State of the Art Technology Senior Maritime Forum

MARINTEC CHINA, 4 December, 2023, Shanghai, People's Republic of China

Renewable Wave Energy

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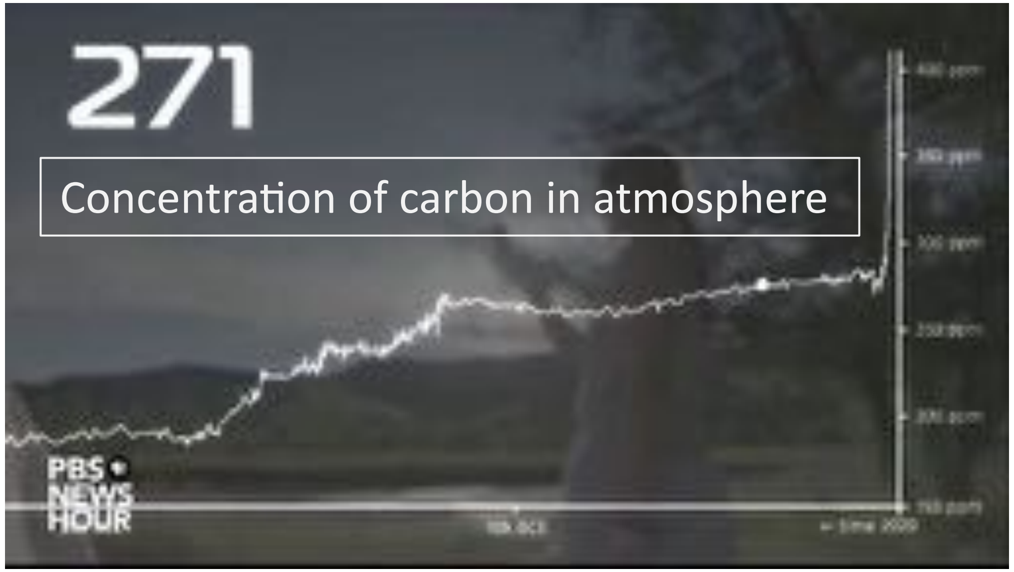
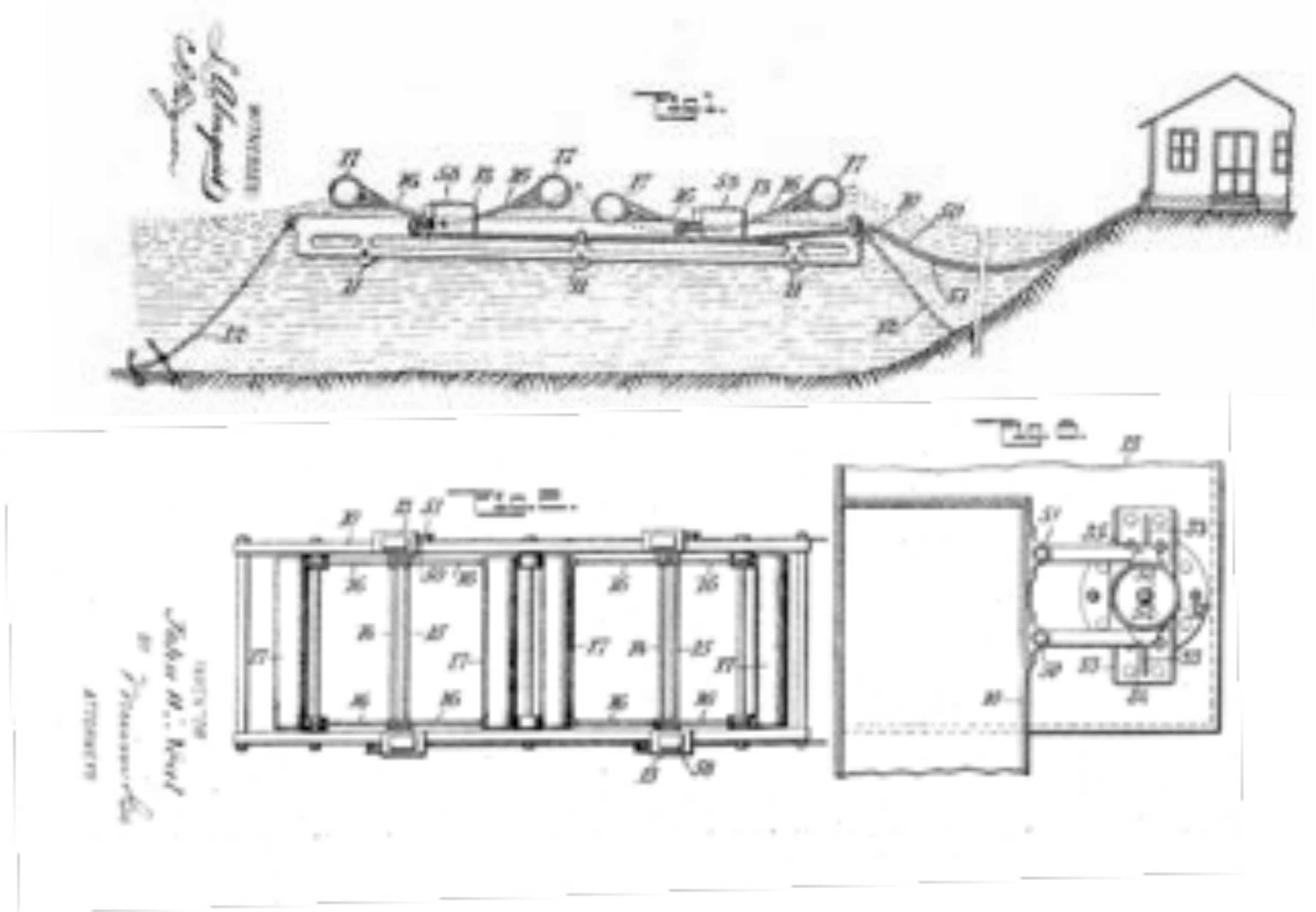


Sir David Attenborough speaks at COP26 climate summit in Glasgow

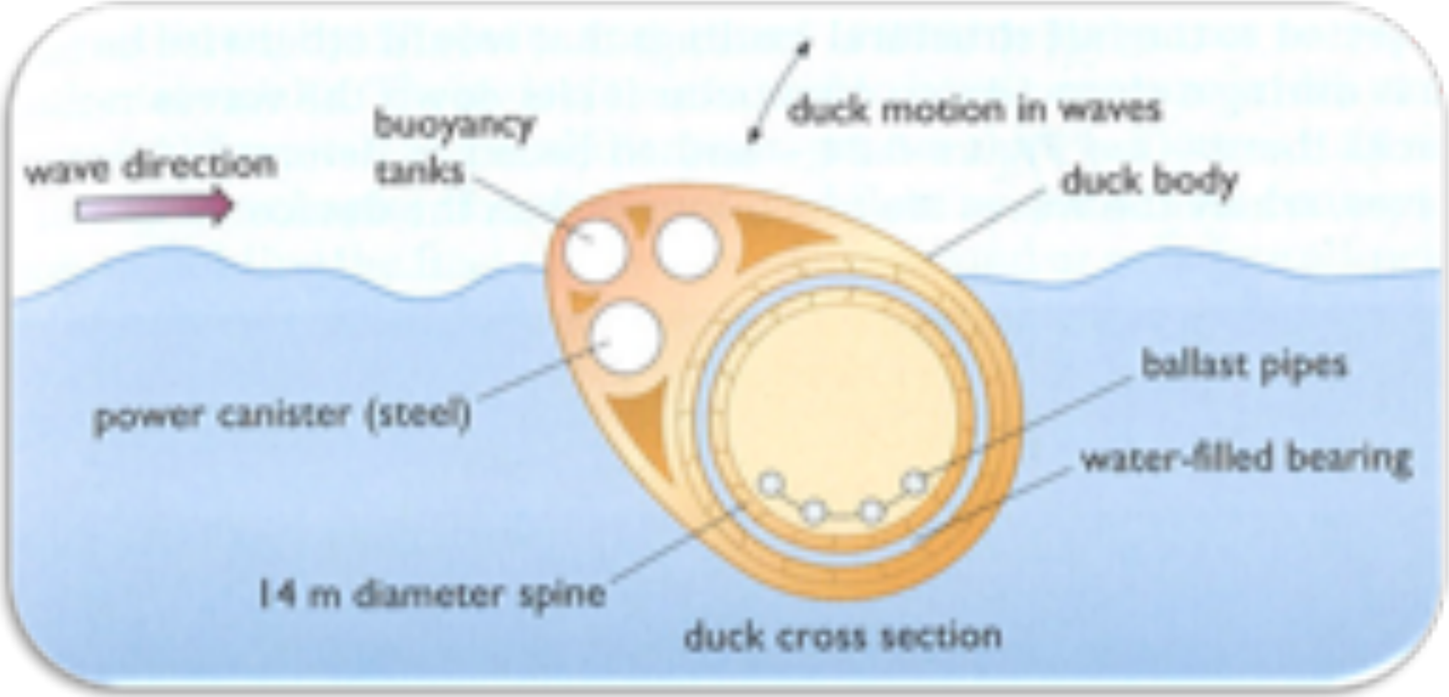
Brief history of WEC development

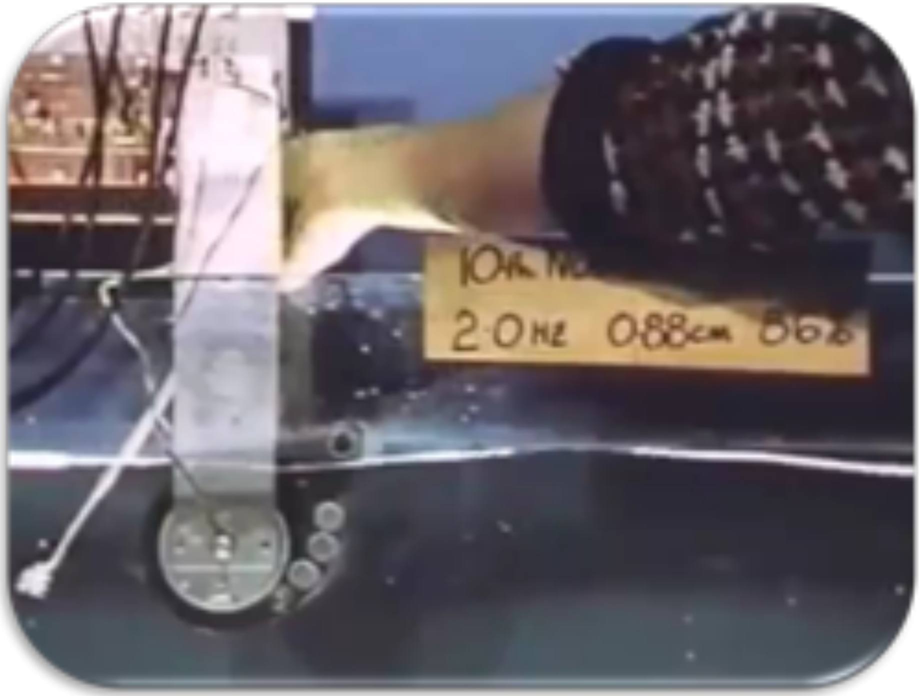
J.W. Neal Wave Motor patented in 1907



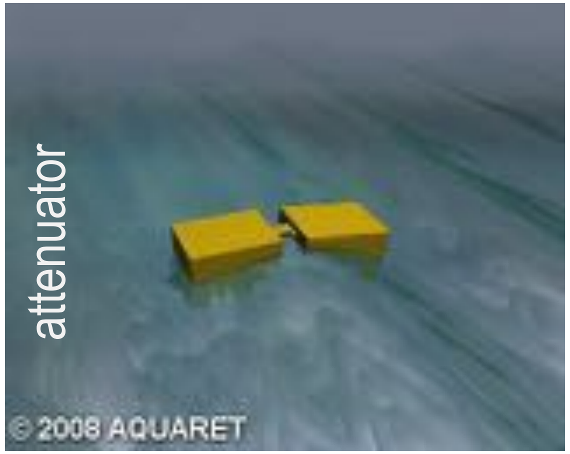
Salters Duck patented in 1979

Invented in response to the oil shortage in the 1970s. Converts rotation into electricity with efficiency of up to 90%

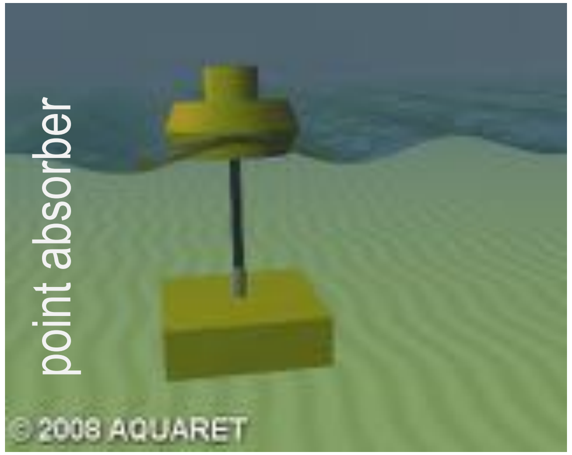




types of wave devices

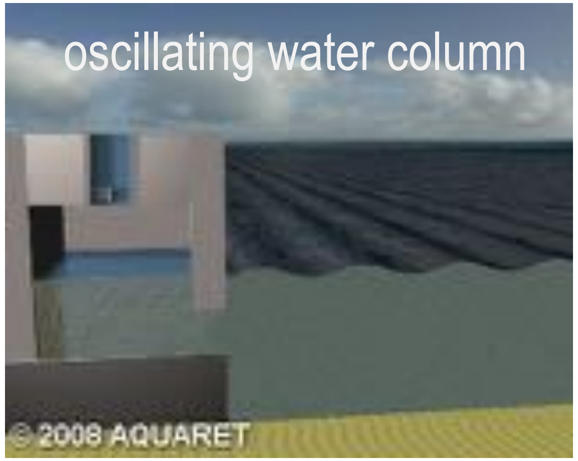


Operates parallel to the wave direction



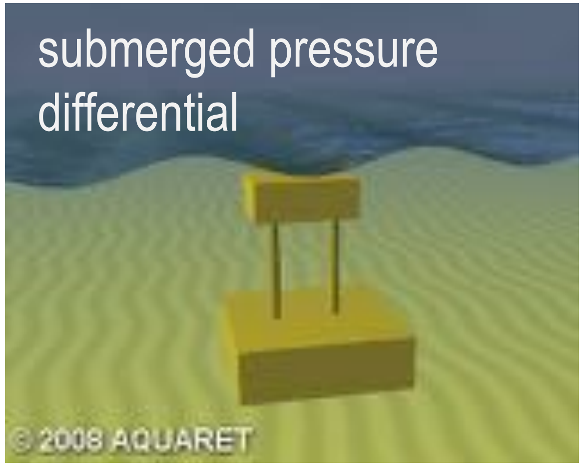
Converts the motion of buoyant top relative to the base into electricity

