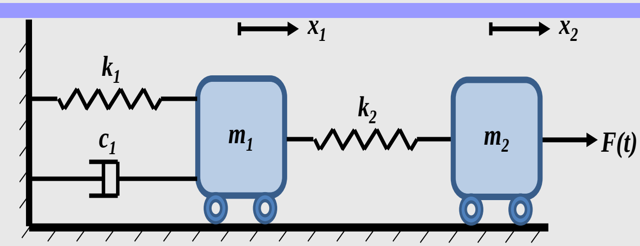
$$\zeta = \frac{c_1}{2 m_1 \omega_{i1}} \quad \beta_{i1} = \Omega/\omega_{i1} \quad \beta_{i2} = \Omega/\omega_{i2} \quad \beta_1 = \Omega/\omega_1 \quad \beta_2 = \Omega/\omega_2$$

$$\omega_{1,2}^2 = \frac{1}{2}\left\{\omega_{i1}^2 + (1+r)\omega_{i2}^2 \pm \sqrt{\left(\omega_{i1}^2 + (1+r)\omega_{i2}^2\right)^2 - 4\omega_{i1}^2\omega_{i2}^2}\right\}$$

$$\omega_{i1} = \sqrt{k_1/m_1} \qquad \omega_{i2} = \sqrt{k_2/m_2} \qquad r = m_2/m_1$$

Enhancing the Efficiency (Dual-Mass System Application)

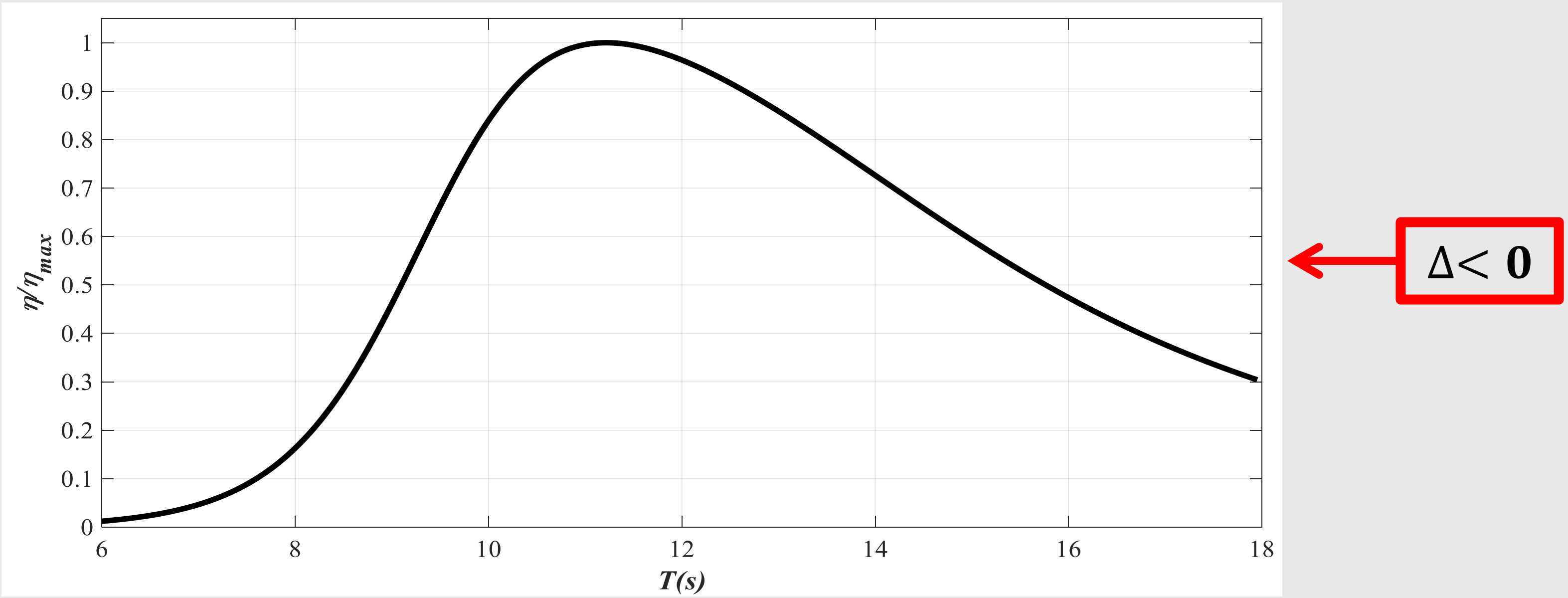
- The efficiency curve of the dual-mass WEC system can have one or two peaks depending on the value of the discriminant parameter, Δ:



$$\Delta = 256a_4^3a_0^3 - 128a_4^2a_2^2a_0^2 + 144a_4a_3^2a_2a_0^2 + 16a_4a_2^4a_0 - 27a_3^4a_0^2 - 4a_3^2a_2^3a_0$$

$$a_4 = -3, \quad a_3 = -8\zeta^2\omega_{i1}^2 + 4(1+r)\omega_{i2}^2 + 4\omega_{i1}^2,$$

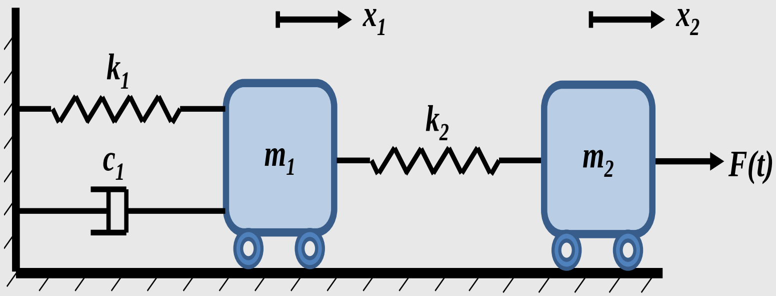
$$a_2 = 8\zeta^2\omega_{i1}^2\omega_{i2}^2 - (1+r)^2\omega_{i2}^4 - 2(2+r)\omega_{i1}^2\omega_{i2}^2 - \omega_{i1}^4, \quad a_0 = \omega_{i1}^4\omega_{i2}^4$$

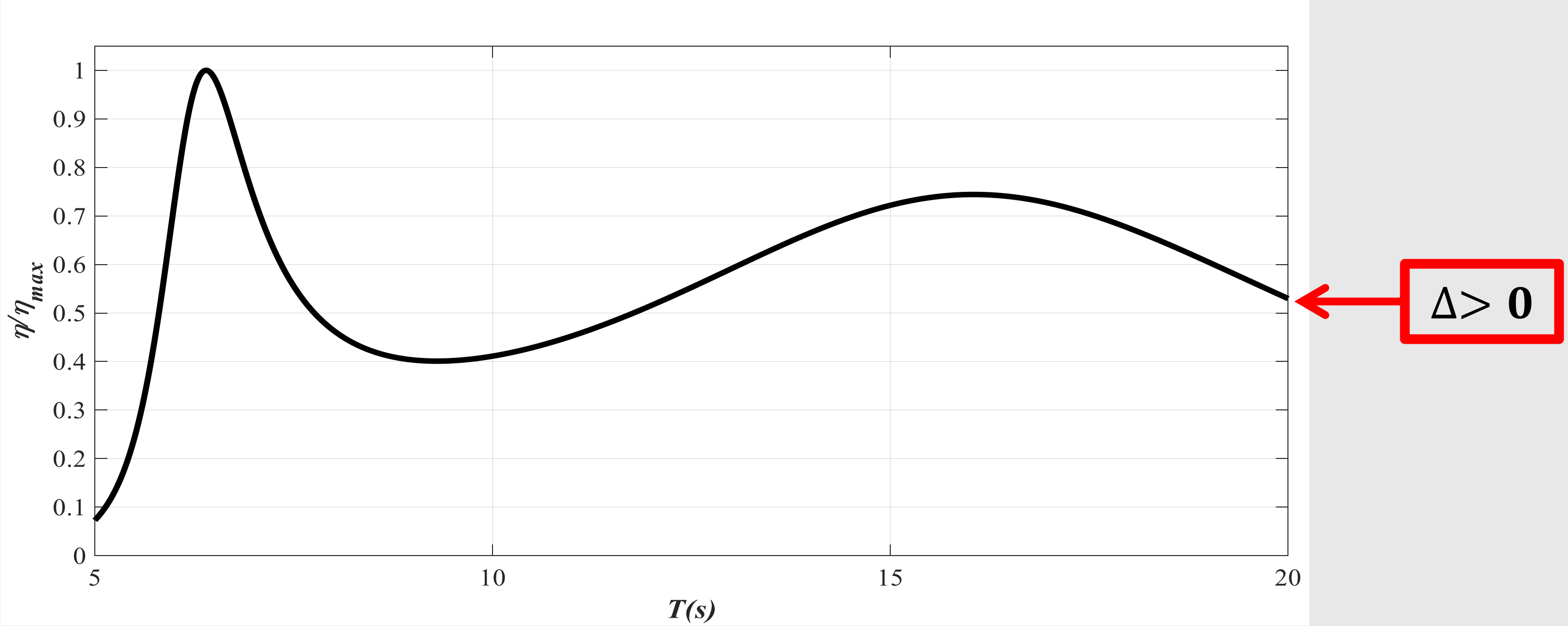


Variation of η/η_{max} versus wave period T ($\zeta = 0.6$, $r = 0.4$, $\omega_{i1} = 2\pi/12$ and $\omega_{i2} = 2\pi/11$)

Enhancing the Efficiency (Dual-Mass System Application)

- The efficiency curve of the dual-mass WEC system can have one or two peaks depending on the value of the discriminant parameter, Δ.



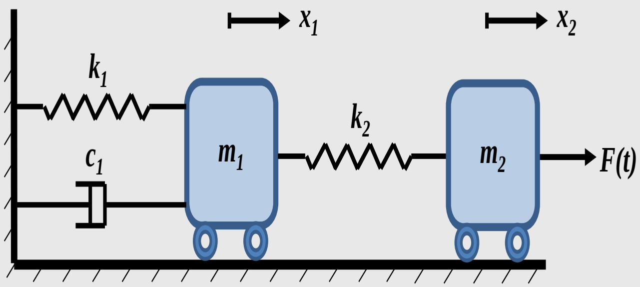


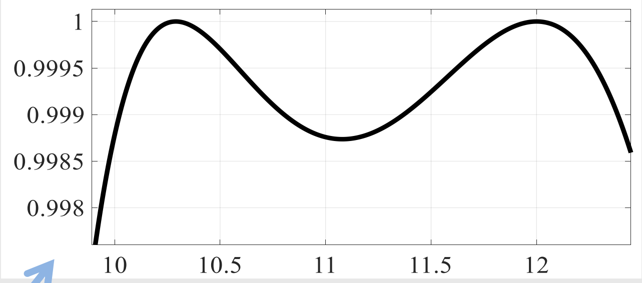
Variation of η/η_{max} versus wave period T ($\zeta = 0.5$, $r = 0.6$, $\omega_{i1} = 2\pi/13$ rad/s and $\omega_{i2} = 2\pi/8$ rad/s)

Reference: Rezanejad, K. & Guedes Soares, C. 2018. Enhancing the primary efficiency of an oscillating water column wave energy converter based on a dual-mass system analogy. Renewable Energy 123: 730-747.

