Wave Induced Vibration Energy Harvesting

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***Abstract*—**
Ocean waves hold great promise as a renewable energy source, yet effectively harnessing this energy necessitates the enhancements of technologies. Despite the advancements in Wave Energy Converters (WECs), several current limitations in wave energy harvesting technologies hinder widespread commercial adoption. WECs have demonstrated their potential for electrical power generation but there is a recognition that a single type of energy harvesting mechanism may not fully exploit the vast energy potential of the marine environment. This study explores Vortex Induced Vibrations (VIV) as a complementary energy harvesting mechanism for WECs: the basic idea is to exploit wave-induced VIV. The paper investigates the viability of this approach, focusing on clarifying the necessary conditions required to enable this innovative energy harvesting approach. The results provided in this paper contribute to a deeper understanding of the practicality of wave induced VIV harvesting, highlighting some potential challenges associated with deploying such a system.

***Index Terms*—Wave Energy, Vortex Induced Vibration, WEC**

I. INTRODUCTION

The increasingly damaging effects of global warming have indicated society's need to re-evaluate reliance on fossil fuels as the primary energy source [1]. With global energy consumption increasing by a third since the year 2000 and projected to continue growing to reach 740 million terajoules, amounting to a 77% increase by 2040 [2], it is undeniable that alternative resources are required as, due to their impact on climate, society cannot continue to rely significantly on fossil fuel as the principle source of energy. The installation of land-based renewable sources, such as solar panels and fixed horizontal axis wind turbines (HAWT), has visibly increased in the past decades. There is considerable interest in acquiring energy from these and other offshore resources: wind, solar, wave, tide, and ocean thermal. Up to the present, it is evident that wind energy has a successful monopoly on offshore renewable energy, and has made the largest contribution. However, wave energy offers the largest potential, with oceans being vast and covering 140 million square miles, approximately 72% of the earth's surface, but wave motions are more complex than winds' motion, and fresh methods will need to be devised to achieve its full potential [3]. Background studies [4] of this research have shown that solutions based on wave energy alone cannot provide viable energy output, and enhanced arrangements with links to other energy generation concepts are needed. Therefore, the paper aims to discuss a case for wave induced energy harvesting with a special focus on the concept of harvesting energy by exploiting wave-generated vortex-induced vibration (VIV) and, in particular, through structural vibrations.

The main result derived from this paper's research at this stage, is that the feasibility of the wave energy systems proposed here appears promising. The research at this initial level of analysis suggests it may be viable to capture energy from ocean waves with an added complementary VIV methodology. The results lay the groundwork for future quantitative investigations to substantiate these initial observations.

II. METHODS OF EXTRACTING ENERGY FROM WAVES - WEC

Gravity water waves are formed through the transfer of energy. In simpler terms, waves can be seen as a concentrated form of solar energy because they result from the sun's uneven heating of the Earth, which in turn creates wind, and this wind generates waves. It is the wave particle motions that can be studied as waves move and transmit energy, not water [5]. To capture this energy from the sea waves, it is necessary to intercept the waves with a structure that will react in an appropriate manner to the forces applied to it by the waves [6]. These structures are wave energy converters (WECs). Classifying WECs is complicated [7] as designs vary widely. One of the most popular classifications of wave energy devices is based on their basic working principle [8].

The classification used in this paper is demonstrated in Figure 1, which shows the main methods of extracting wave

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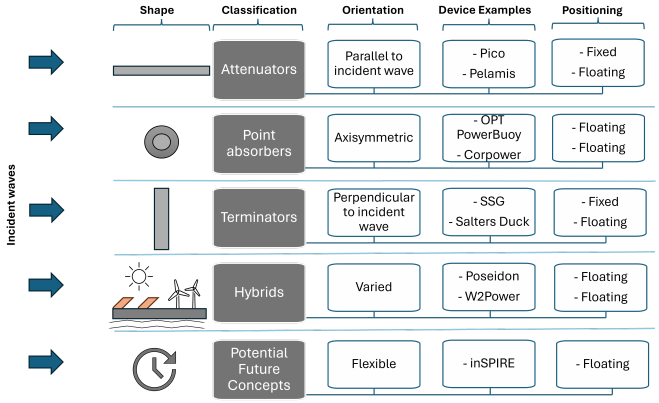


Fig. 1. A sample classification of WECs by orientation, geometry, and including examples of various WEC devices and their positioning

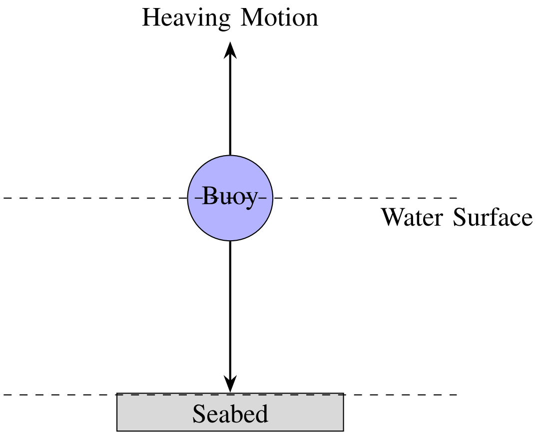


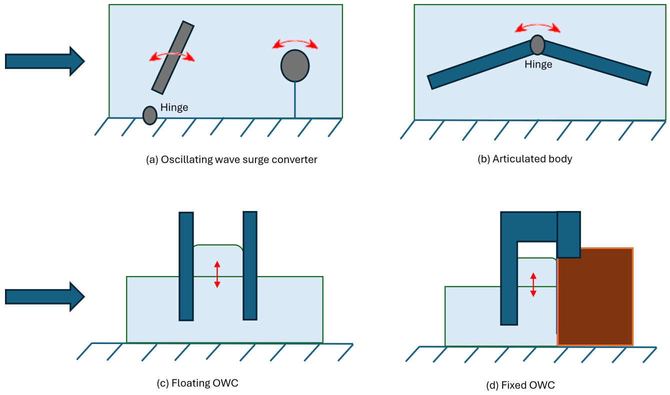
Fig. 2. A typical heaving (buoy) body system

Text

energy according to their orientation and geometry, together with some WEC examples.