Converts energy from wave surges into electricity

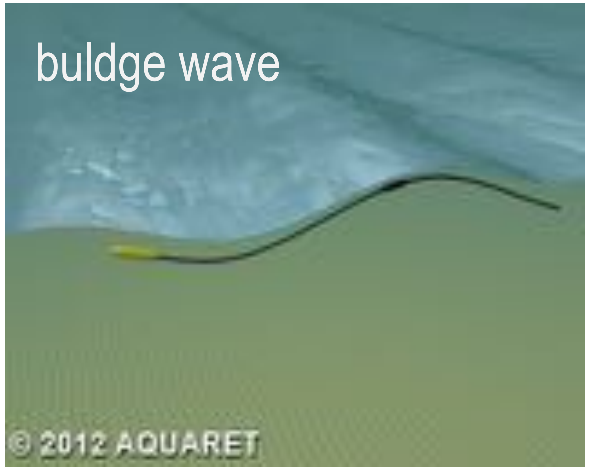


Compresses & decompresses trapped air which rotates a turbine

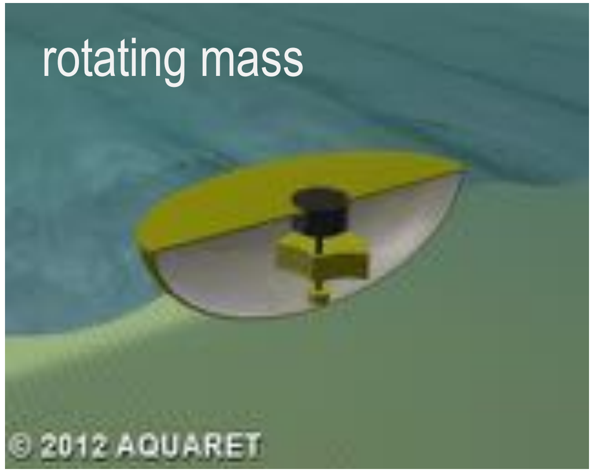
Captures water as waves break into a storage reservoir. Water returns to the sea through a low head turbine



Due to change of sea level above the device alternating pressure pumps fluid through system



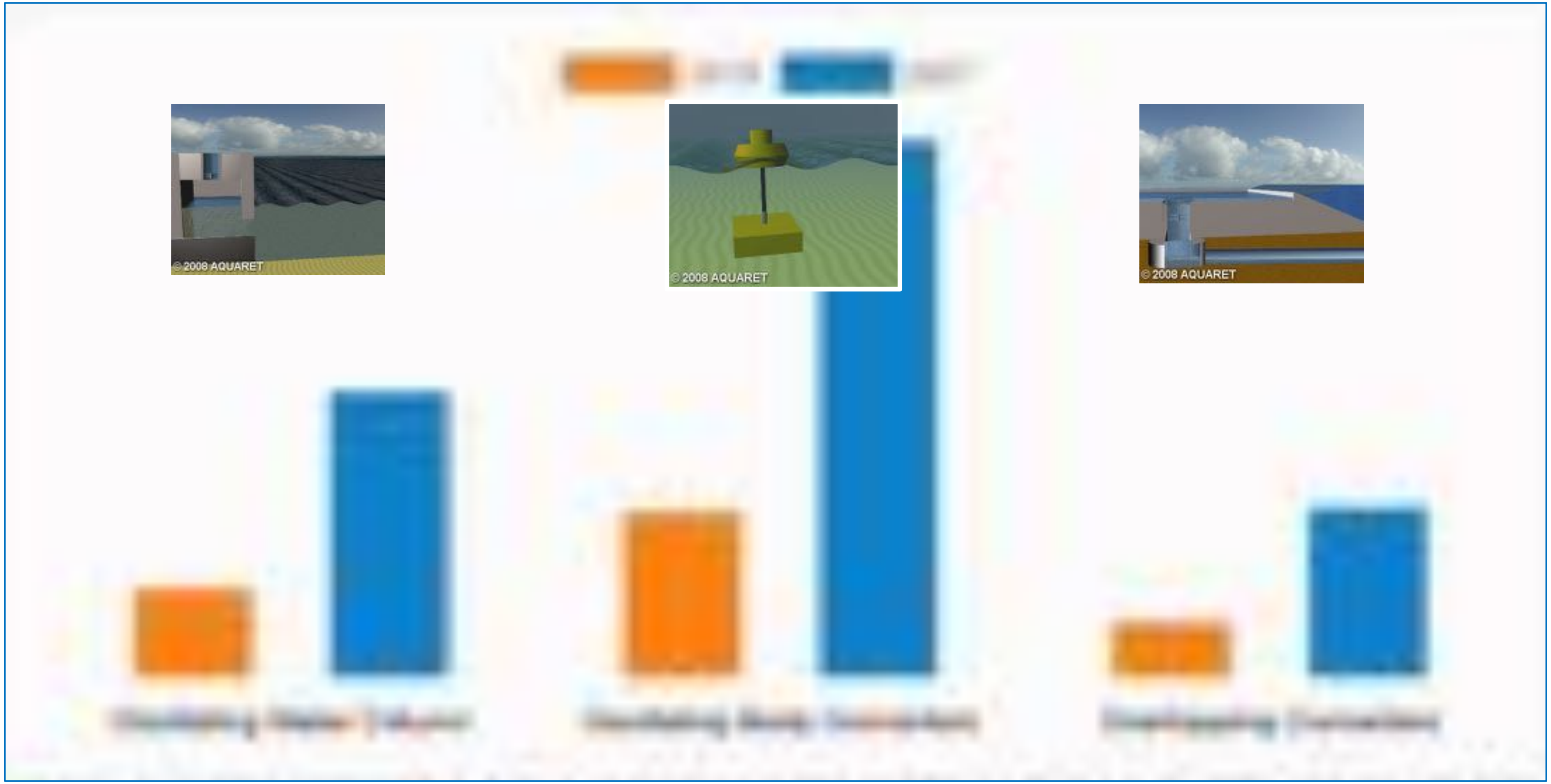
A buldge created by pressure variation along a rubber tube travels to the bow where it rotates a low head turbine



The wave-induced motion drives an eccentric weight or a gyroscope which rotate an electric generator

Wave Energy Market by Technology

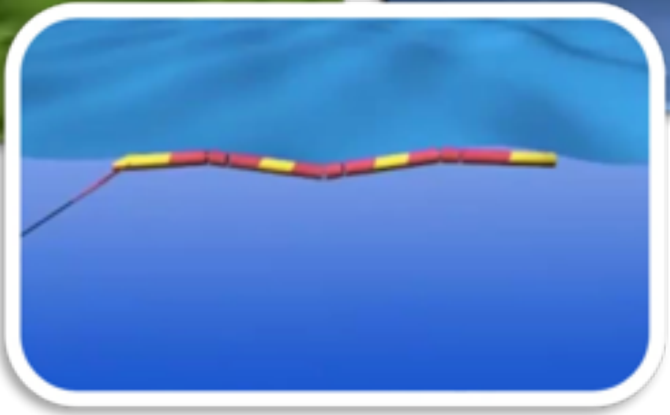
PROS: ZERO EMISSIONS RENEWABLE ENERGY POTENTIAL RELIABLE



CONS: ENVIRONMENTAL EFFECTS HIGH COSTS SCALABILITY

Pelamis Wave Power Snake-Like Generator 2004

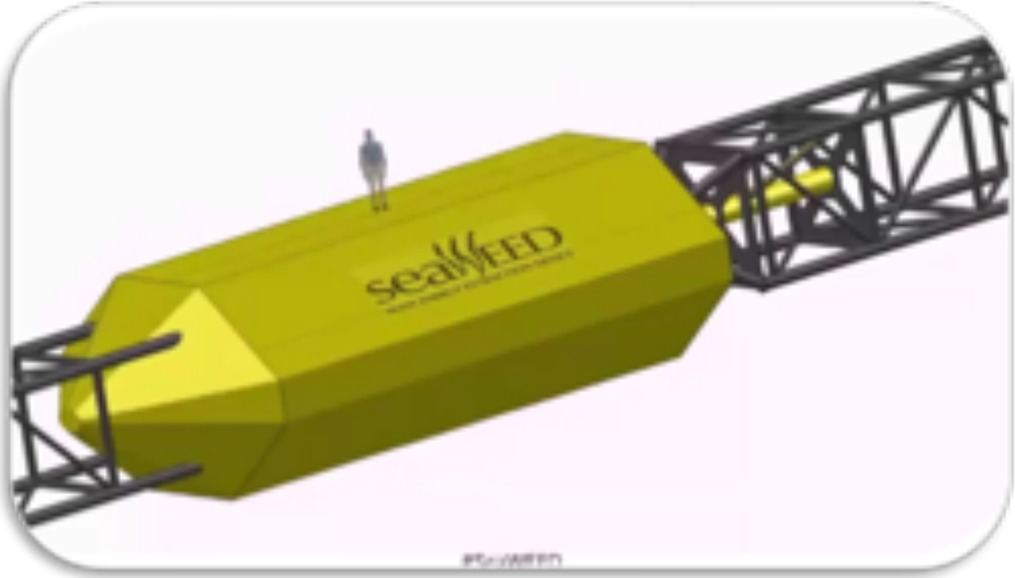
P2: 180 m length, 4 m diameter



Made up of connected sections which flex and bend as waves pass

Wave-induced motion is resisted by hydraulic cylinders which drive electrical generators. Electricity through umbilical to a junction on the seabed

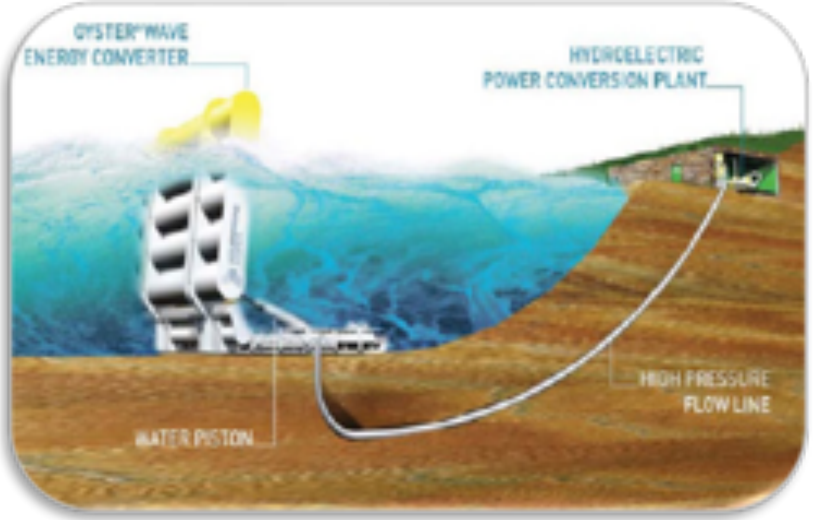
SeaWEED – Wave Energy Extraction Device

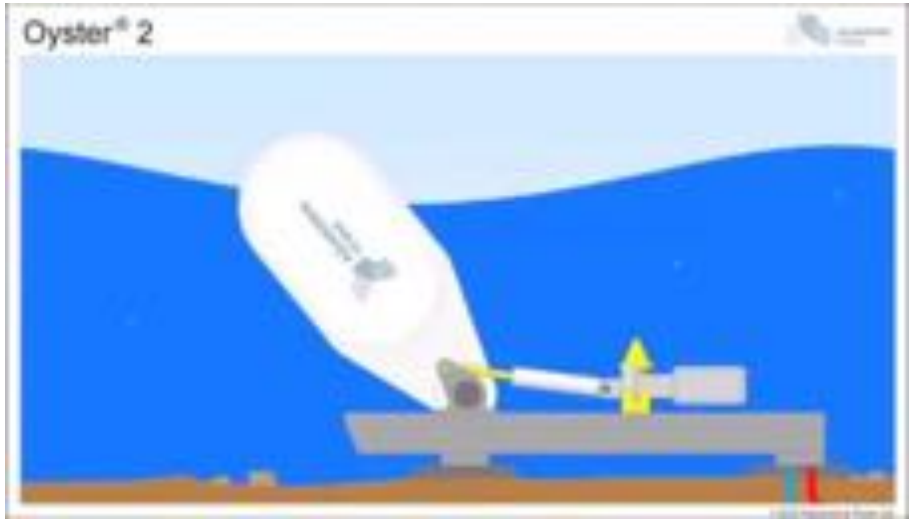


A multi-body wave energy converter with hinged joints developed by Grey Island Energy Inc, Canada

Wave Surge Converter Oyster

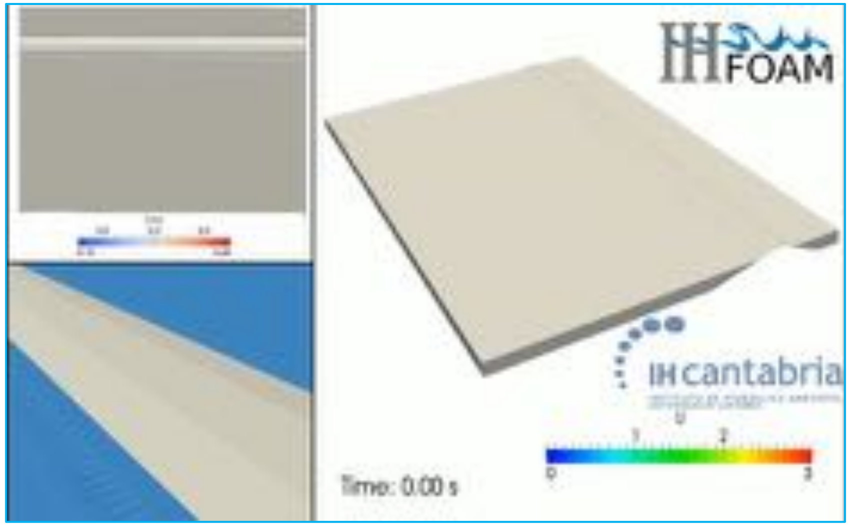
Oscillating wave surge converters (OWSCs) exploits enhanced horizontal fluid particle movement in the nearshore coastal zone with water depths of 10-20 m. Oyster 1 (2009), Oyster 2 (2011)

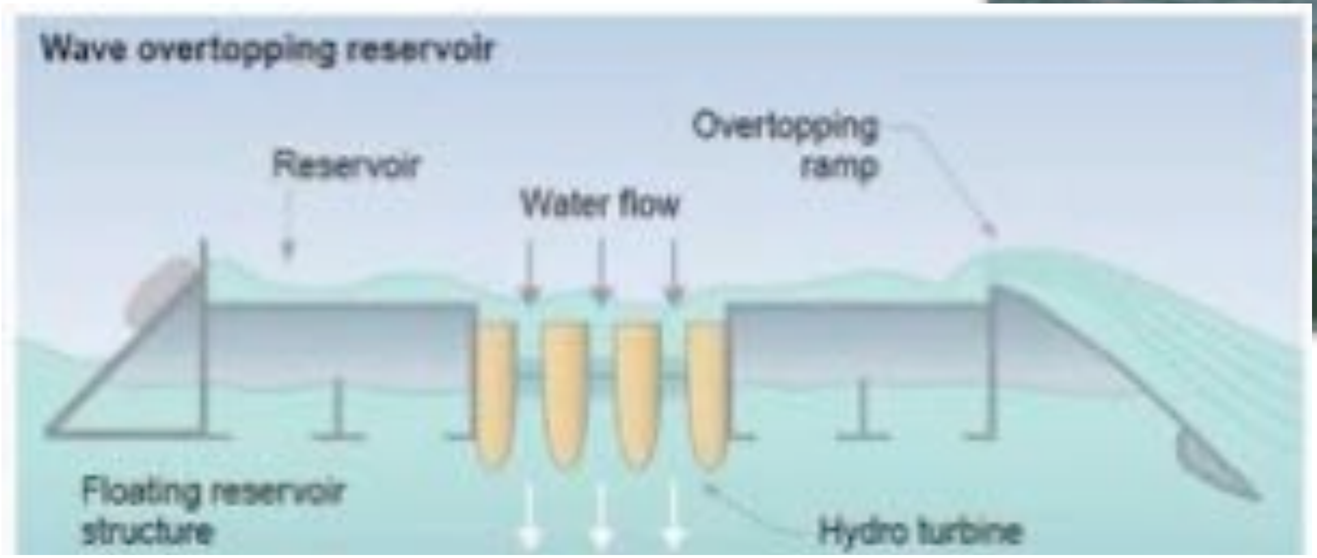




Individual flap modules are not likely to exceed 1 MW in installed capacity. Generating stations should be made up of line arrays of flaps with communal power conversion every 5-10 units