Enhancing the Efficiency (Dual-Mass System Application)

- Appropriate tuning of the WEC system could increase the bandwidth of the efficiency curve as the peaks occur consecutively.



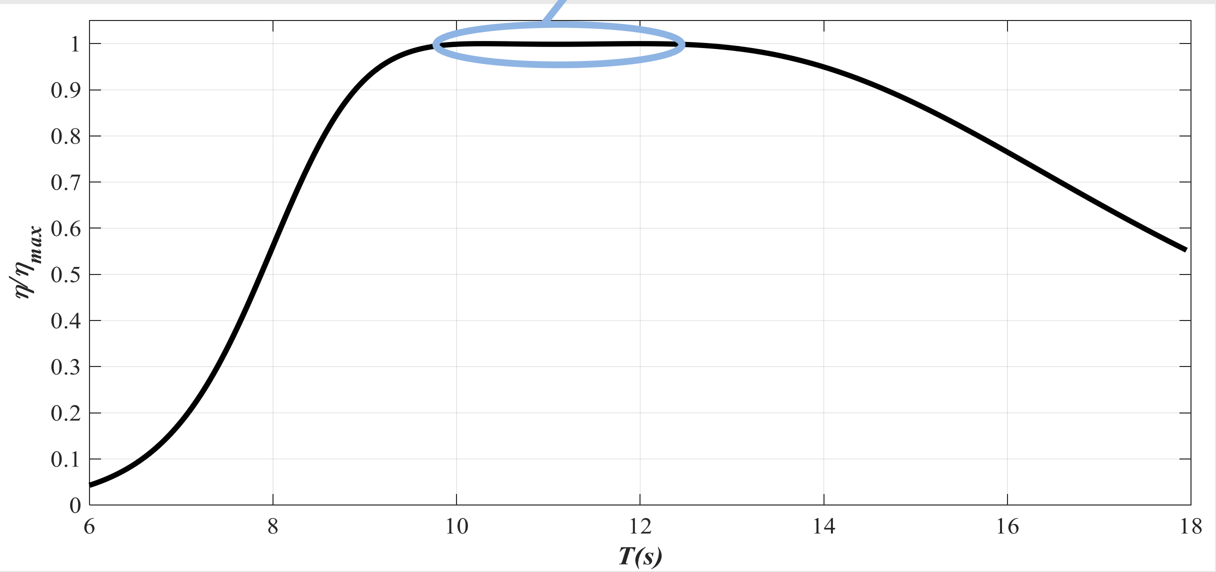


$$\begin{cases} r = \dfrac{2\zeta^2}{1+\zeta^2} \\ \omega_{i2} = \sqrt{1+\zeta^2}\,\omega_{i1} \end{cases}$$

$$r = m_2/m_1$$

$$\omega_{i1} = \sqrt{k_1/m_1}$$

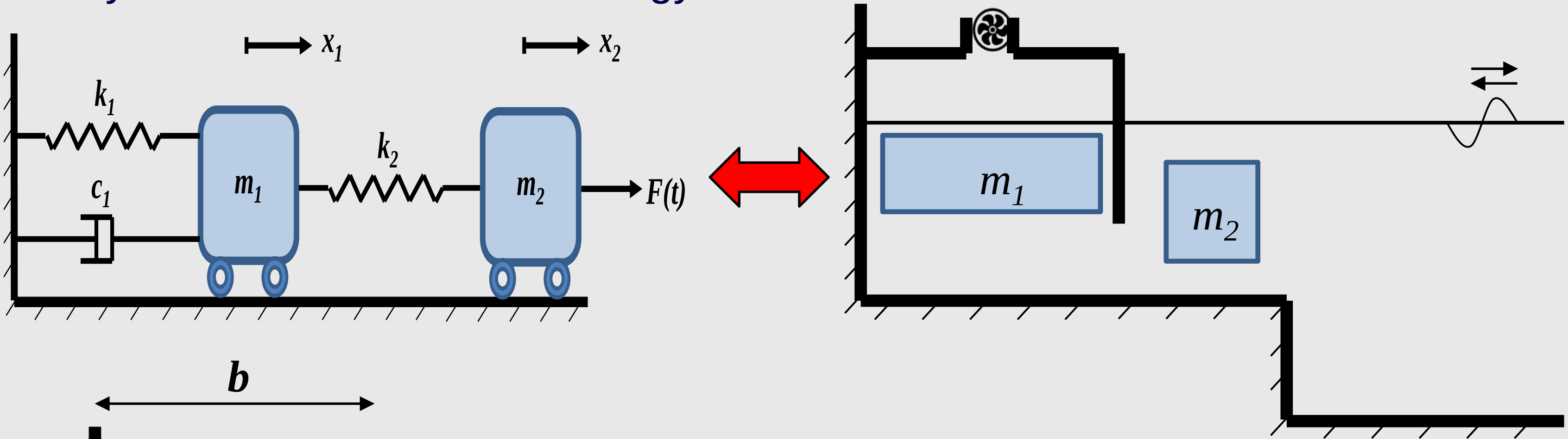
$$\omega_{i2} = \sqrt{k_2/m_2}$$

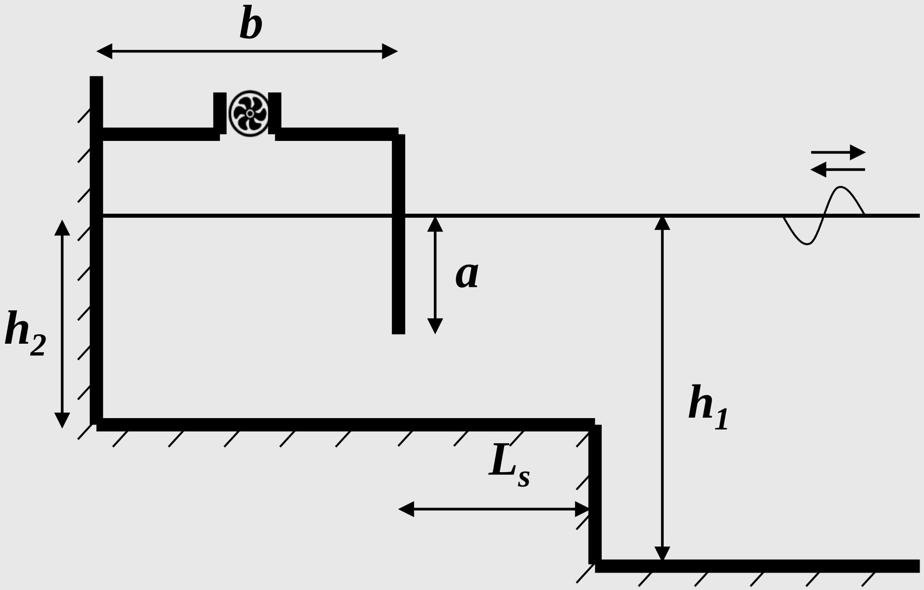


Variation of η/η_{max} in the dual-mass WEC system with respect to incident wave period T for the case that $\zeta = 0.6$, $\omega_{i1} = 2\pi/12$ rad/s, $r = \frac{2\zeta^2}{1+\zeta^2} = 0.53$ and $\omega_{i2} = \sqrt{1+\zeta^2}\omega_{i1} = 2\pi/10.29$ rad/s

Enhancing the Efficiency (Dual-Mass System Application)

- Oscillating Water Column (OWC) device exploited in the stepped sea bottom condition could be considered as an application of a Dual-mass system to harvest wave energy.





- Natural Freqyency of m_1:

$$\omega = \sqrt{g/a}$$

- Natural Freqyency of m_2:

$$\omega = \sqrt{gh_2/bL_S}$$

Contents

OWC Device in Stepped Sea Bottom Condition

- OWC device exploited in the stepped sea bottom condition could be considered as an application of a Dual-mass system to harvest wave energy.

Wave period=2.2 s,
Wave height=0.02 m

- **Reference:** Rezanejad, K., Gadelho, J.F.M., Guedes Soares, C., Hydrodynamic analysis of an oscillating water column wave energy converter in the stepped bottom condition using CFD. Renewable Energy 135, pp. 1241-1259.