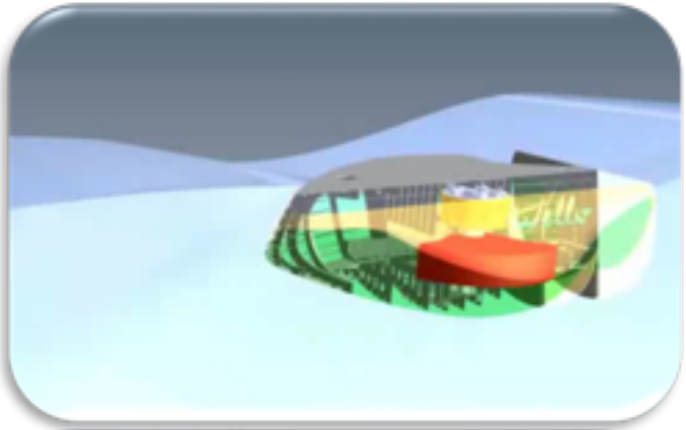
Wave Overtopping Devices





Sloshing/Pendulum WEC

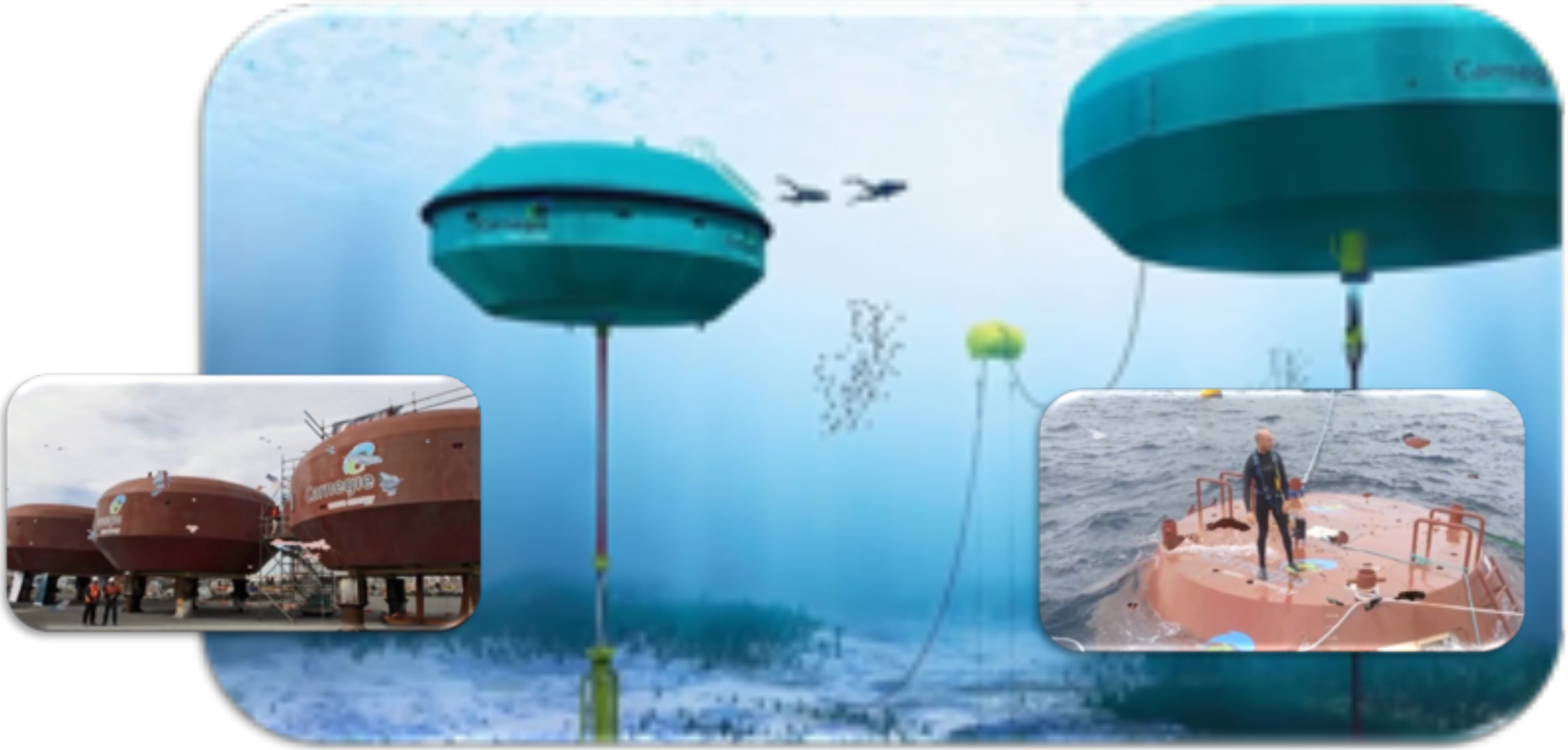
08 September 2021 this 600 kW WEC started to generate electricity to the local Basque grid from the ocean. *Wello* designed a hull as unstable as possible gyrating and generating with the constant onslaught of waves berating the device



The Wello Oy 'Penguin' wave energy converter


Salters Duck Family WEC

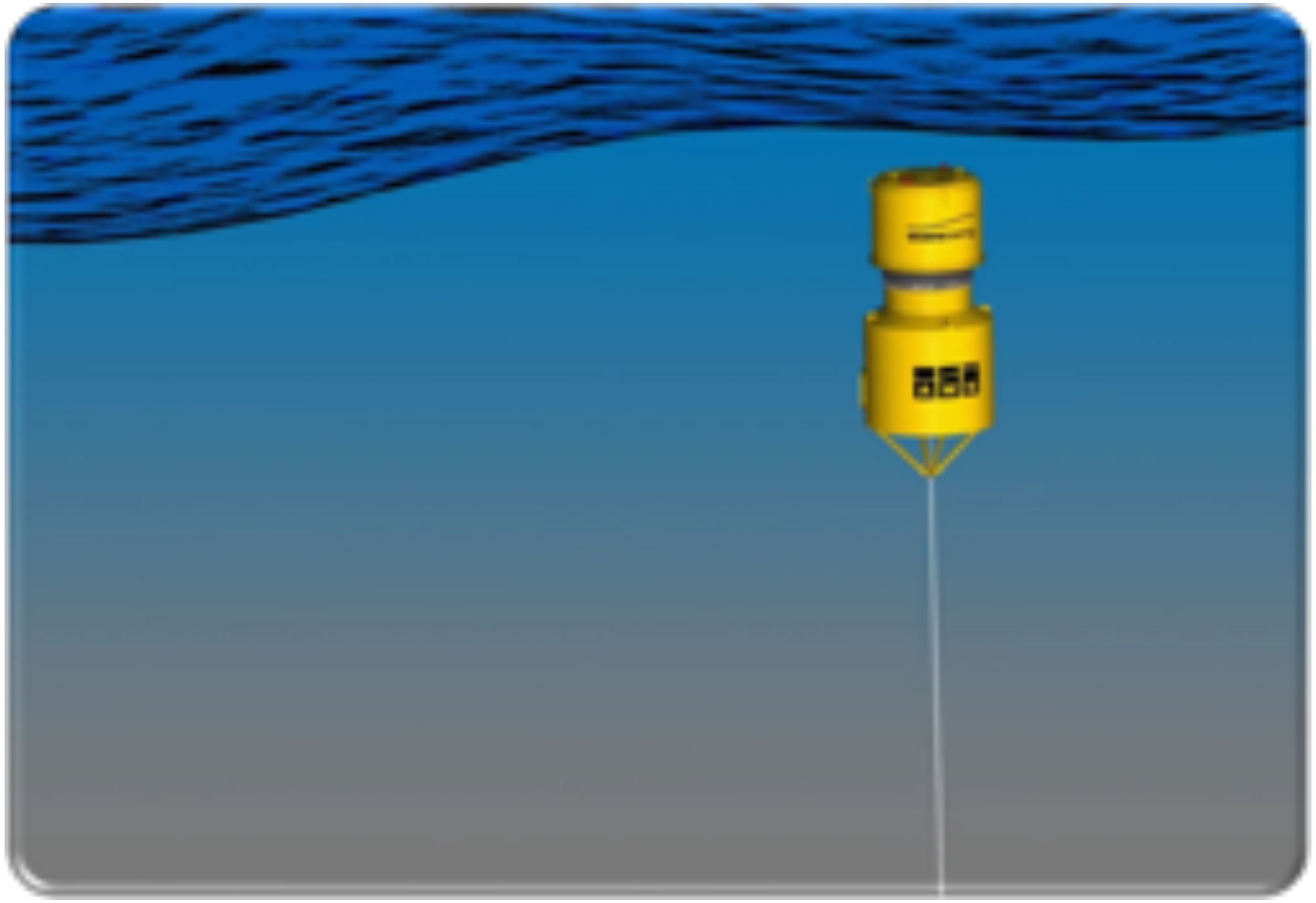
Carnegie Green Energy WEC (CETO)



OPTIMIZING WEC USING RESONANT MODES

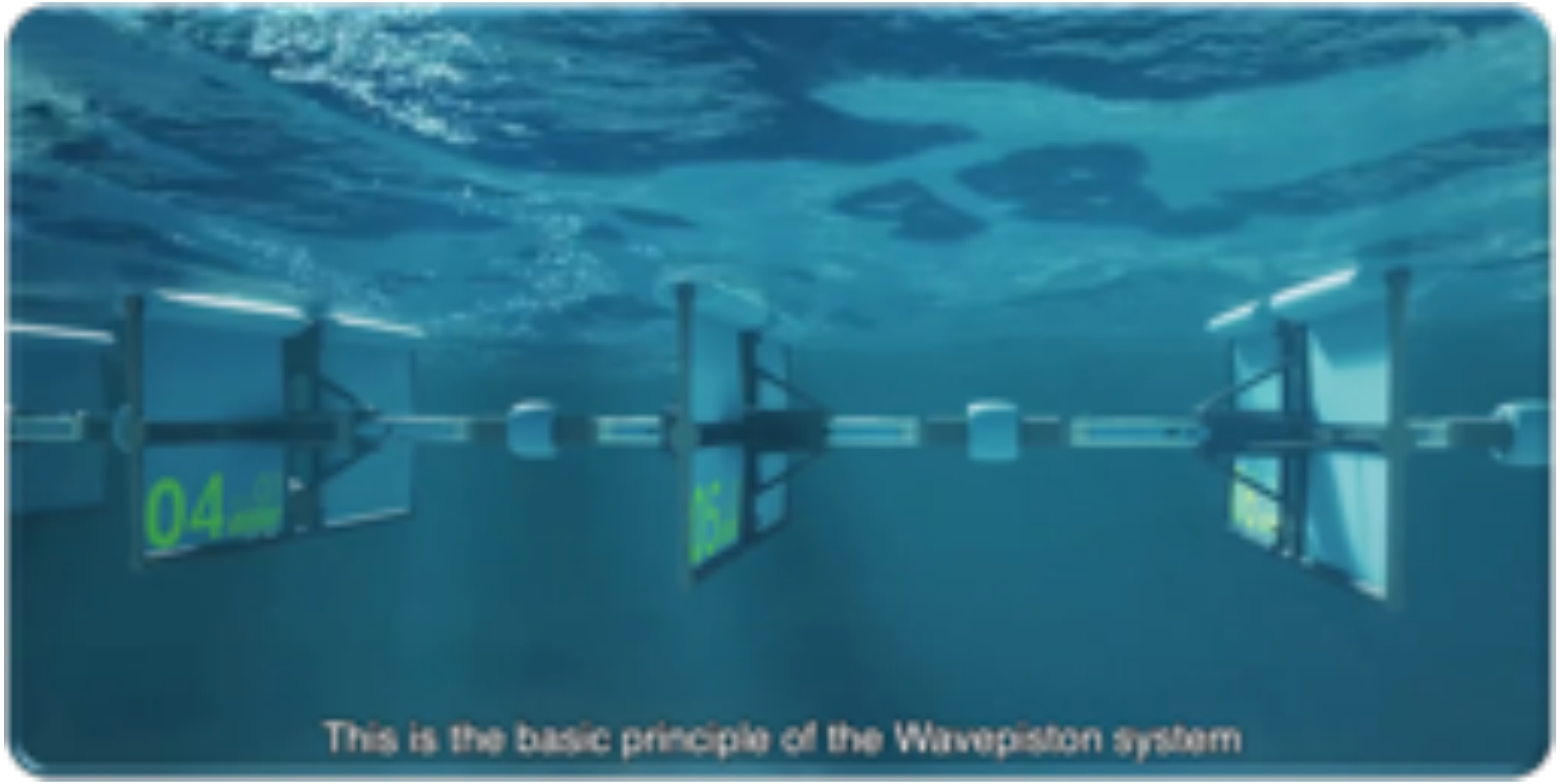
Resonant Wave Energy Converter by CorPower Ocean (Sweden) is a compact, high efficiency WEC inspired by the pumping principles of the human heart. Using a patented phase control method, the buoys oscillate in resonance with a wide range of incoming waves, thereby greatly amplifying energy generating motion of the device. This allows a large amount of power to be generated with a small buoy at a cost of energy that can compete with established energy resources

AWS Ocean Energy-Archimedes Wave Swing



Archimedes subsea pressure actuated buoy tethered to the sea bed It works on a similar principle as a cartesian diver toy. It contains a floater and a silo which together with a rolling seal enclose a volume of air. Under a wave crest the increasing hydrostatic pressure forces the floater downwards compressing the air which in turn acts as a spring to return the floater upwards Hydraulic cylinder coupled to hydraulic motor converts this reciprocating linear motion to rotary motion

SOME OTHER IDEAS: WAVE-PISTON WEC



Eco Wave Power

Comparing Sun, Wind and Wave Renewables: Solar panels provide about 1kW/sq. m Wind: 1 kW/sq. m   at 12 m/s. Wave: 25 kW/sq. m (SF coast)

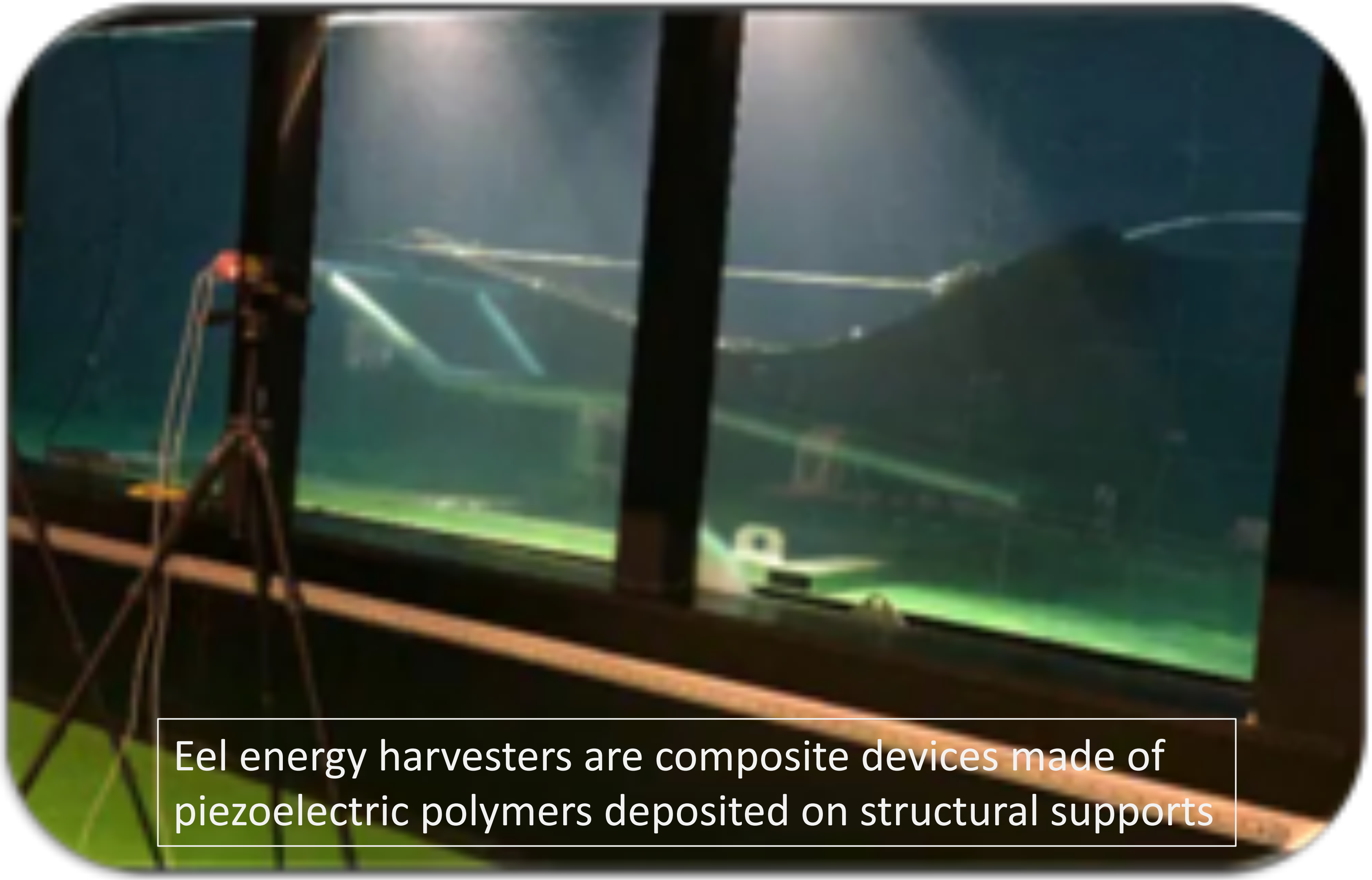
SOME OTHER IDEAS

Piezoelectric Eel Generator

Uses piezoelectric polymers to convert flow energy into electricity

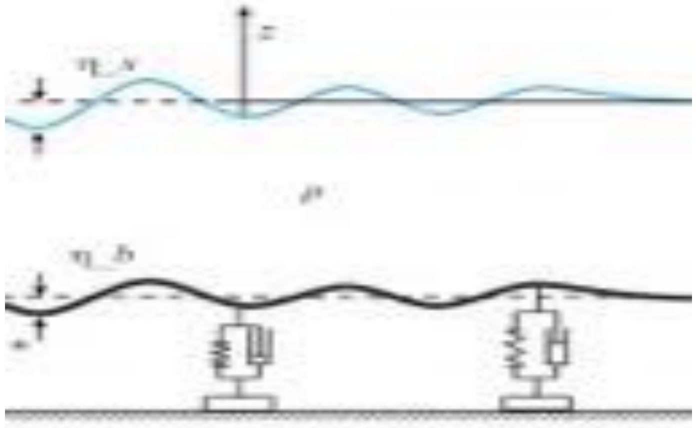
Makes use of Karman vortices behind bluff bodies to strain the piezoelectric elements

Piezoelectric Eel Energy Generator



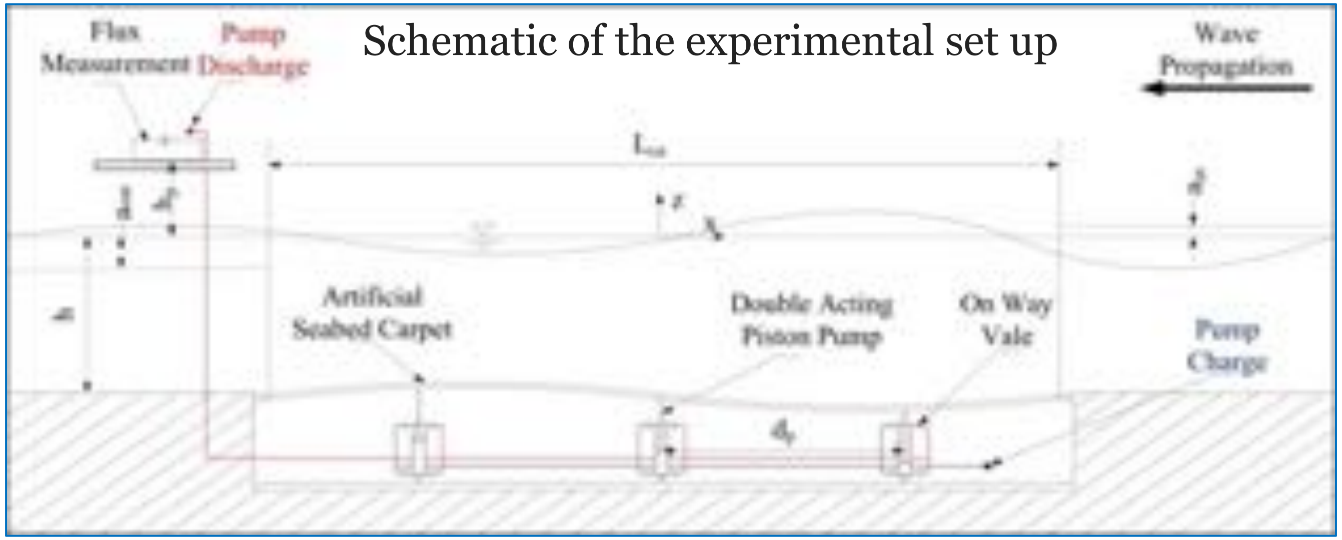
Eel energy harvesters are composite devices made of piezoelectric polymers deposited on structural supports

Berkeley Team Wave Carpet Energy Converter



Synthetic viscoelastic carpet on the seafloor for extracting energy from surface gravity waves

$$E_{\text{tot}} = \frac{1}{2}\rho g a_s^2 \left\{ \frac{\sinh 2kh}{2}\left(\frac{\omega^2}{gk} + \frac{gk}{\omega^2}\right) - 2\sinh^2(kh) + \rho g (a_s^2 - a_b^2) + k^* a_b^2 \right\}$$



Schematic of the experimental set up

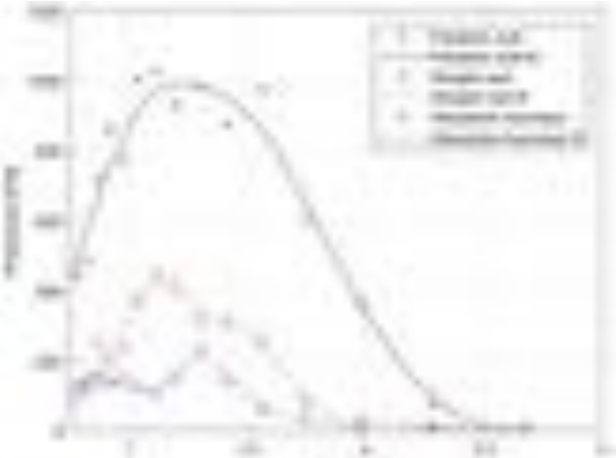
LAMINARIA - Surge Operated Attenuator

Pushing the endurance of autonomous systems in the ocean

WEC by Columbia Power Technologies

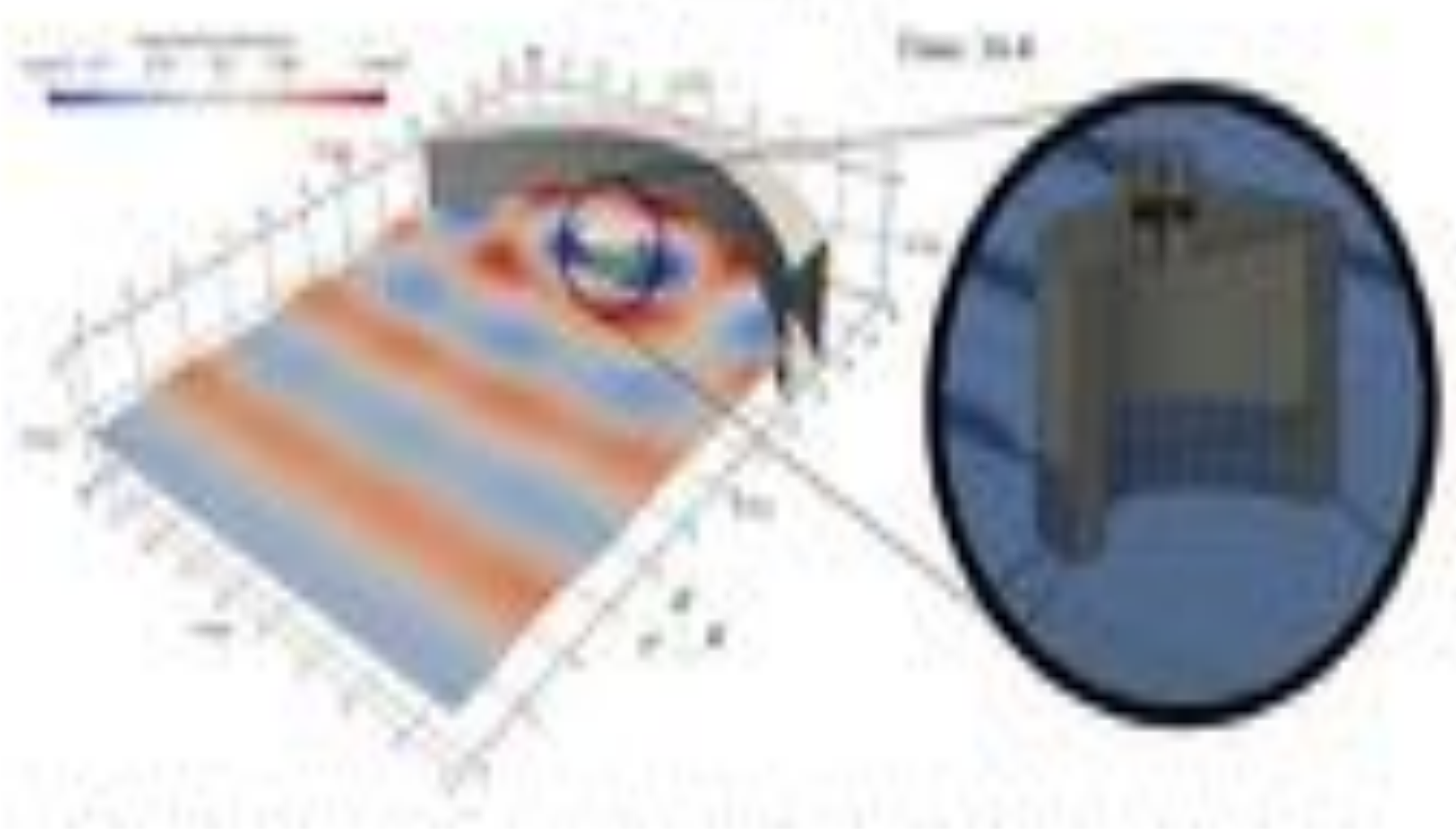
WEC MATHEMATICAL MODELING EXAMPLES

- **Wave focusing by a parabolic reflector wall** to a point sink is demonstrated.
- A cylindrical Oscillating Water Column is located at the parabola focal point.
- A 650% energy harvesting efficiency is realized by the proposed configuration.
- The wave energy capture bandwidth is significantly enhanced using this design.