OWC Device in Stepped Sea Bottom Condition

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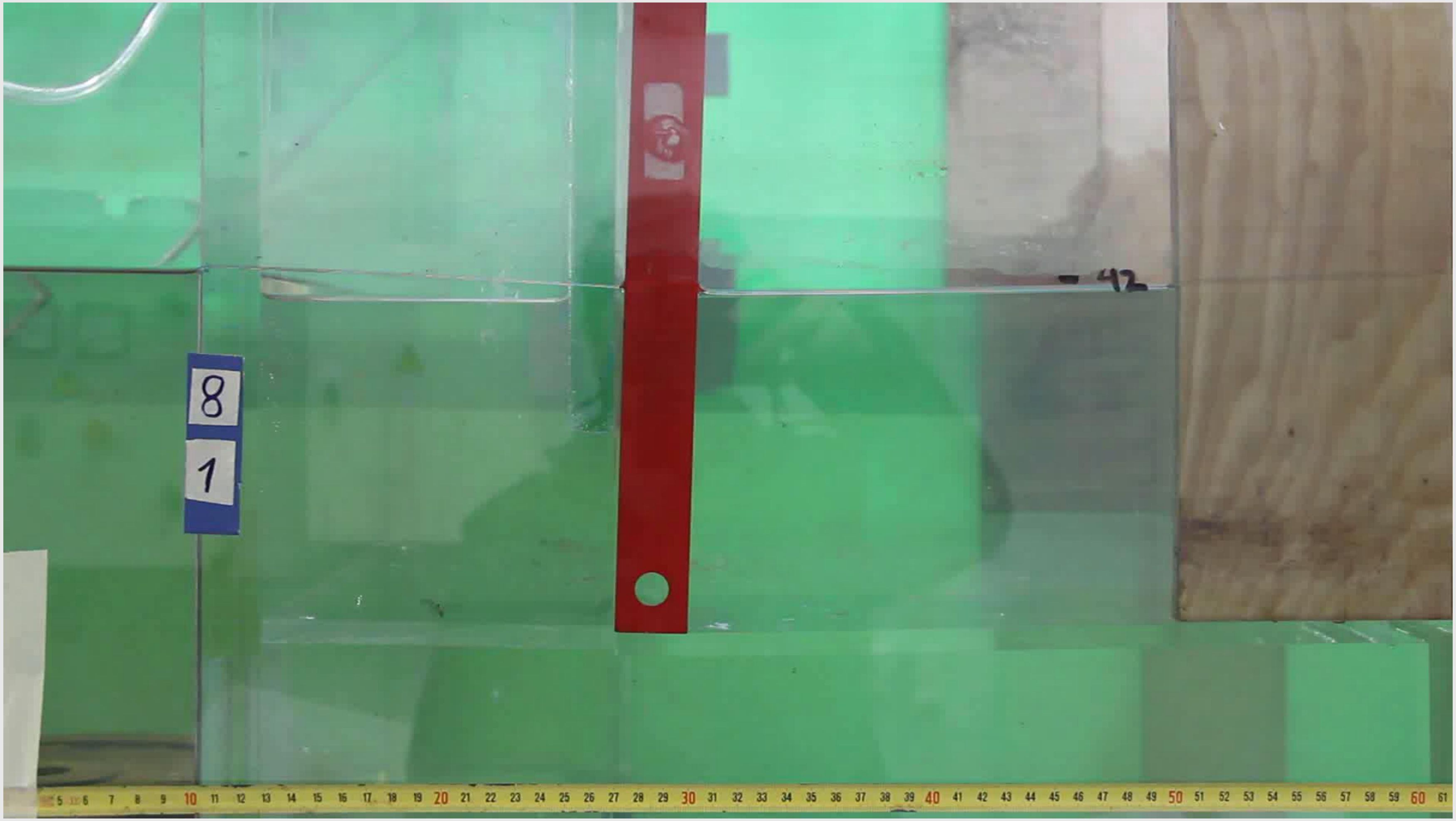
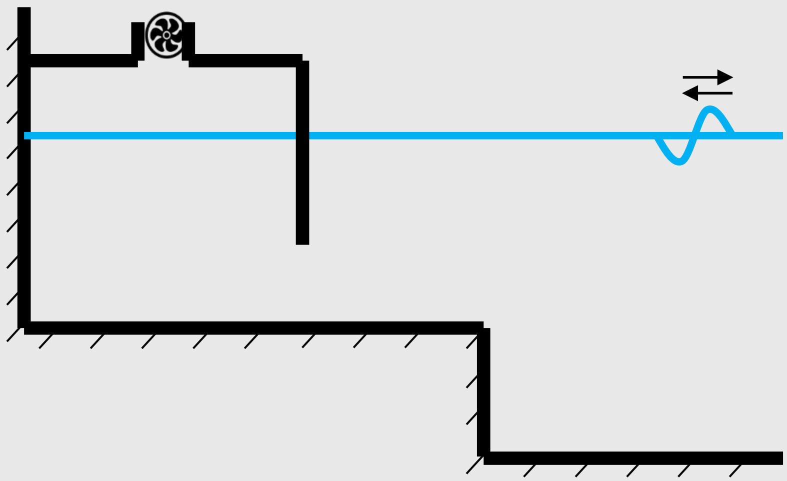


OWC Device in Stepped Sea Bottom Cond.: Numerical Model

- The corresponding numerical problem is solved in frequency domain using 2D in-house BEM code.
- Linear wave theory is implemented to formulate the hydrodynamic problem.
- It is assumed that there exists a velocity potential $\varphi(x,z,t) = \mathrm{Re}\{\varphi^*(x,z)\mathrm{e}^{-\mathrm{i}\omega t}\}$, with the spatial velocity potential $\varphi^*(x,z)$.
- Total potential $\varphi^*(x,z)$ is decomposed into two parts: $\varphi^* = \varphi^S + \varphi^R$



OWC Device in Stepped Sea Bottom Cond.: Numerical Model

- The influence of the turbines has been modelled by assuming that the volume flux through them is linearly proportional to the pressure drop across the corresponding internal free surface:

$$q^* = \lambda p^*$$

- The mean rate of work done by the pressure forces over one wave period ($W_{Reg.}$) :

$$W_{Reg.} = \frac{1}{2}\lambda\,|p^*|^2$$

- Maximum primary efficiency of the dual-chamber floating OWC system:

$$\eta_{Reg.,max} = \frac{W_{Reg.,max}}{W_w}$$

Wave power: $W_w = E c_g$

Wave energy: $E = \frac{1}{2}\rho g L A^2$

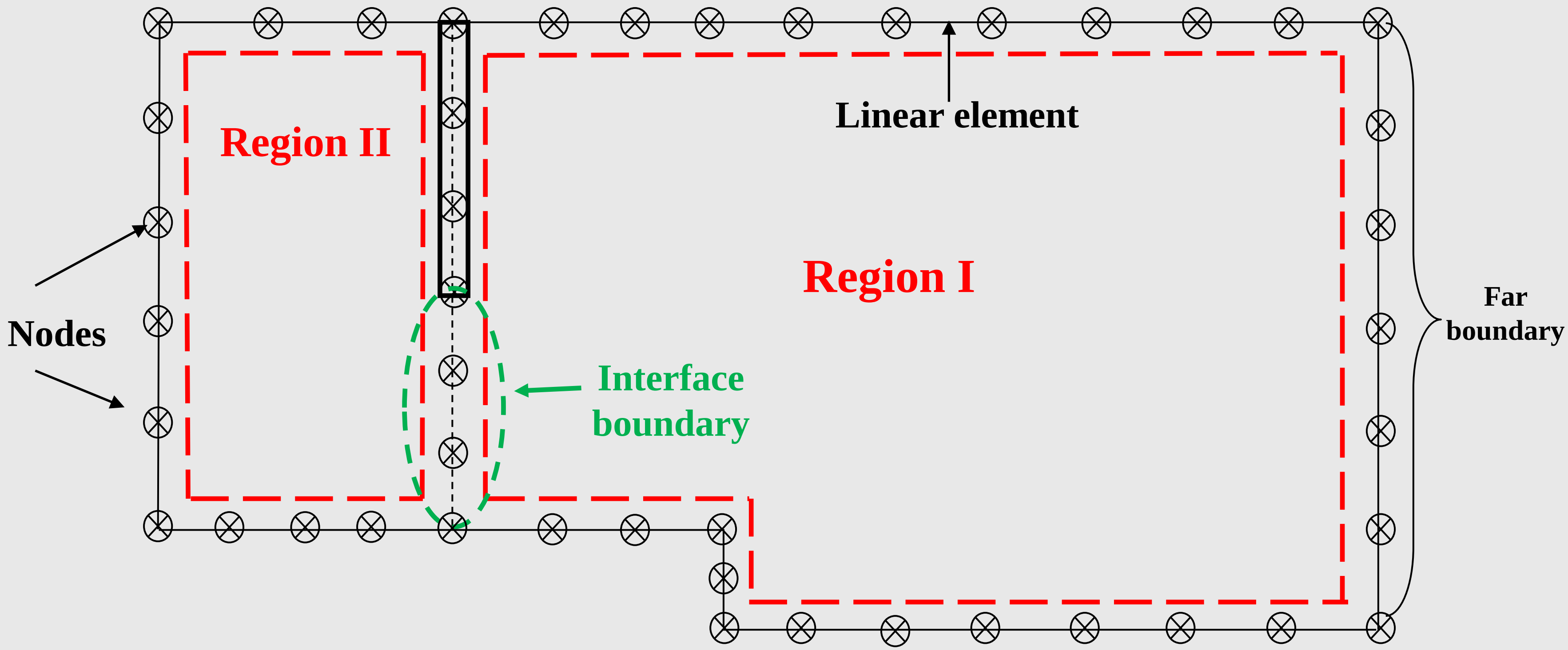
Group velocity: $c_g = \frac{1}{2}\frac{\omega}{k}\left(1 + \frac{2kh}{\sinh 2kh}\right)$

OWC Device in Stepped Sea Bottom Cond.: Numerical Model

- Boundary Element Method has been implemented to solve the corresponding diffraction and radiation problems:

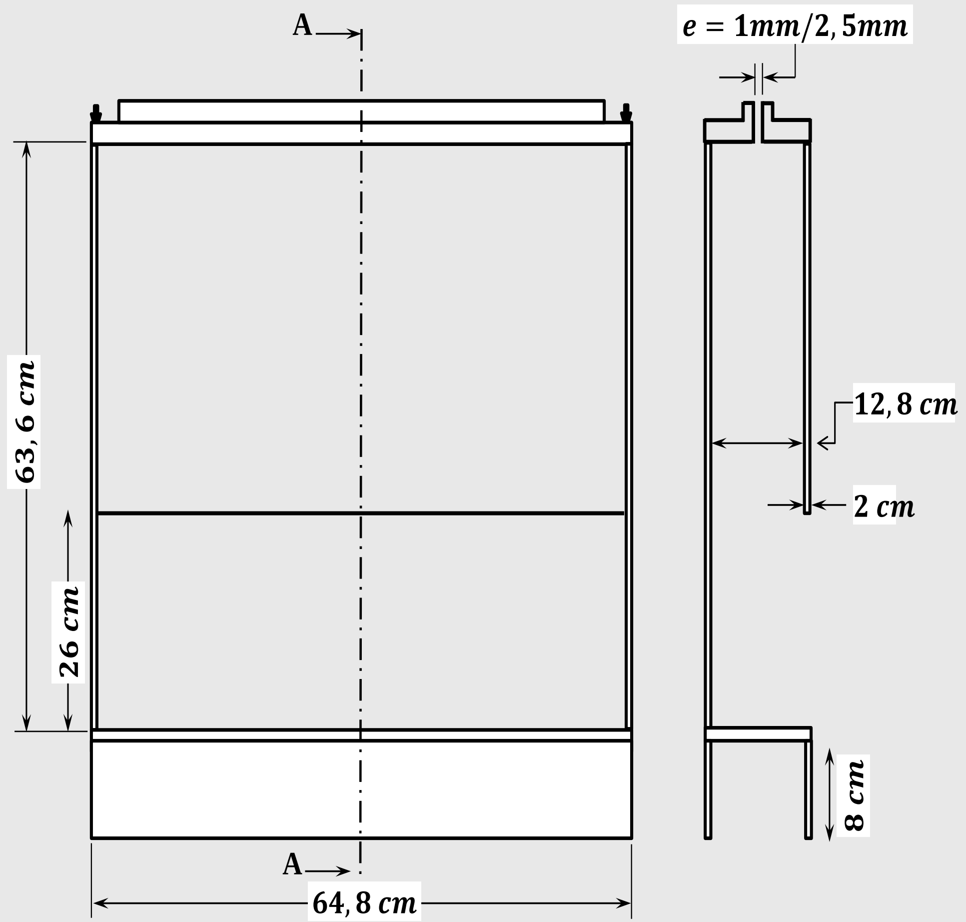
$$c(X)\phi(X)+\int_{\partial D}\phi(Y)\frac{\partial\psi}{\partial n}(X,Y)ds(Y)=\int_{\partial D}\psi(X,Y)\frac{\partial\phi}{\partial n}(Y)ds(Y)$$