Steady state chamber air pressures versus wave number

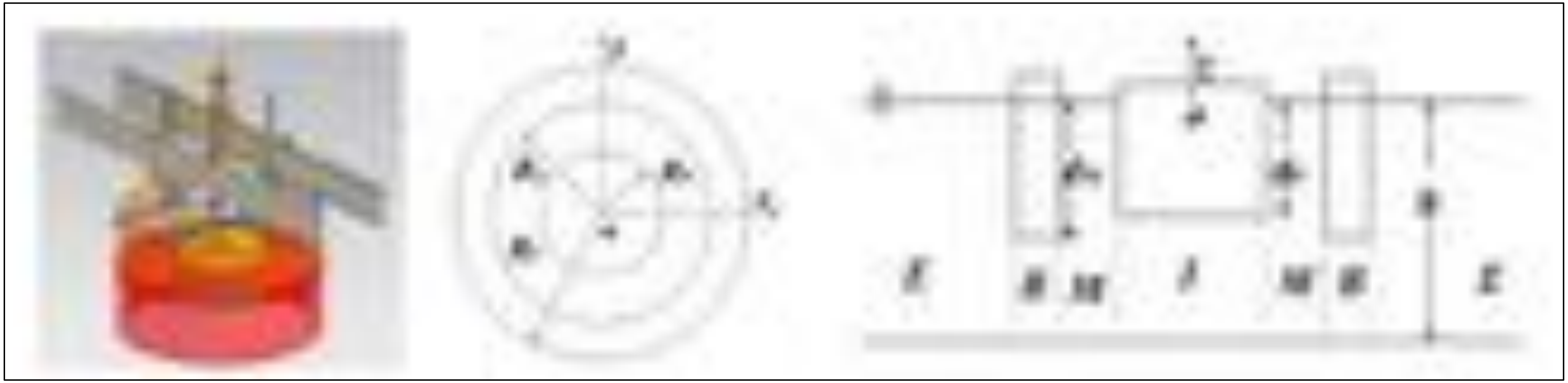
Applied Energy 304 (2021) 117795

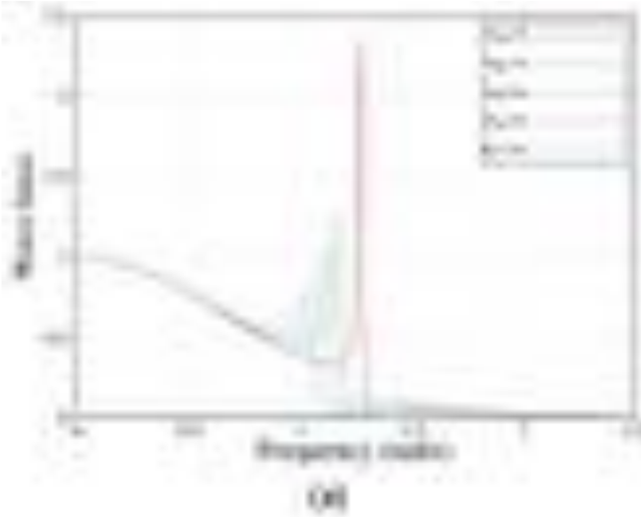


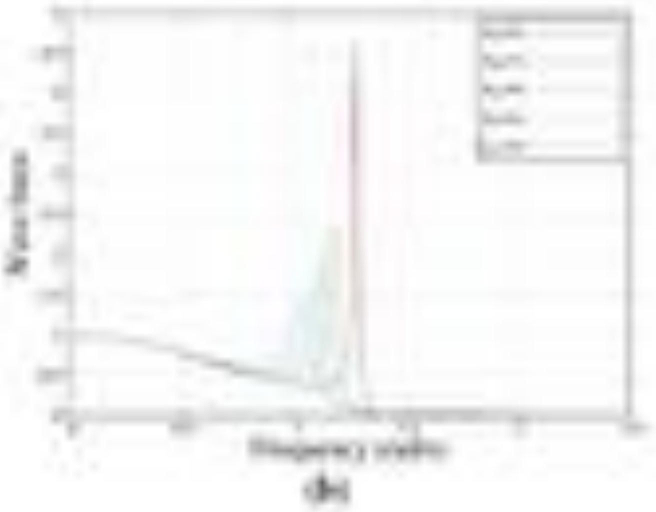
Maximum amplitude of free surface elevation

Math modeling examples: Analytical and Numerical Analysis of the **Dynamics of a Moonpool Platform–Wave Energy Buoy** (MP–WEB)

Energies 2019, 12, 4083; doi:10.3390/en12214083



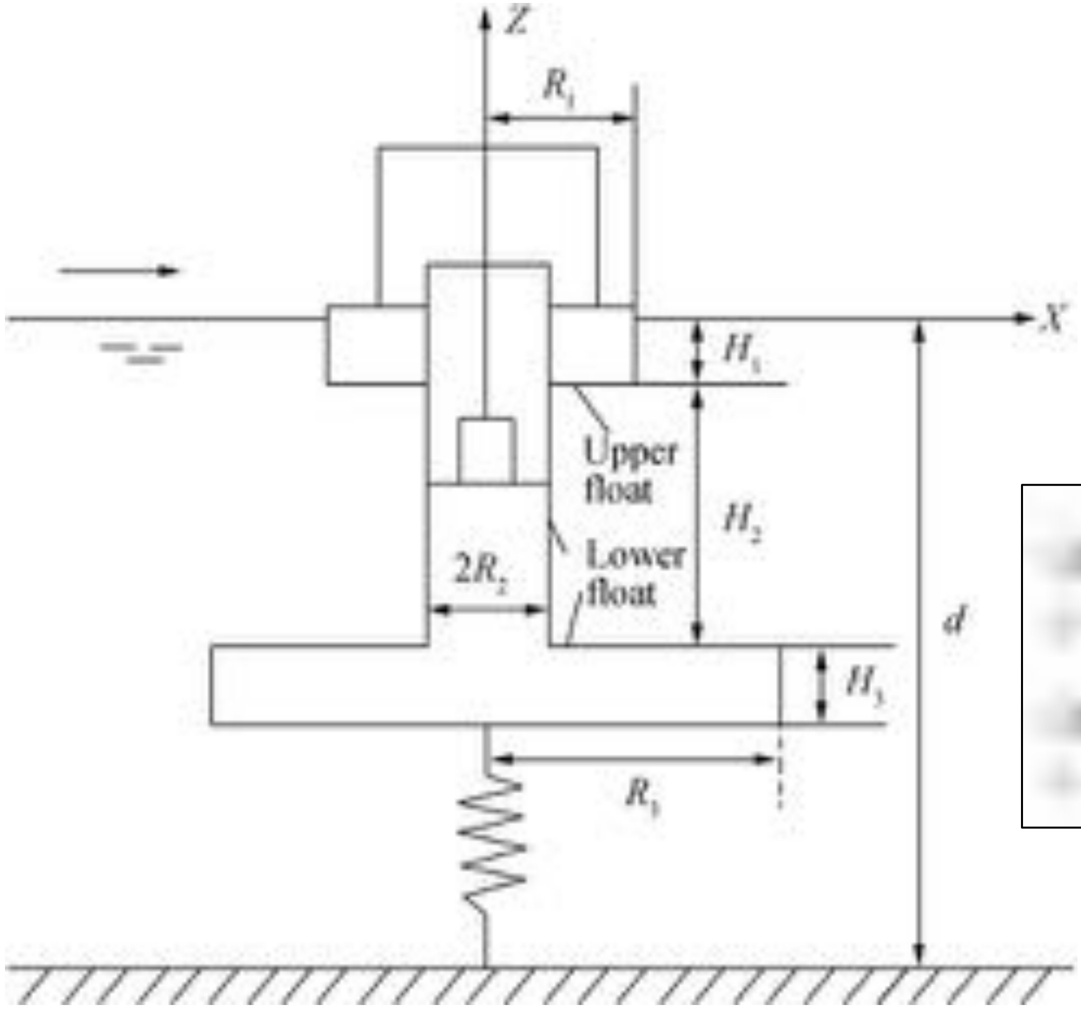




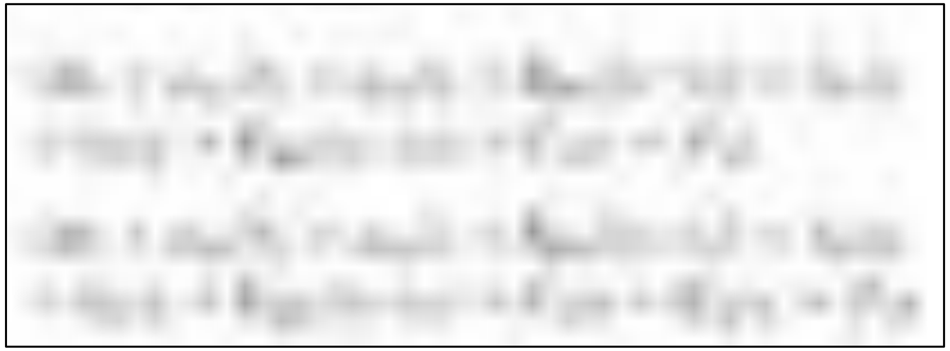
WEC based on MP–WEB combination has been studied for a range of geometrical parameters and frequencies of excitation. It was found that the wave gathering effect of the moonpool intensified the motion of the buoy, and the motion of the buoy promoted the motion of the moonpool.

Journal of Marine Science and Application (2019) 18:54–63
https://doi.org/10.1007/s11804-019-00083-9

Math modeling examples: Oscillation and Conversion Performance of **Double-Float Wave Energy Converter**

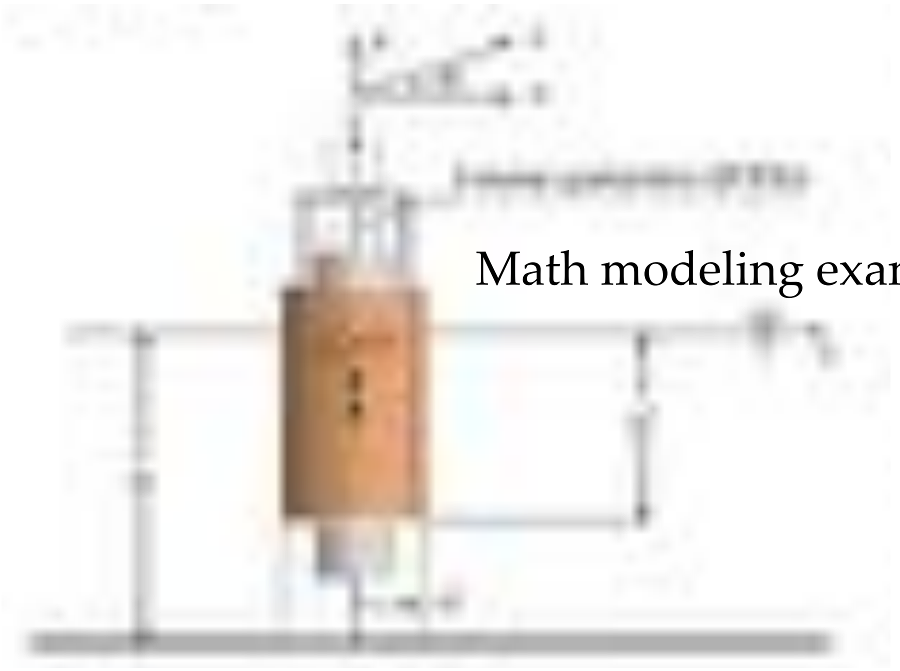


The **double-float WEC, which is in the point absorber category, has high conversion efficiency** and simple construction, and has become a hot spot in the study of wave energy extraction.

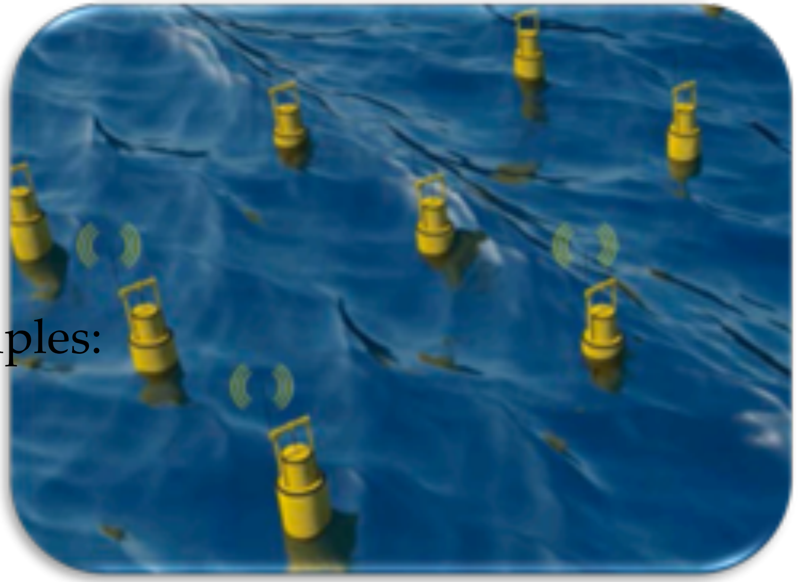


Math modeling examples: **optimal energy-extraction performance of arrays of wave-energy converters**, with account of wave and multi-body interactions

Ocean Engineering 250 (2022) 110863



Math modeling examples:



A community of WEC working in consonance, in communication with a global controller or among one another

Schematic of heaving point single absorber

Studies were conducted the optimal power generated by an array under constraints, in both regular and irregular waves, with the system modeled as linear. The wave-interaction effects were studied for arrays of different configurations, different spacings, and different wave-incident angles.

Ships & Marine Vehicles Propelled by Waves

Shipping provides transportation of more than *80% of the world trade*, but at the same time *makes the largest contribution to environmental pollution* (of the order of 800 megaton of carbon oxide a year).

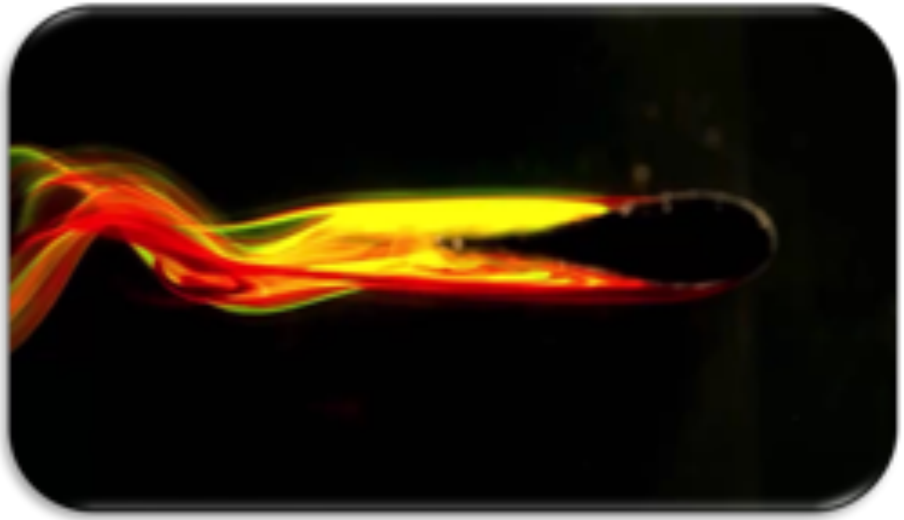
IMO introduced *ship energy efficiency design index* (EEDI) the level of which is controlled by classification societies. Besides, there exists a *requirement of decreasing ship emissions*, which are predicted to exceed a threshold increment of global temperature by 1.5 degrees with respect to preindustrial level as established by Paris agreement of 2015.

Important way of decreasing anthropogenic environmental impact of ships consists in full or partial transition to using renewable (sun, wind and wind) energy of the ocean.