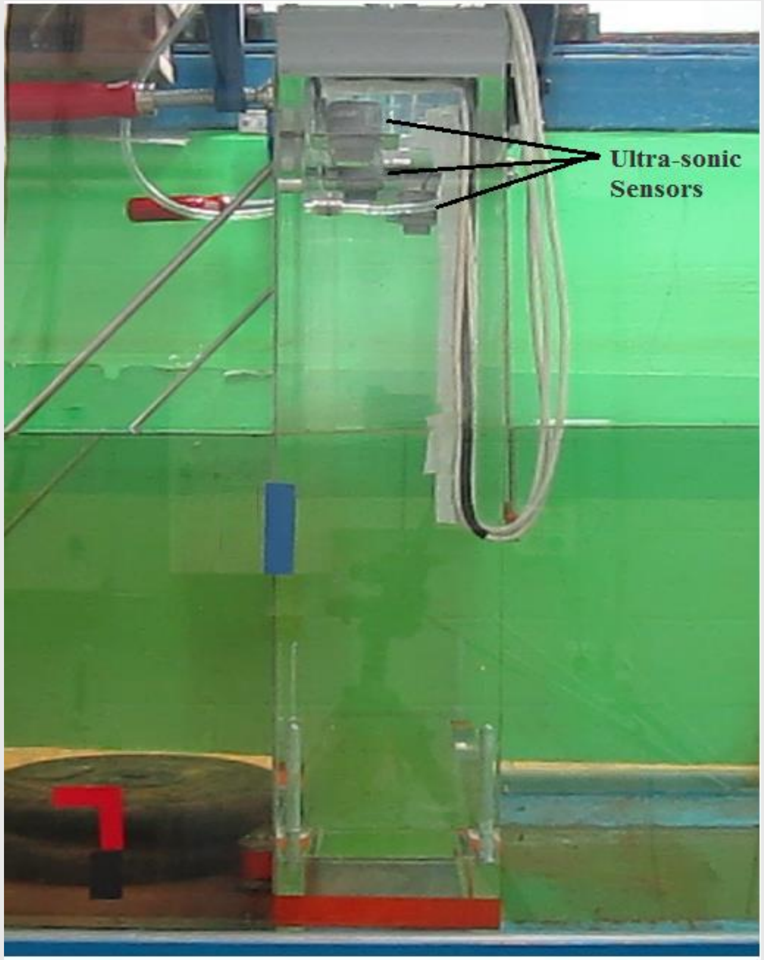
- Multi region concept is used to overcome the thin barrier problem which increases numerical errors.



OWC Device in Stepped Sea Bottom Cond.: Experimental Set-up

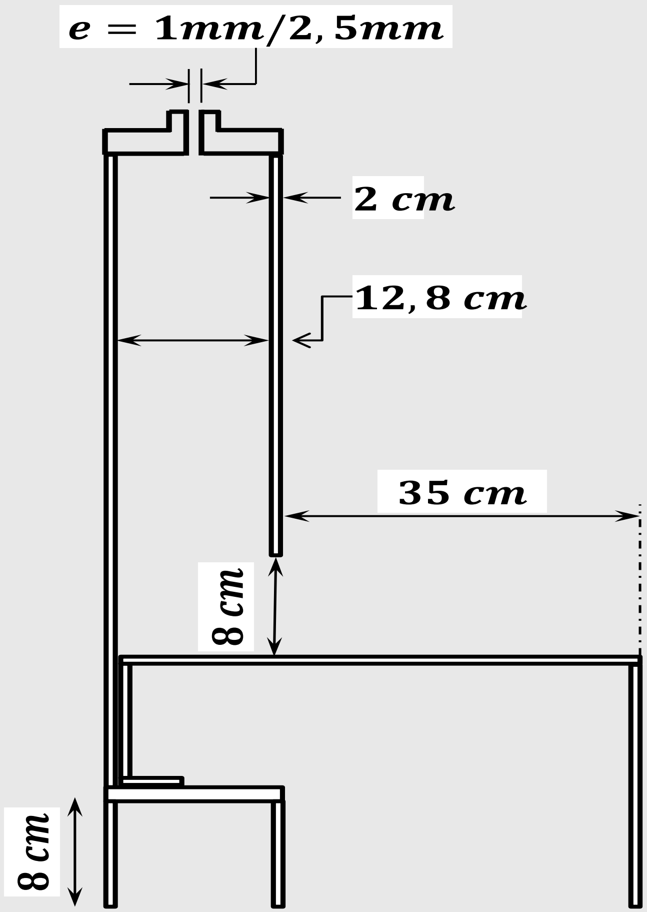
- The following conventional type OWC device (scale factor 1/25) has been investigated using both numerical and experimental approaches.

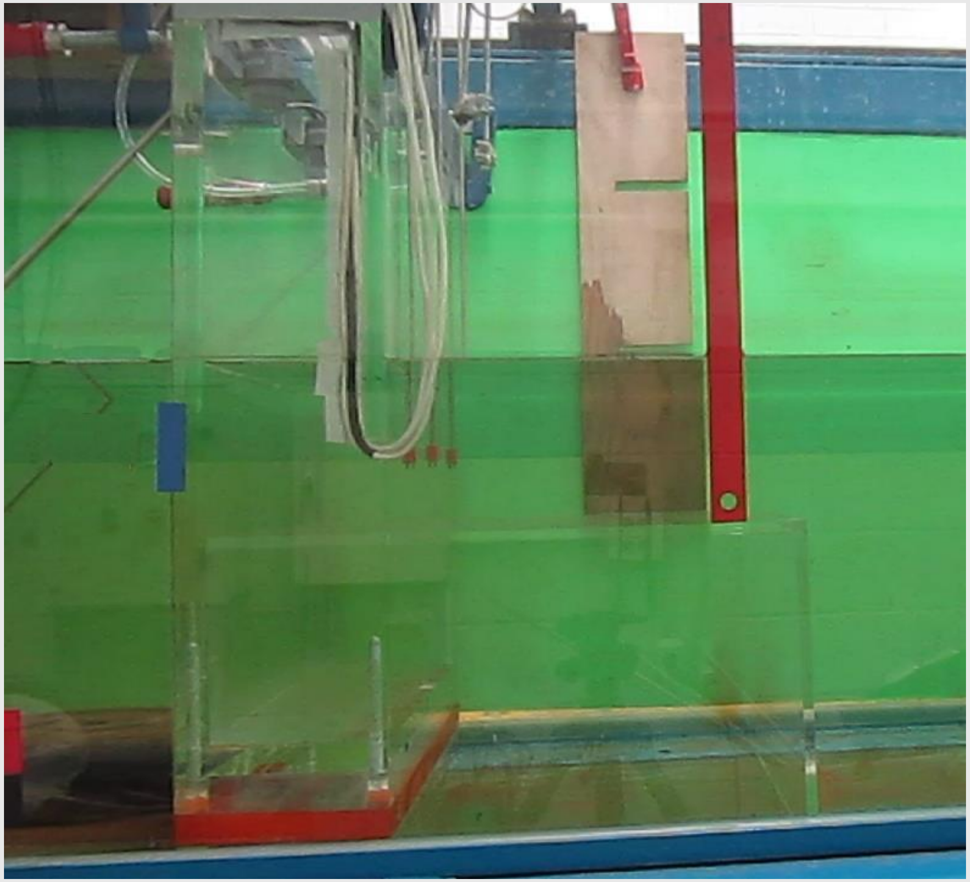




OWC Device in Stepped Sea Bottom Cond.: Experimental Set-up

- The performance of the former OWC device with the attached step is then assessed using the same numerical and experimental approaches.





OWC Device in Stepped Sea Bottom Cond.: Experimental Set-up

- The water depth was set to 0.42 m.
- The influence of the PTO unit (e.g. the air turbine) has been simulated by applying the following two different slot widths in the cap of the model: 1 mm (high damping) and 2.5 mm (low damping).
- Regular wave tests: ten wave periods ($T = 1, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6$ and $2.8\,s$) and three wave heights ($H = 0.02, 0.04$ and $0.06\,m$) were combined.
- Average power absorbed from regular waves $P_{Reg.}$:

$$P_{Reg.} = \frac{1}{t_{max}} \int_0^{t_{max}} P\,Q\,dt$$

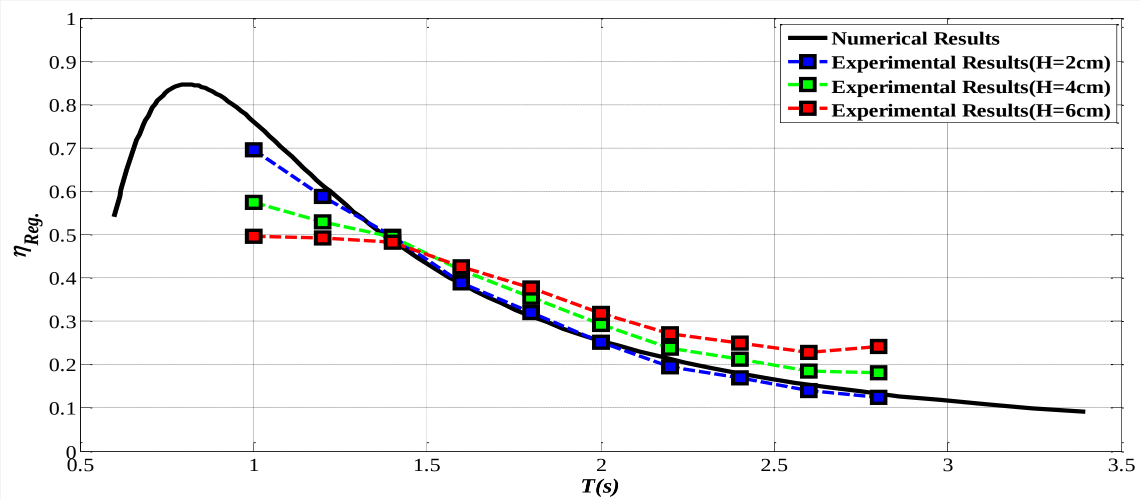
- Efficiency of the device in regular waves:

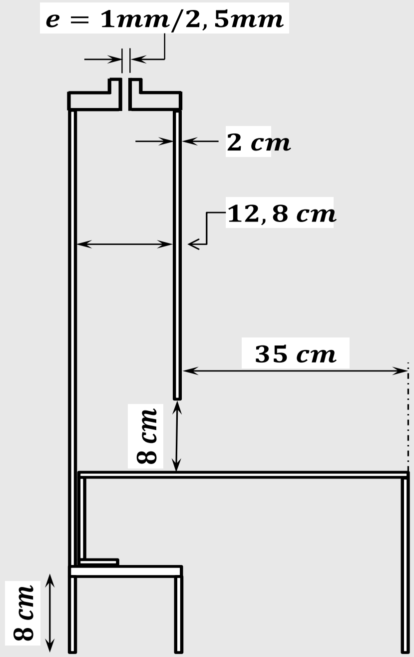
$$\eta_{Reg.} = \frac{P_{Reg.}}{\bar{P}_w}$$

OWC Device in Stepped Sea Bottom Cond.: Results & Discussions

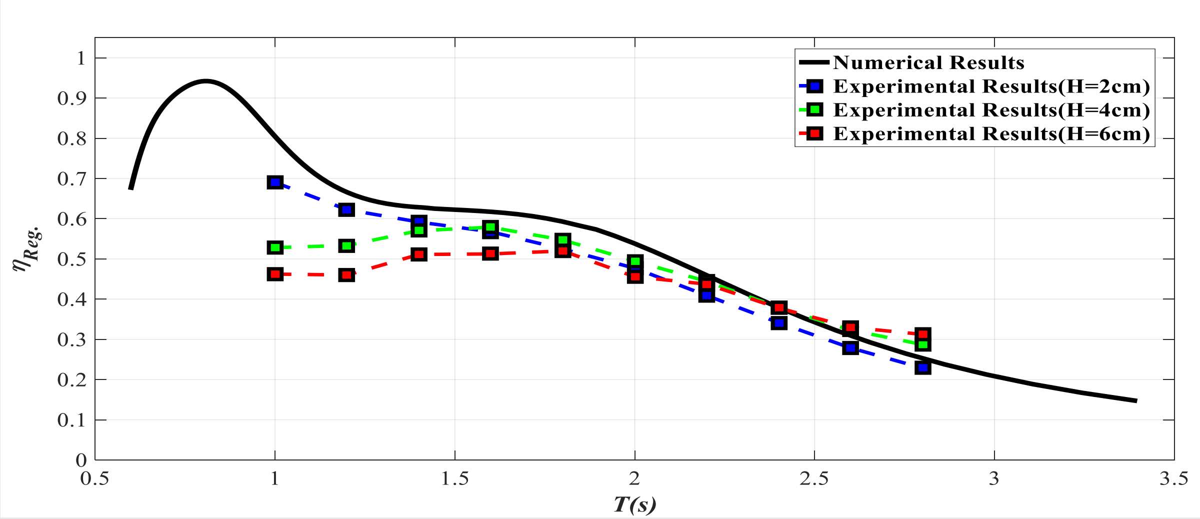
- The performance of the device is increased significantly by integrating the attached step. The relative efficiency improvements ($\Delta\eta_{Reg.}$) is improved by 100%.

OWC without step (conventional type)





OWC with attached step

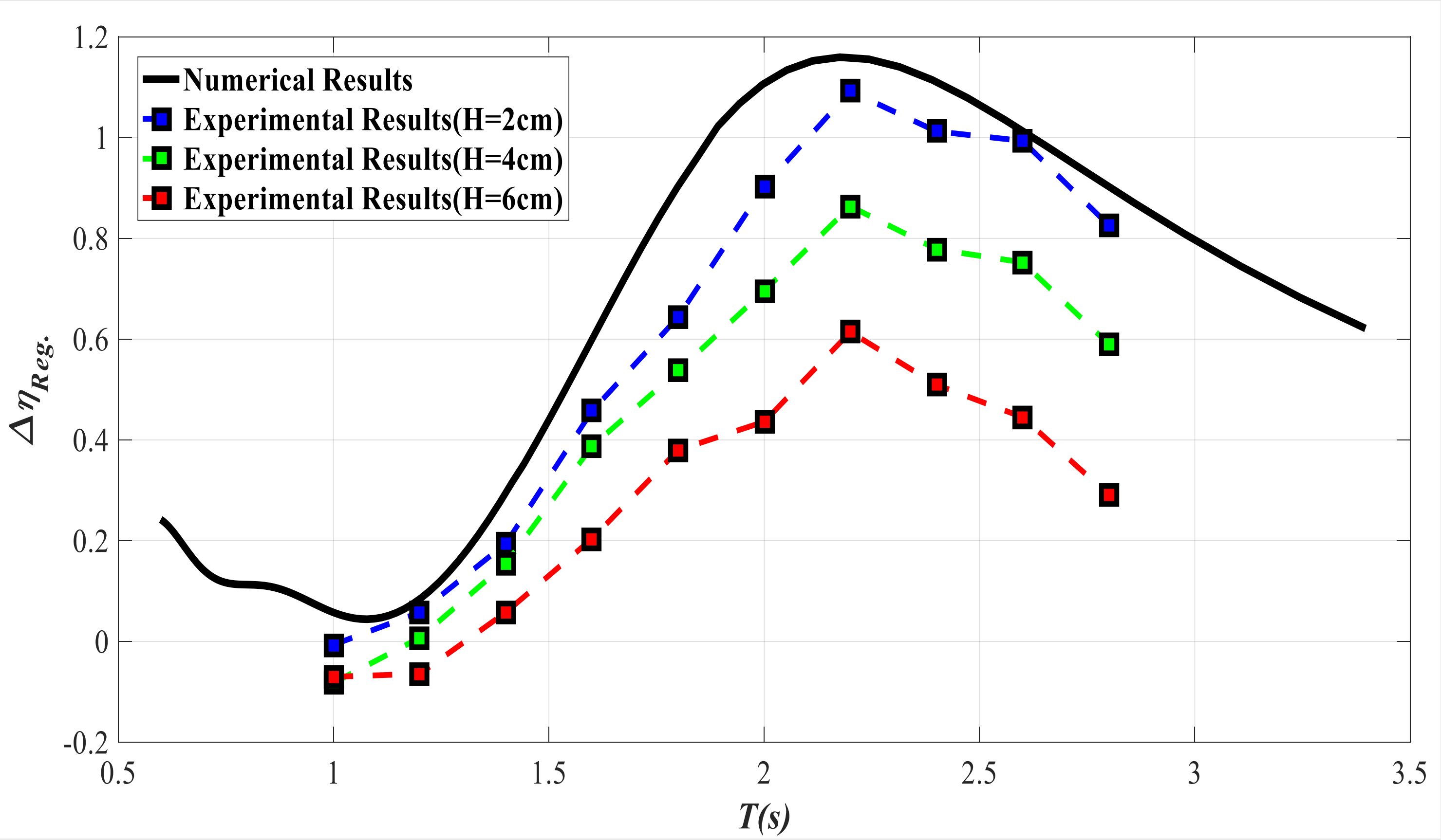


OWC Device in Stepped Sea Bottom Cond.: Results & Discussions

- The performance of the device is increased significantly by integrating the attached step. The relative efficiency improvements ($\Delta\eta_{Reg.}$) is improved by 100%.

Relative efficiency improvement parameter:

$$\Delta\eta_{Reg.} = \frac{\eta_{Reg.} - \eta_{Reg._{ws}}}{\eta_{Reg._{ws}}}$$



OWC Device in Stepped Sea Bottom Cond.: Results & Discussions

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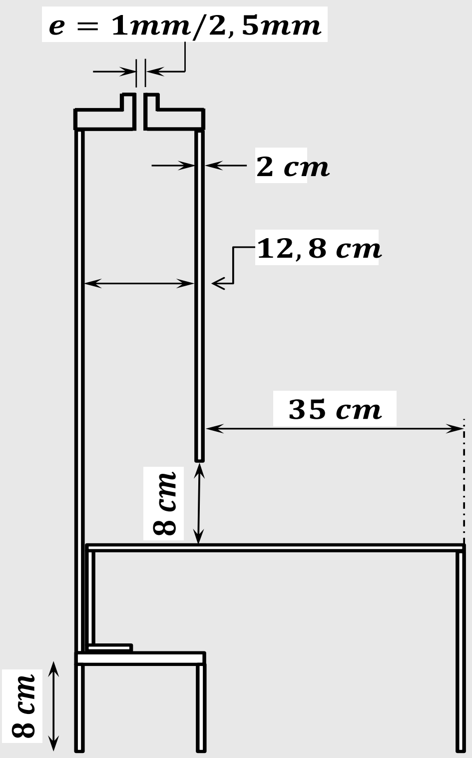