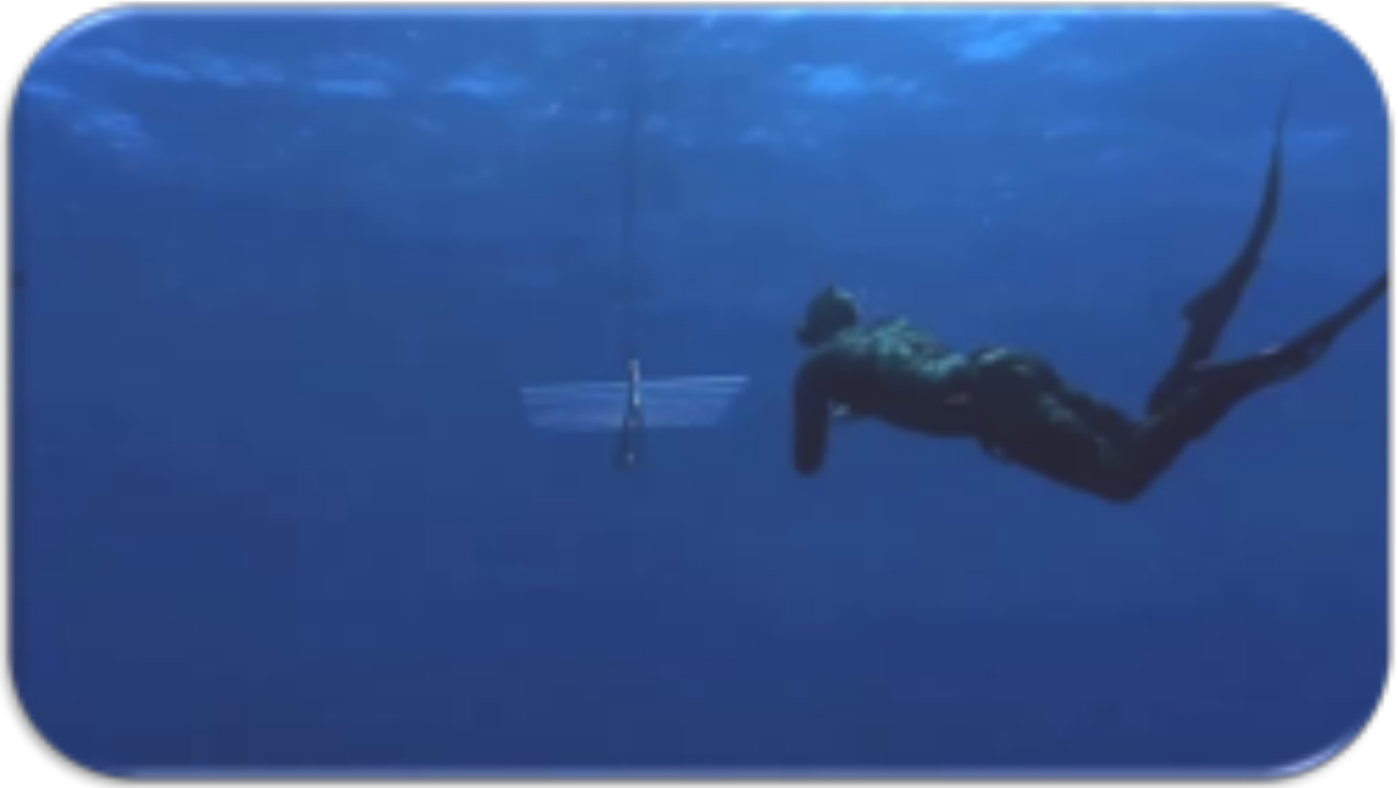
An option to solving the problem under discussion consists in using ships with energy saving wings which are both to be built or to be modernized through installation of such devices

In this case the mechanism of wave energy conversion consists in that motions of a ship with wings result in thrust generation leading to decrease of the required installed engine power. Therewith, reduced are both amplitudes of ship motions, fuel consumption and oxide dioxide exhaust into marine environment and atmosphere.

Flapping Wing as a Mechanism for Propulsion



What is Wave Glider?



Liquid Robotics *Wave Glider*

SMTU Wave Gliders

Design Technology Based on Equation of Oscillations of the Upper Body with Wings

Dimensional equation of oscillations of the WG

$$(M+m)\ddot{y} + \rho g[S^{0}_{WL} + S'_{WL}(0)y]y = R_{y_{wing}} + R_{y_{wave}}$$

$$R_{y_{wing}} = R^{\dot{y}}_{y_{wing}}\dot{y} + R^{\ddot{y}}_{y_{wing}}\ddot{y}$$

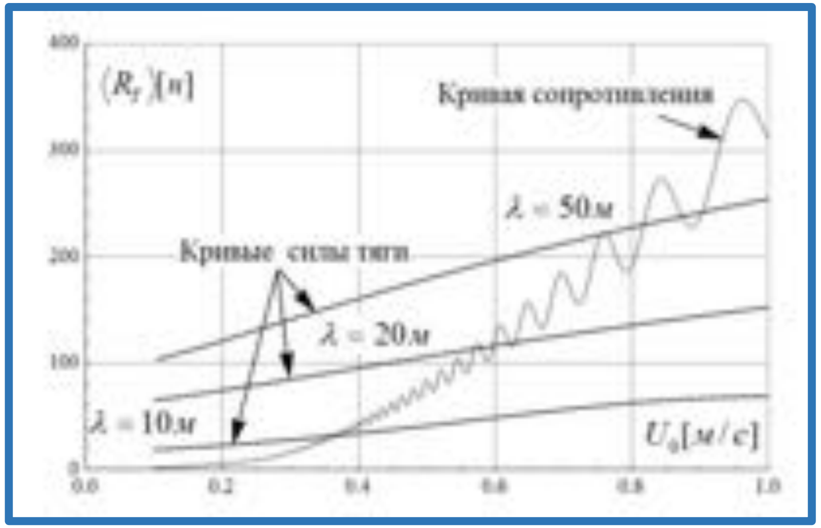
Reduced dimensional equation of oscillations of the WG under action of waves

$$(M+m-R^{\ddot{y}}_{y_{wing}})\ddot{y} - R^{\dot{y}}_{y_{wing}}\dot{y} + \rho g S^{0}_{WL} y + \rho g S'_{WL}(0) y^{2} = \frac{2\rho g b a_{w}}{k_{\lambda}} \sin\left(\frac{\pi \cdot l}{\lambda}\right)\cos(\omega_{e} t).$$

Rendering the equation for the WG oscillations to a non-dimensional form

$$\tau = t\frac{2U_{0}}{c}, \eta = \frac{2y}{c}, k_{e} = \frac{\omega_{e} c}{2U_{0}}$$

Example of Calculation of Thrust & Speed of the WG



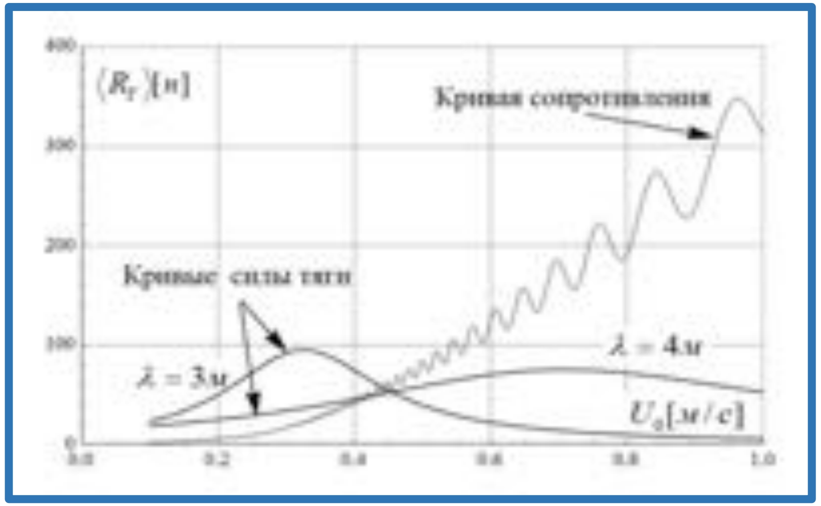


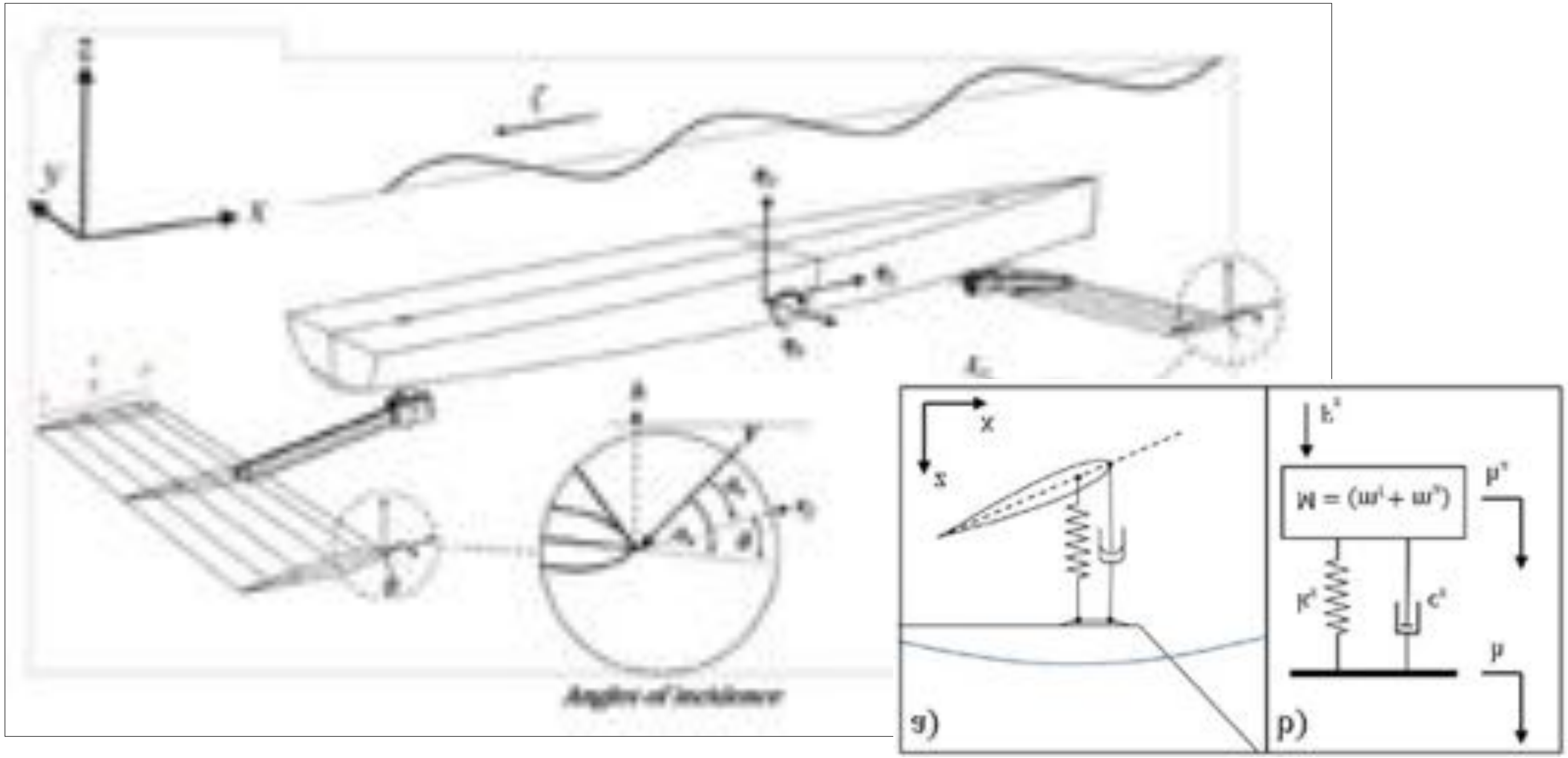
Таблица 1

Скорость, тяга и идеальный КПД ВГ в расчетном случае для волн различной длины

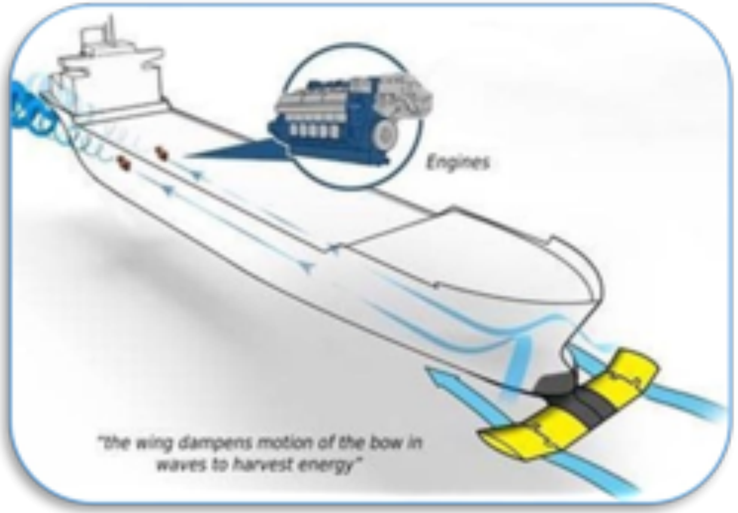
λ [м]	$U_\oplus$ [м/с]	$\langle R_T \rangle$ [н]	η_i
3	0.43	60	0.53
4	0.40	45	0.53
5	0.37	33	0.53
10	0.38	38	0.53
20	0.51	72	0.54
30	0.62	117	0.56
40	0.73	172	0.57
50	0.90	241	0.58

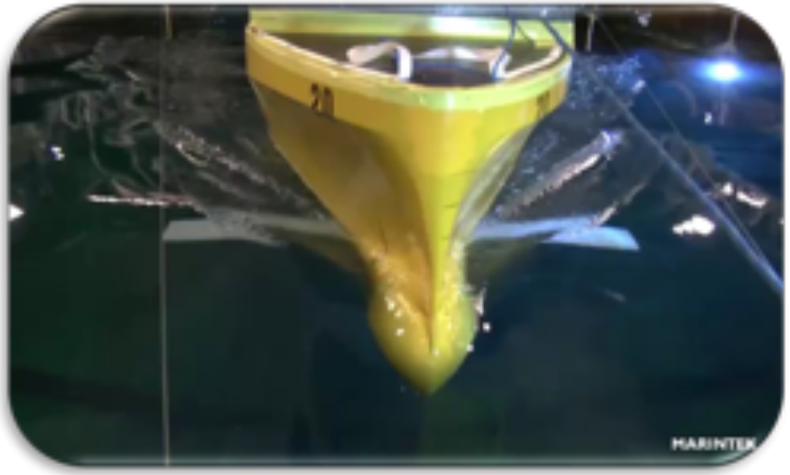
Wave Glider Autonaut (QinetiQ)

Mechanism of motion and additional wave energy extraction of ASV *Autonaut*



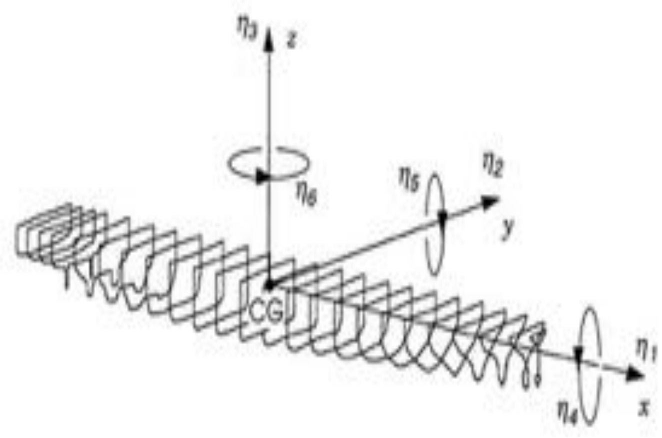
Ships Equipped With Wave Energy Extraction Devices



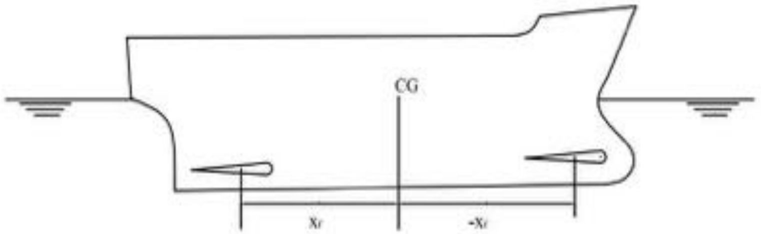


Rozhdestvensky & Ryzhov, Progress in Aerospace Sciences 39(2003), 585-633

Mathematical Models of Ships with Wings



Coordinate system



A ship with wings

equations of longitudinal motions of an elongated ship

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{35}\ddot{\eta}_5 + B_{35}\dot{\eta}_5 + C_{35}\eta_5 = F_3 e^{i\omega_e t}$$