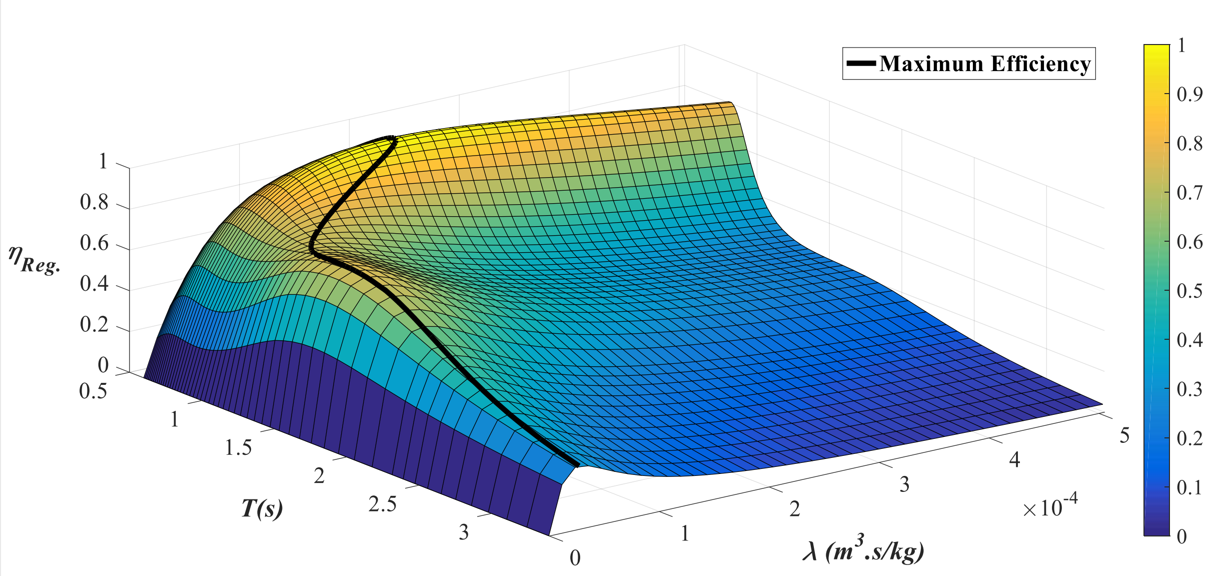

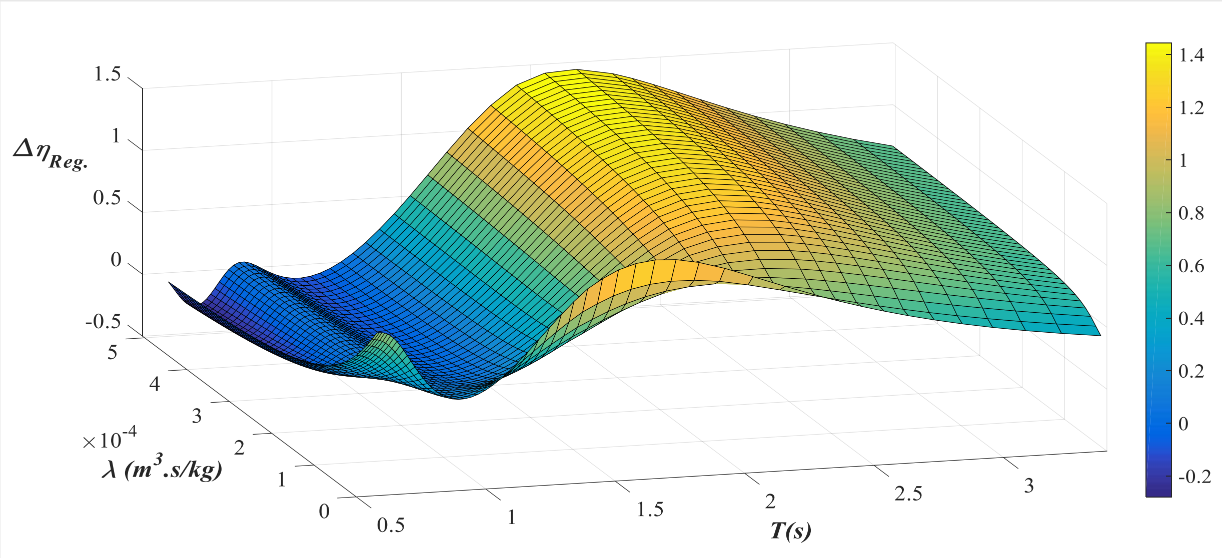

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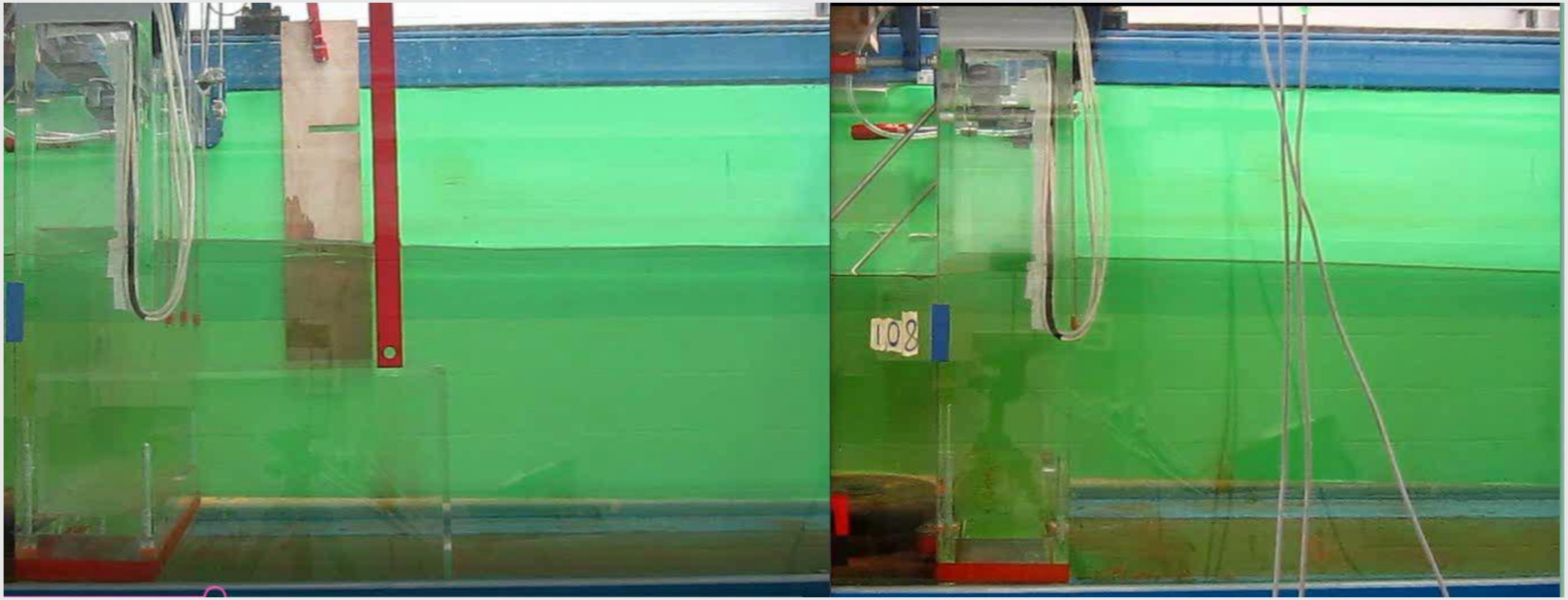

(Wave period=2.4 s, Wave height=0.04 m)

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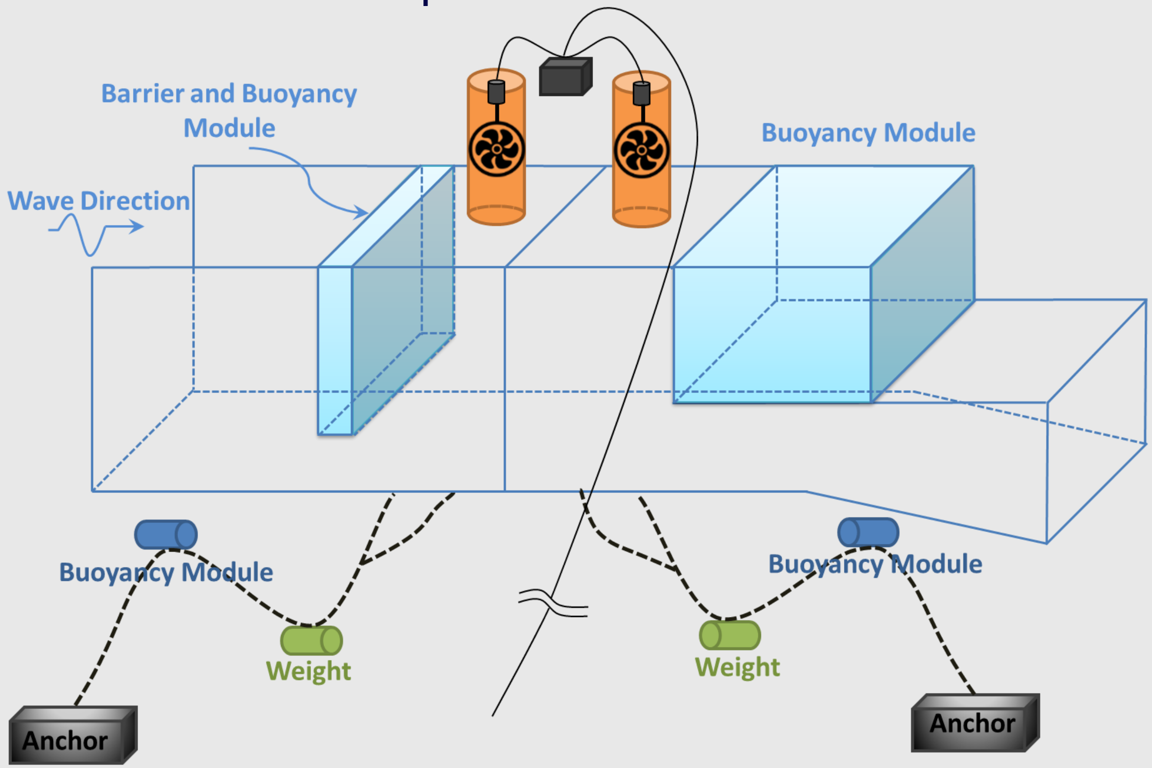
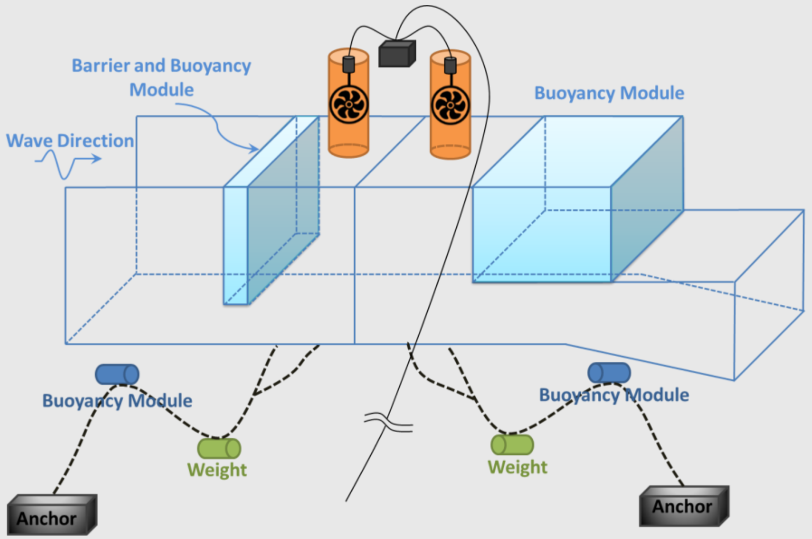
Floating Dual-Chamber OWC Device

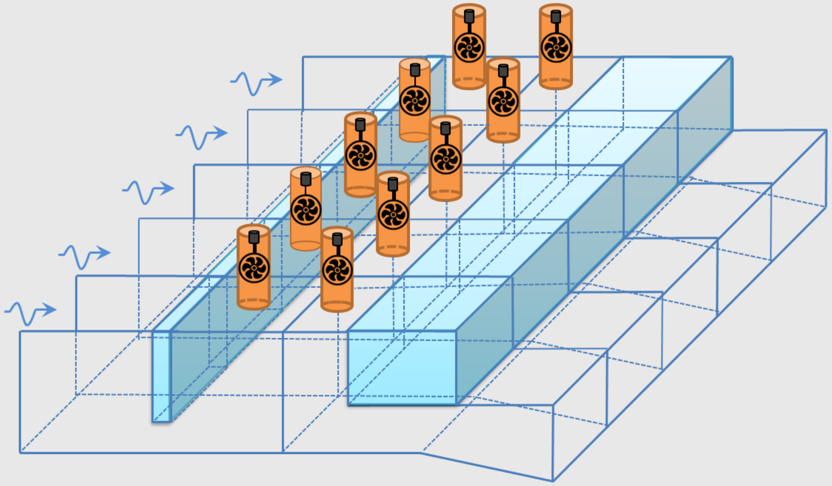
- The novel WEC system involves two chambers placed in the upstream (fore chamber) and in the downstream (rear chamber) with respect to the incident wave direction.
- The rear chamber acts similarly to a Backward Bent Duct Buoy (BBDB) system, while the design of the fore chamber follows conventional types of OWC systems with the harbour plates.



Floating Dual-Chamber OWC Device

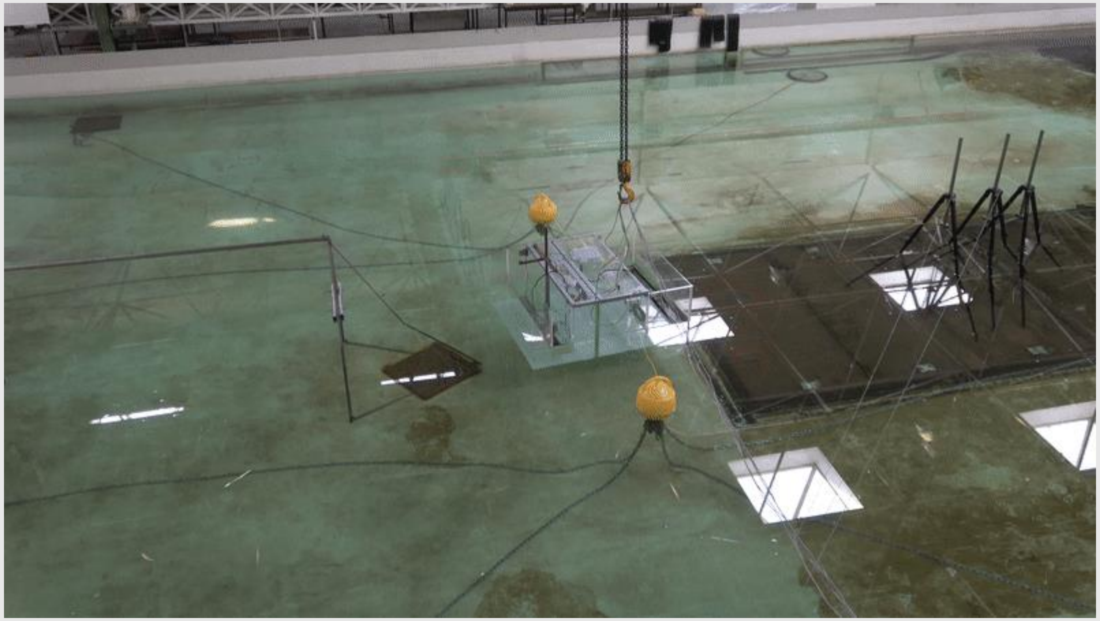
- It has Improved hydrodynamic performance.
- It can be utilized as the floating breakwater (multi purpose platform to produce energy simultaneously with the harbour protection application).
- The floating modules of the device are relatively large. Hence, they can be implemented to store the energy in the form of hydrogen. Hence, the need to transmit the energy by using the underwater cables for the offshore applications will be eliminated.
- In case of storing energy in the form of hydrogen, the device can be implemented to provide fuel for the hi-tech marine vessels (see for instance HyDIME project)
- It is expected that the device has the smooth or even negative drift forces in a specific range of wave frequencies which reduces the mooring forces.





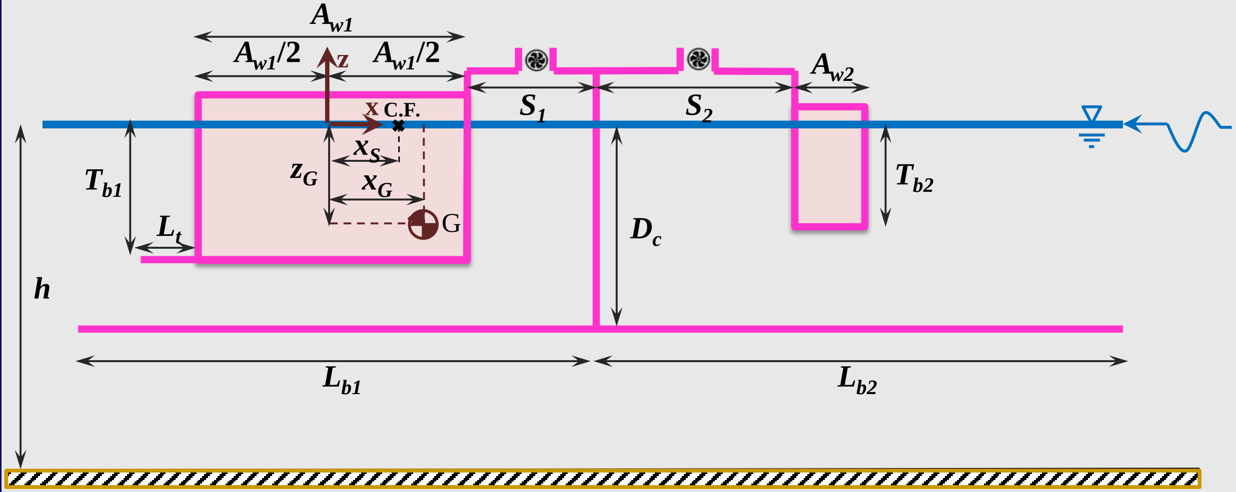
Floating Dual-Chamber OWC Device

- Limited experiments with the scale factor 1:50 was performed in regular waves, with *H=0.04 m* and *T=0.8 – 2.2s.*



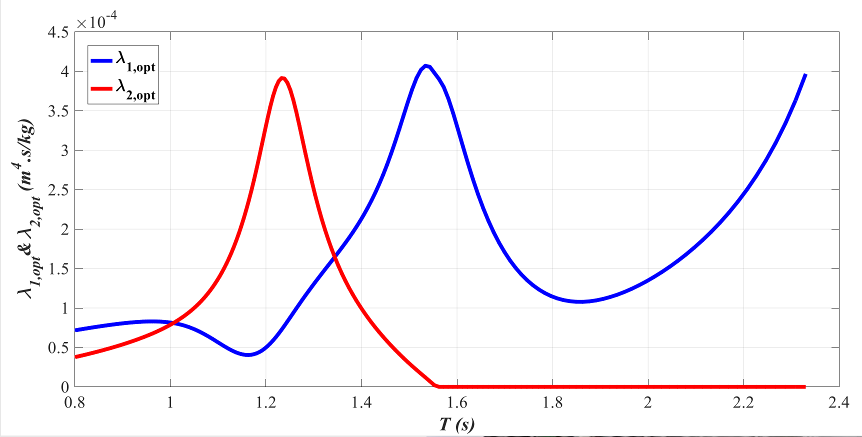
Floating Dual-Chamber OWC Device

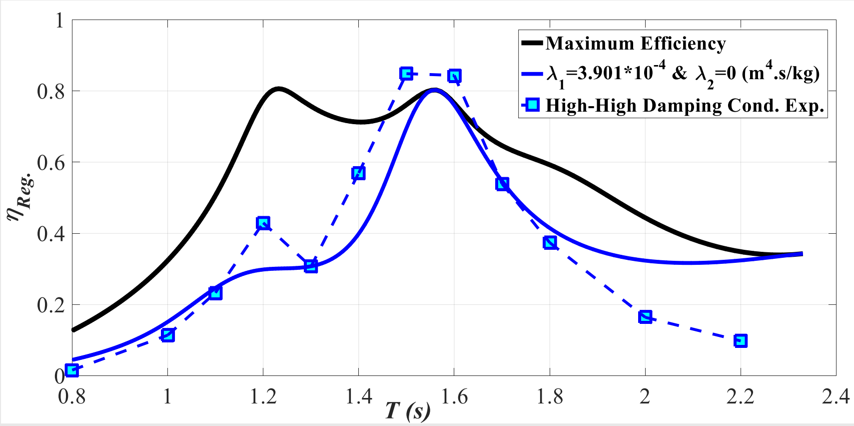
Charactersitics of the Case Study Model



D_c	0.30 m
L_{b1}	0.75 m
L_{b2}	0.48 m
A_{w1}	0.35 m
A_{w2}	0.17 m
L_t	0.05 m
T_{b1}	0.08 m
T_{b2}	0.17 m
S_1	0.35 m
S_2	0.18 m
Mass per unit width	90.2 kg
Pitch radius of gyration	0.41 m