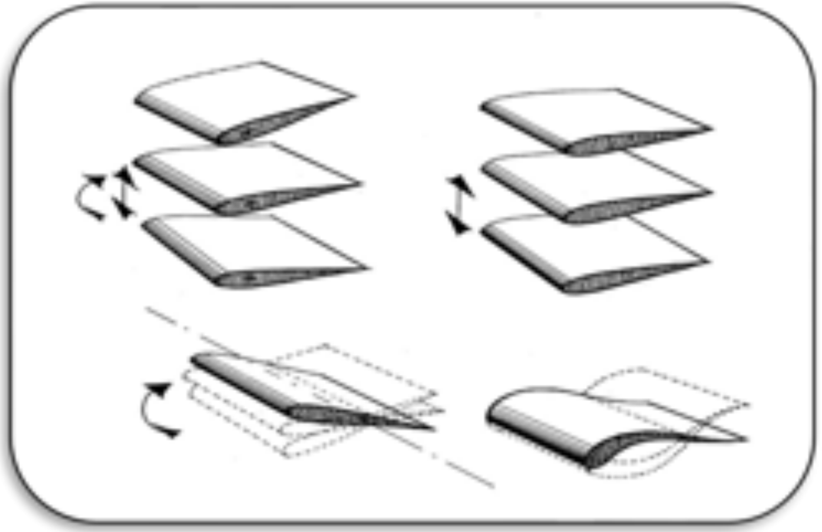
$$A_{53}\ddot{\eta}_3 + B_{53}\dot{\eta}_3 + C_{53}\eta_3 + (I_5 + A_{55})\ddot{\eta}_5 + B_{55}\dot{\eta}_5 + C_{55}\eta_5 = F_5 e^{i\omega_e t}$$

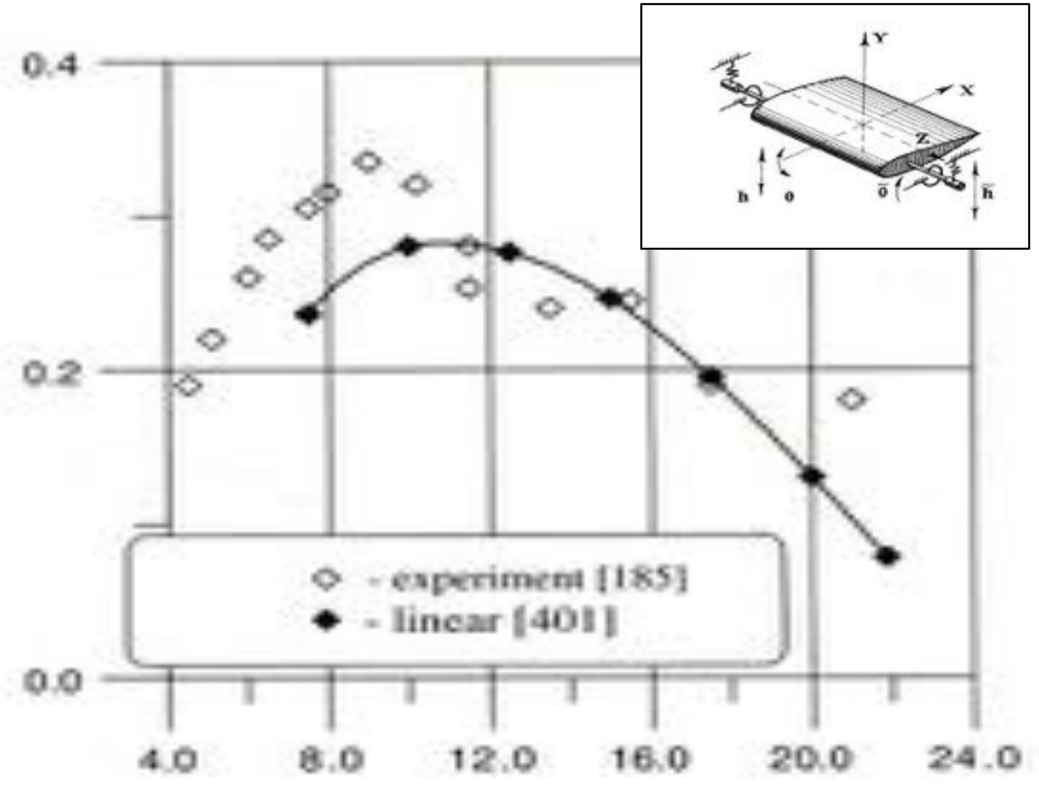
Equations of longitudinal motions of an elongated ship equipped with energy saving wings

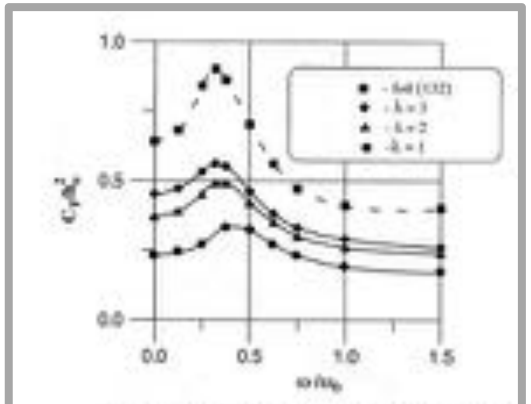
$$(M + A_{33} + A_{33,foil})\ddot{\eta}_3 + (B_{33} + B_{33,foil})\dot{\eta}_3 + C_{33}\eta_3 + (A_{35} + A_{35,foil})\ddot{\eta}_5$$
$$+(B_{35} + B_{35,foil})\dot{\eta}_5 + (C_{35} + C_{35,foil})\eta_5 = F_3 e^{i\omega_e t} + F_{3W,foil}$$

$$(A_{53} + A_{53,foil})\ddot{\eta}_3 + (B_{53} + B_{53,foil})\dot{\eta}_3 + C_{53}\eta_3 + (I_5 + A_{55} + A_{55,foil})\ddot{\eta}_5$$
$$+(B_{55} + B_{55,foil})\dot{\eta}_5 + (C_{55} + C_{55,foil})\eta_5 = F_5 e^{i\omega_e t} + F_{5W,foil}$$

Wings motions and Resonant Modes

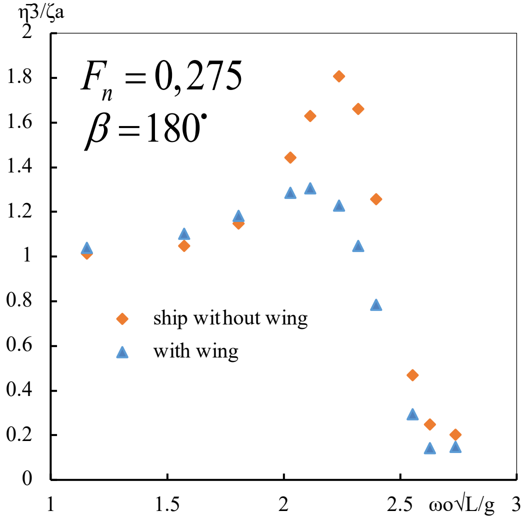


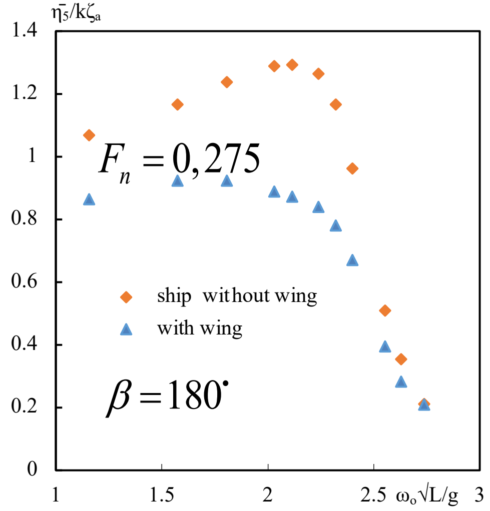




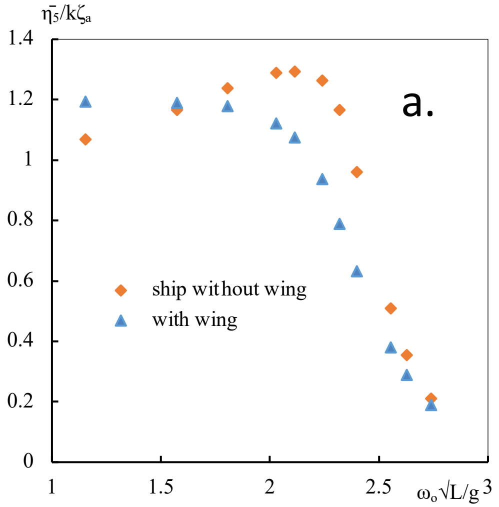
Period-averaged thrust coefficient [400]. Rectangular wings of different aspect ratio, performing prescribed heaving oscillations and having elastic link in pitching. Unbounded fluid. Parameters:

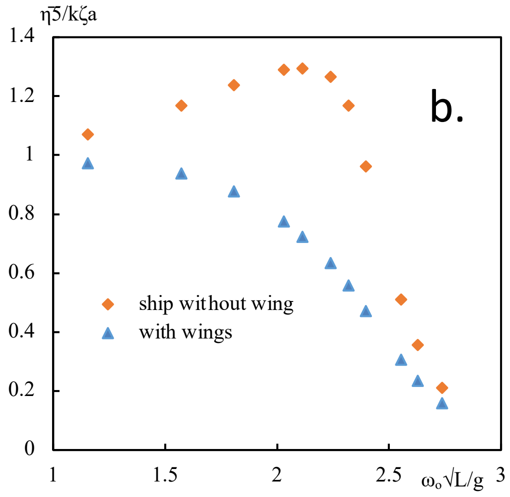
Influence of Wings on Amplitude-Frequency Characteristics (AFC) in Regular Waves





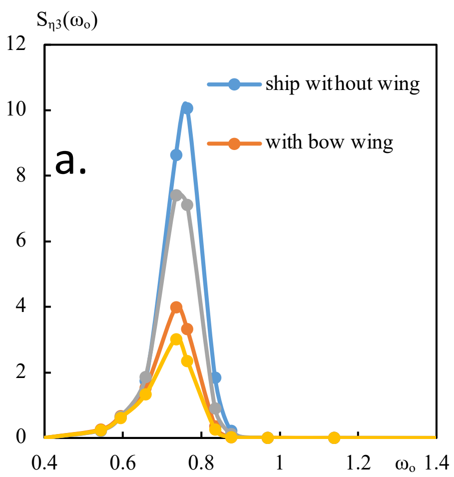
AFC of heaving of containership S-175 for oncoming regular waves without wings and with bow wing (aspect ratio 5, foil section NACA 0012)

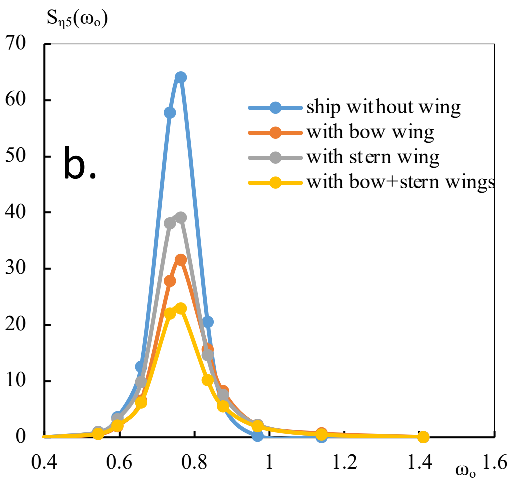




AFC of pitching of containership S-175 for oncoming regular waves without wings (a) with a bow wing (b) with bow and stern wings

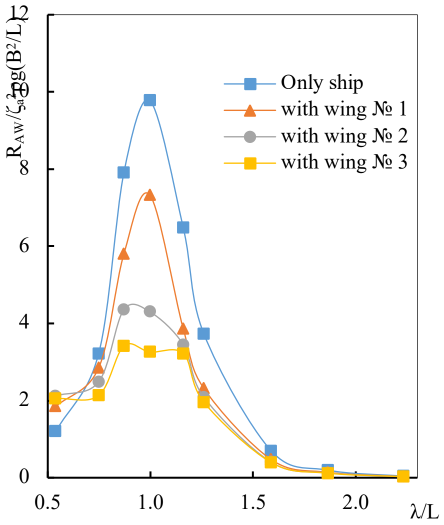
Ship Motions Spectra in Irregular Waves

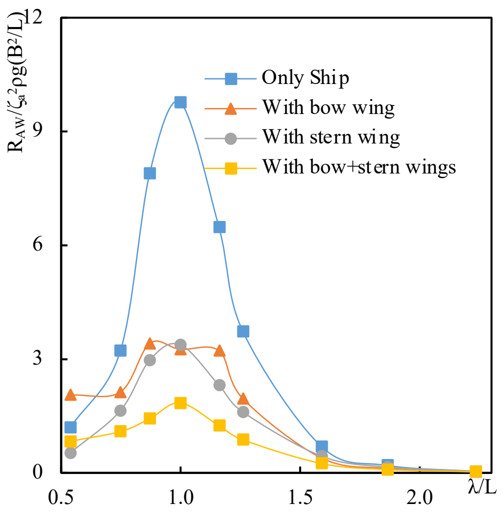




Spectral densities of heaving (a) and (b) pitching for containership S-175 (oncoming irregular waves and for different wing ararngements)

Added Wave Resistance With & Without Wings

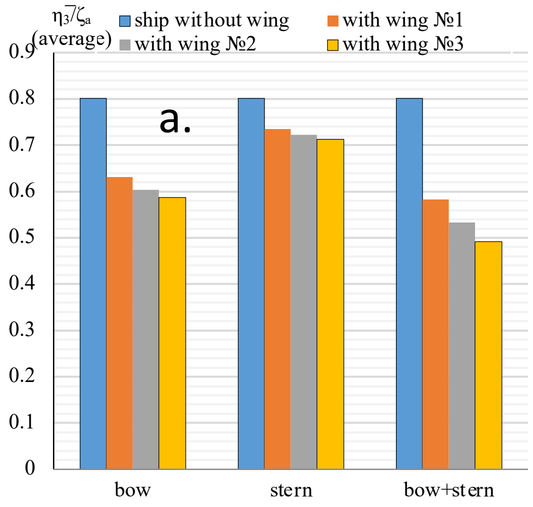


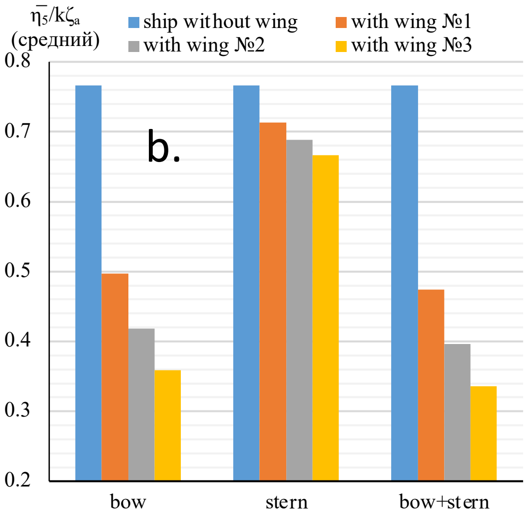


Added wave resistance of containership S-175 (oncoming regular waves without wings and with wings)