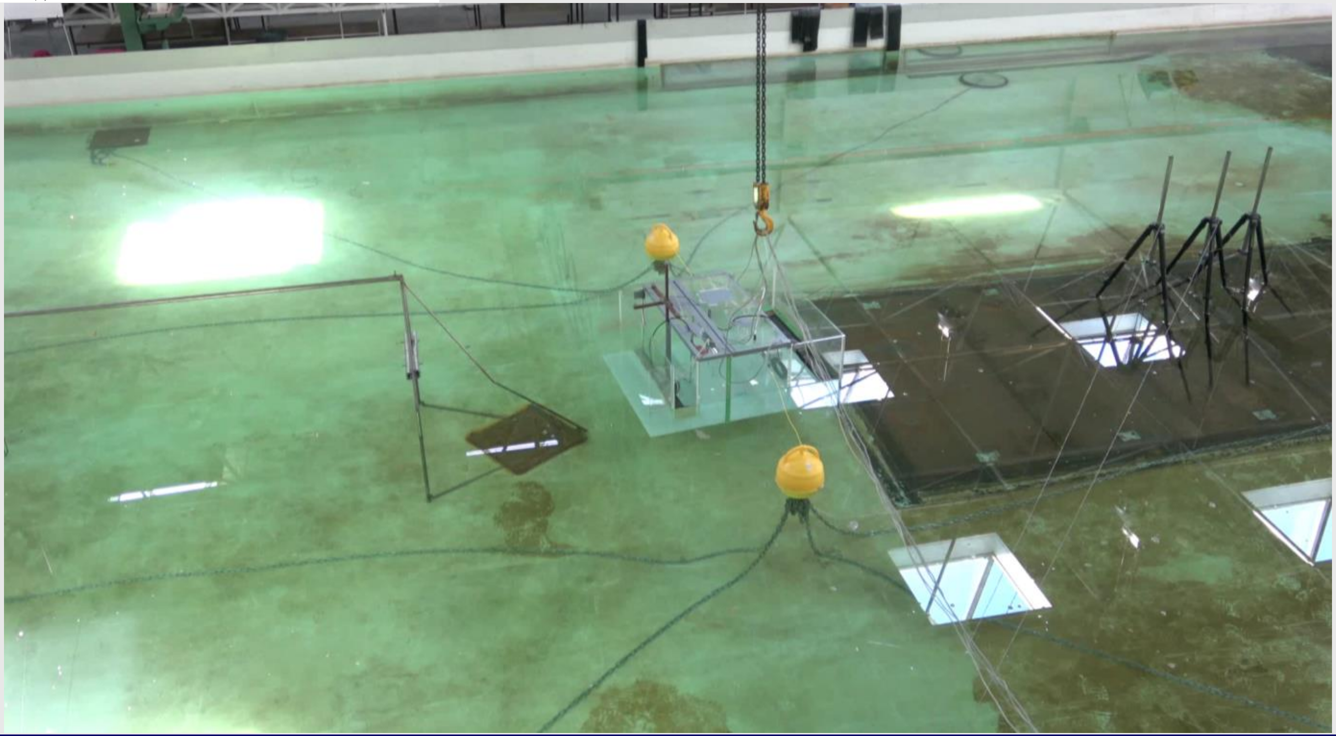
Floating Dual-Chamber OWC Device



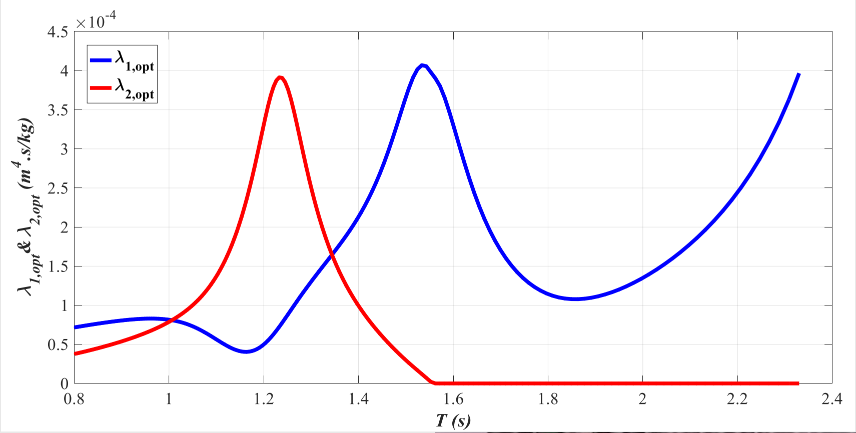


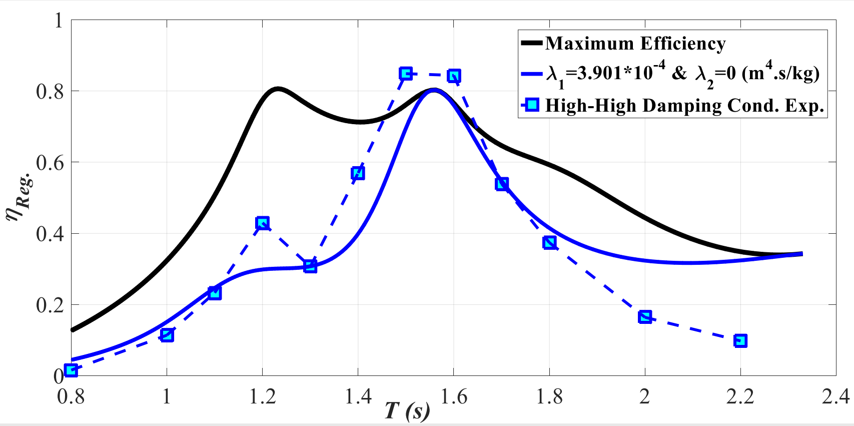
$H = 0.04\ m$

$T = 1.2\ s$

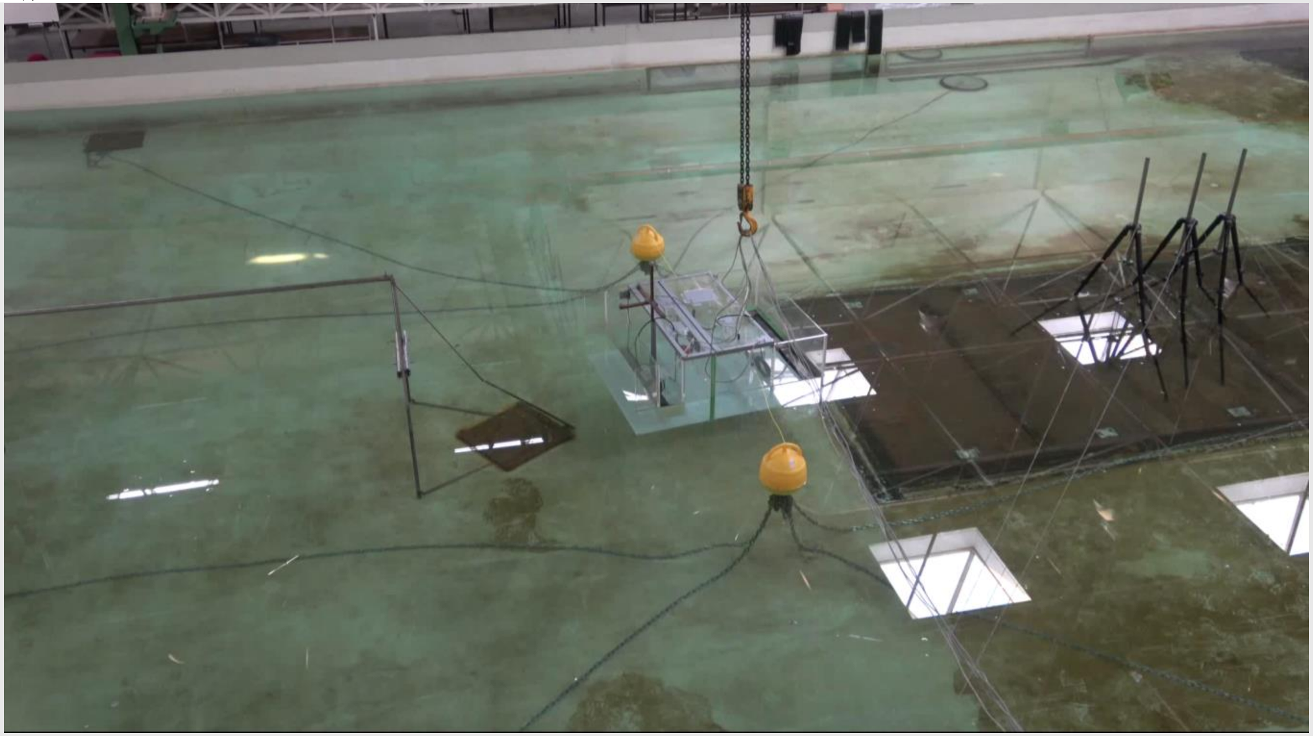


Floating Dual-Chamber OWC Device





$$H = 0.04\ m$$
$$T = 1.6\ s$$



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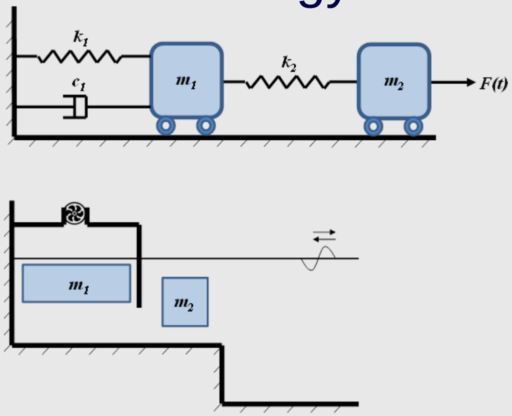
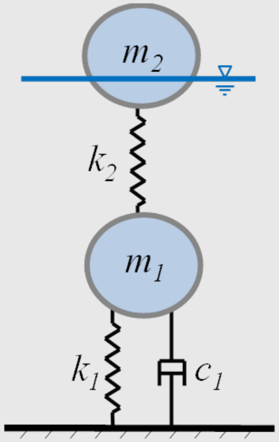
- Introduction
- Motivation
- Simplified 1-DOF model of WEC
- Enhancing the Efficiency (Dual-Mass System Application)
- OWC Device in Stepped Sea Bottom Condition
- Floating Dual-Chamber OWC Device
- **Conclusions**

Conclusions

- The OWC device in the stepped sea bottom acts analogous to a generic dual-mass WEC system which has inherent enhanced potential to absorb energy of the excitation source.





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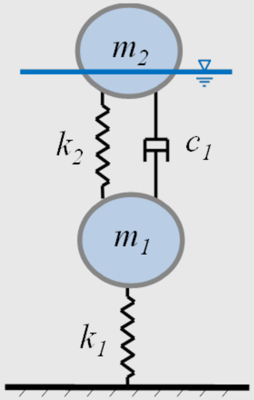

- Significant improvements (up to 150%) can be obtained by the implementation of the step configuration.

- The numerical analysis carried out on a case study model of Dual-Chamber floating OWC device shows that the maximum efficiency of the devised system is higher than 70% in the periods varying in the range between 9.0 to 13 s in real seas which covers most of the energetic sea states.

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Thank you for your attentions!

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Hydrodynamic Analysis and Optimization of Oscillating Water Column Wave Energy Converters

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THE HYDRODYNAMICS OF WAVE ENERGY CONVERTORS 2 (Hywec 2)

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