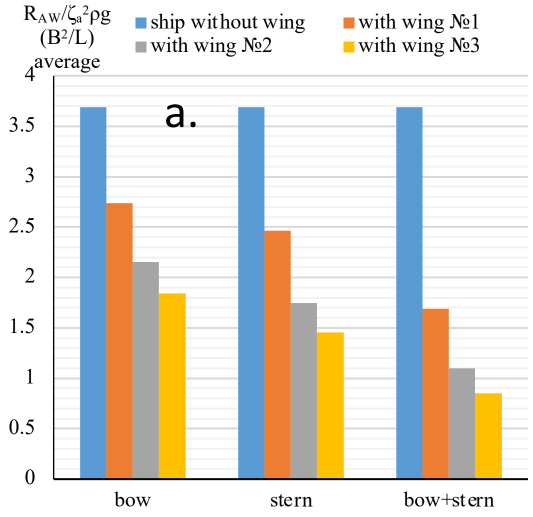
AFC averaged data on added resistance in waves and EEDI index for ships with and without wings

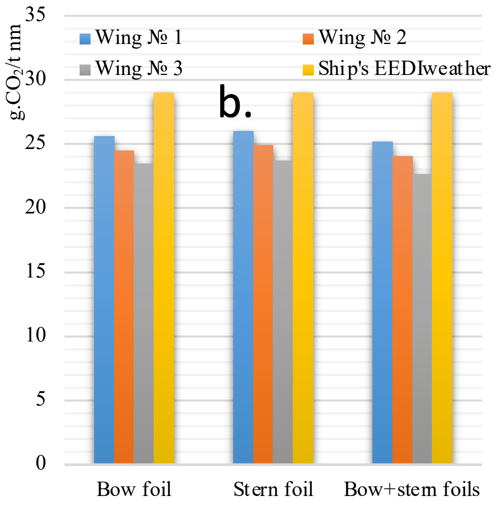
Mathematical model of ship with wings propelled by waves, Springer Nature, 2021





AFC for containership S-175 (oncoming regular waves without wings and with a bow wing of aspect ratio 5, foil section NACA 0012)





(a) Averaged values of added resistance in waves for a ship with wings for representative waves

(b) Averaged values of the EEDI for a ship with wings at representative waves at speed of 22 knots

Wing Modules for Modernization of Existing Ships (Norway Experience)

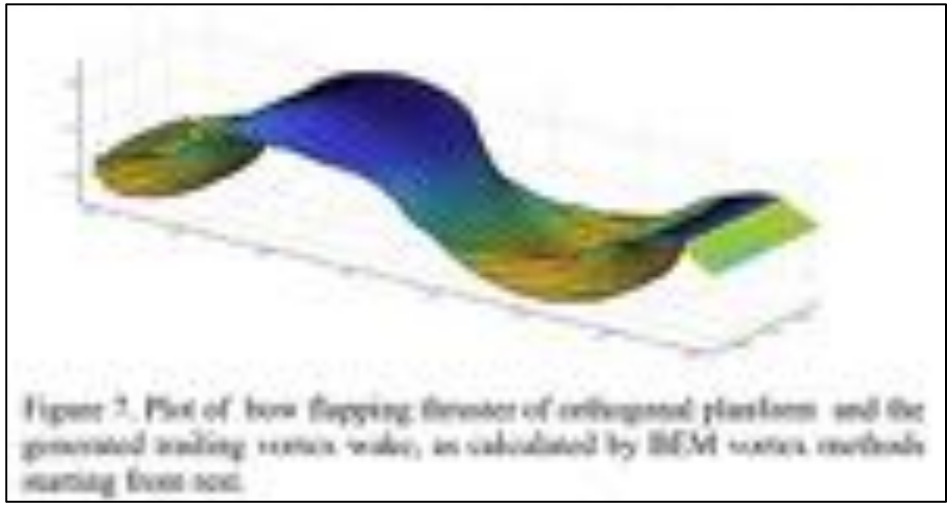
Wavefoil | Passenger ferry M/F TEISTIN





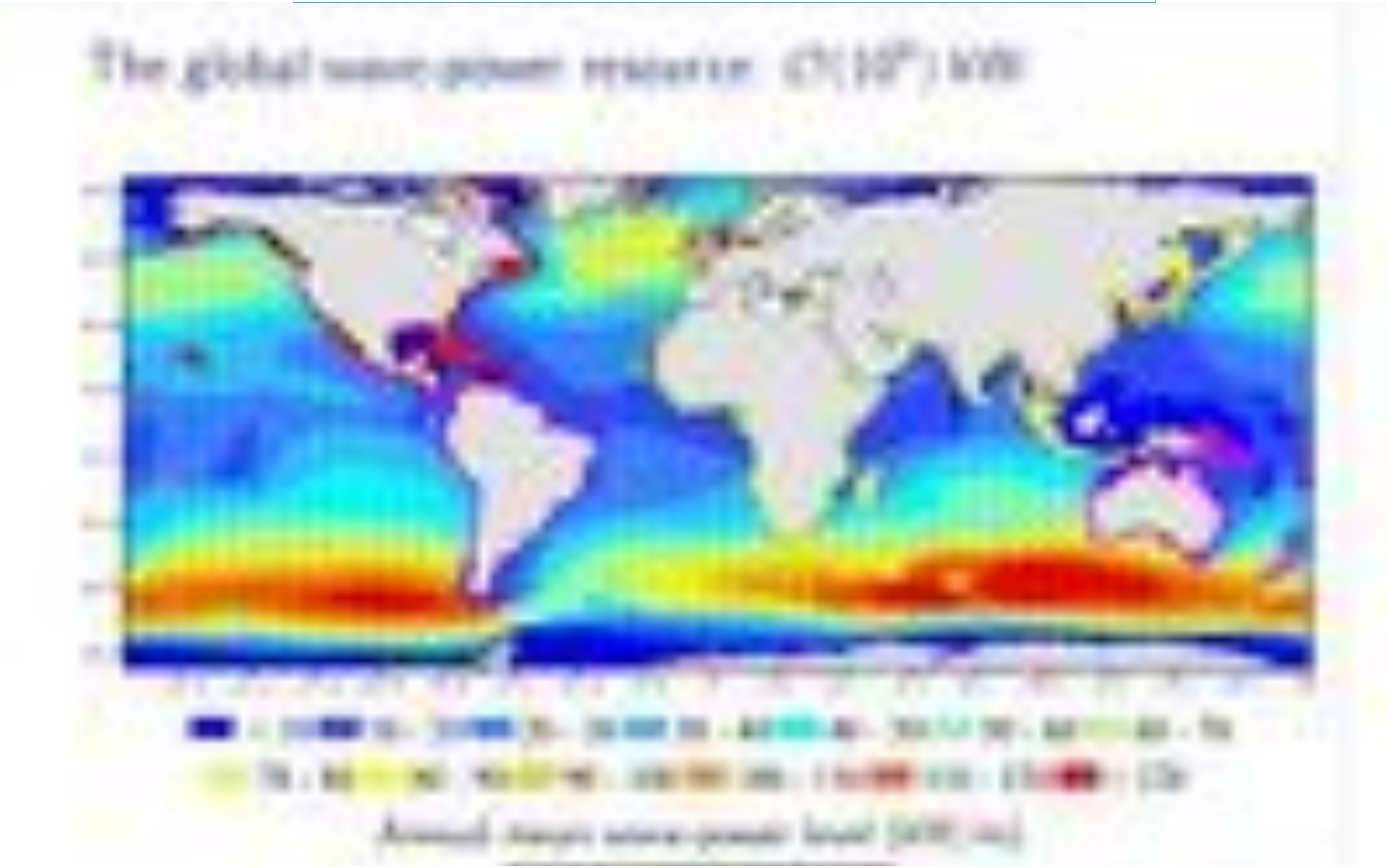
Wing Modules for Modernization of Existing Ships (Norway Experience)

Wavefoil |Catamaran Bard



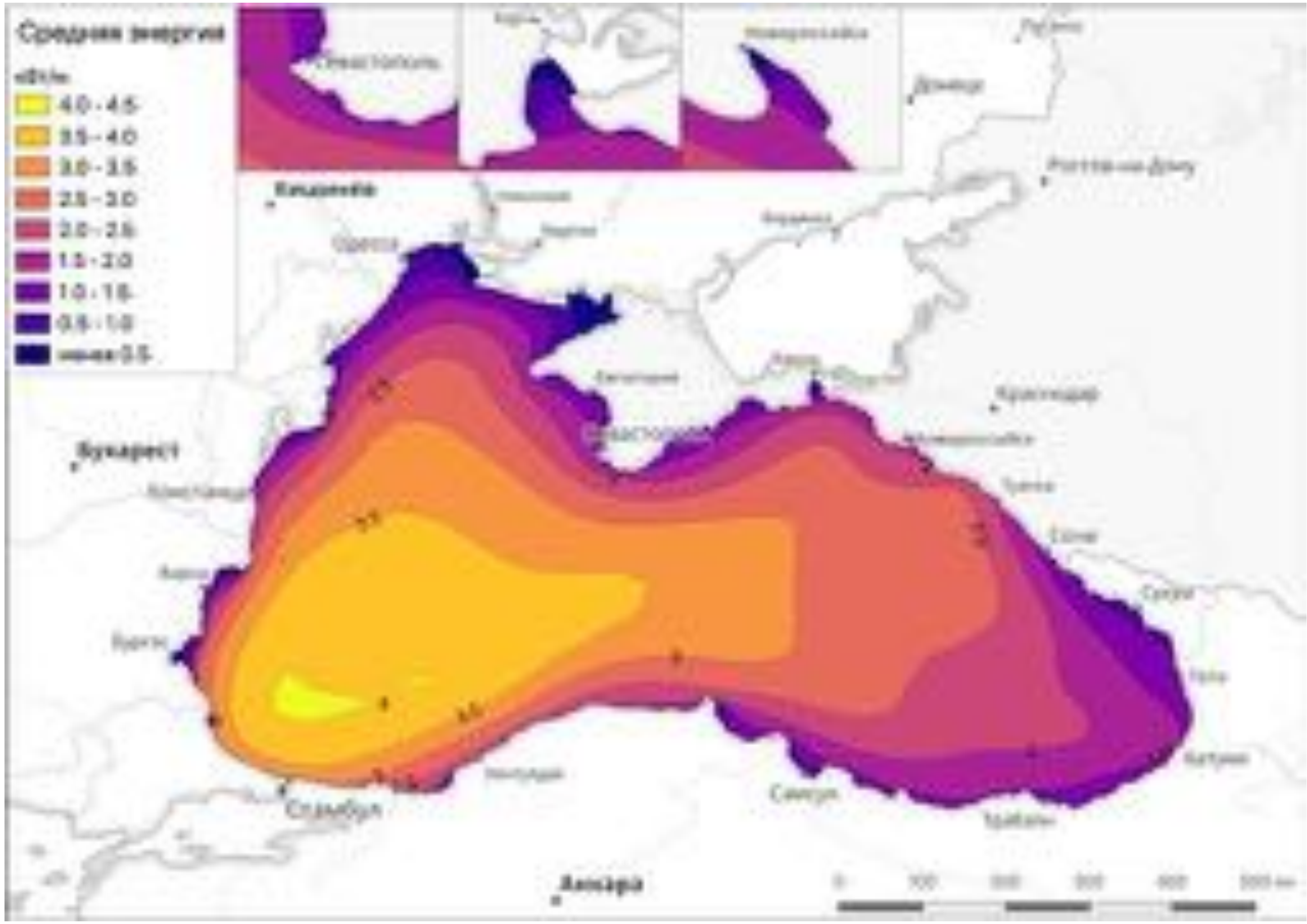
Kostas Belibassakis et al. Combined performance of innovative biomimetic ship propulsion system in waves with dual fuel ship engine and application to short –sea shipping. Proc. 31st (2021) International Ocean and Polar Engineering Conference, Rhodes, Greece, June 2025, 2021, p. 2815-2822

WORLD WAVE POWER RESOURCES



WORLD WAVE POWER RESOURCES

Web-Atlas of Accessible Wave & Wind Power of Russia Seas by Moscow State University



THE OCEANS ARE RELENTLESS

What is the reason why wave energy is still behind the wind and sun?

Not because the wind or solar are easier but the ocean presents a big challenge. It is a unique and incredibly powerful resource. It is much more energetic than the wind or the sun from energy density prospective. It is irregular from wave to wave. Hence you have to create a system that is tolerant to that irregularity.

Since the first attempts to create devices to use renewable wave energy there emerged hundreds of projects of WEC and thousands of patents world wide. Extensive numerical and experimental studies carried out to evaluate performance of WECs

Hundreds of WEC developing companies and testing grounds have been created in different countries of the world to harness the wave power. Motivation for using wave power is growing as there is no single renewable that would give us 100%.

But the **Wave Power Extraction systems are still far from being established.**

Further Roadmap Toward Implementation

- Existing wave energy technology has been designed for ocean waves, which, however, shorten the lifespan of wave energy converters and mooring systems. Furthermore, commissioning and maintenance in the harsh ocean conditions are challenging and expensive. For wave energy technology to realize its full potential and become commercially attractive, smaller, more economical, and resilient converters should be first introduced, tested, and optimized, as was the case with wind energy. **Low energy seas** such as the Mediterranean, Baltic, Caspian, Black, and Red Sea are ideal for this purpose. **Existing technology should be downscaled to fit the milder wave regimes.**
- **Climate change tends to increase the wave energy resource**, which could be beneficial for wave energy harnessing, however, will affect beach and coastal erosion and ports functionality. Converters in the nearshore can protect ports and the coast and mitigate erosion.
- **Other secondary functions** include: desalination, hydrogen production, pumped-storage hydroelectricity, extending endurance of marine robotic systems, photovoltaic panel integration, and wave-wind farms co-location. Even though wave energy converters can counter beach erosion, they might also negatively affect aquatic ecosystems through vibrations and low-frequency long-duration noise.

SHOW MUST GO ON

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Monographs, textbooks & review articles : *Matched asymptotics in wing hydromechanics (Sudostroenie, 1979), Aerohydrodynamics of ships with dynamic support (Sudostroenie, 1991, co-authors NB Plissov & VK Treshkov*), *Aerodynamics of a Lifting System in Extreme Ground Effect (Springer, 2000), Aerohydrodynamics of Flapping Wing Propulsors (2003, PAS, Elsevier), Wing-in-ground effect vehicles (2006, PAS-Elsevier), Computer Modeling & Simulations of Dynamic Systems Using Wolfram System Modeler (Springer, 2021), Recent Advances in Hydrodynamics of Wing Propulsive Lifting Systems for Ships and Underwater Vehicles (Physics of Fluids, 2023, co-author Zhao Bowen).*

Research interests: high-speed marine vehicles, marine robotics, bubble dynamics and supercavitation, flapping wing propulsion.