The most popular forms of WECs are those which extract energy using heaving bodies such as the one demonstrated in Figure 2. These are current front-runners in recent research outputs and prototype development.

WECs come in many different forms. Figure 3 shows some alternative designs, such as oscillating wave surge converter (OWSC) and articulated body [7]. The other consideration is the oscillating water column (OWC) in fixed and floating positioning.



(a) Oscillating wave surge converter

(b) Articulated body

(c) Floating OWC

(d) Fixed OWC

Fig. 3. Oscillating body configurations

Point absorbers are the current top contenders for recent development [9], with the method producing many recent prototype patents. In contrast, OWC is considered the most commonly deployed form of wave technology, having been the most tested prototype at sea. An OWC can be considered a point absorber, depending on the design configuration. However, for the WEC design to effectively work with VIV, a pitch or surge type WEC is required.

A. *Possible future extraction methodologies*

Hybrids and flexible wave energy converters (FlexWECs) represent some of the latest innovations in WECs. Other methodologies suggested by Renzi [10] include devices for special applications such as desalination, island microgrids, aquaculture, and coastal protection.

FlexWECs have the potential to be scaled and utilized for utility power generation, whereas wave hybrids have the prospect of being part of the energy mix and making a significant contribution. An example of FlexWEC is the inSPIRE hybrid system with the deformable membrane still in the conceptual stage. Additionally, vibrational-based devices, such as the cyclorotor-based WEC concept, use cyclorotor hydrofoils that follow water particle circulation and have shown potential applicability for mechanical power [11].

Additionally, researchers have developed control algorithms that can adapt to changing wave conditions, for example, Corpower have recently unveiled the *wavespring* advanced control technology that allows the WEC to tune and de-tune to alter the systems response to wave conditions [12]. Overall reports show that efficient control of a WEC can increase its mechanical power output by 14 - 50% [13]. Besides control, advances in material science studies [14] have seen development in WECs durability in marine environments, and ultimately, this contributes to economic viability with reduced maintenance costs and increased potential lifespan of the WECs.

III. CRITERIA FOR A SUCCESSFUL WAVE ENERGY SYSTEM

The classical method of designing or deriving offshore systems begins by defining the desired features. For example, in ship design, see Rawson-Tupper or Misra [15], for offshore devices see EMCE [16], [17] and in project management see [18]. This means the first task would be to outline the criteria for a successful wave energy system.

Table I presents various criteria that could be used to define if a WEC system is successful.

IV. THE CASE FOR A WAVE AND OTHER ENERGY HARVESTING SYSTEM

The main compelling reason for an enhanced wave system is that wave energy systems may not be efficiently scaled up or down to provide commercial outputs. Additionally, there is a

TABLE I
CRITERIA FOR A SUCCESSFUL WEC SYSTEM

CRITERIA	DESCRIPTION
Basic Technology	Basic technological features are already established. Basic technologies have scope for enhancement. System has the potential to be integrated.
Commercialisation	Consider goals and deliverables expected by clients interested in WECs.
Scaling	The system can have the potential to scale up to fulfill commercial outputs or down and maintain its efficiency.
Lifecycle	Design, commission, operate, maintain, and decommission system safely.
Environmental Impact	Considerate and minimal environmental impact on marine life.
Actualisation	System can be viable within a specific time frame, e.g., 5 - 10 years.

TABLE II
EXAMPLES OF RENEWABLE ENERGY HYBRID SYSTEMS, (WAB - WAVE-ACTIVATED BODY TYPE), (OB - OSCILLATING BODY TYPE)

NAME	HYBRID COMBINATION	STAGE
Poseidon [20]	Wind and Wave (WAB)	Up to sea trials
W2Power [21]	Wind and Wave (OB)	Up to sea trials
Hybrid platform	Wind and Wave (OWC)	Early stage lab testing
Kita [22] [23]	Wind and Solar	Operational
Gorona [24]	Wind and Hydro	Operational
inSPIRE [25]	Multiple transducers	Conceptual

need to diversify the energy market by creating a more reliable energy mix. The National Renewable Energy Lab (NREL) published an online article questioning whether hybrid systems were truly the future of the grid [19]. The concluding remark suggested that new techniques and technologies must be employed to develop improved energy capture devices for wave, and indeed the trending methodologies being explored involve creating hybrid systems [3] or enhancing WECs using complementary methodologies.

There are many possibilities to devise enhanced wave-centered energy systems, one possible solution would be to incorporate two wave energy systems, however, other novel combinations can also be considered, such as WEC and solar panels on the decks of floating installations, WEC with wind energy using VAWTs or improvements can be made to some hybrid wave system such as the ones listed on table II.

Current studies show that few other devices incorporate resource systems, as indicated in Table II.

A. The case for extracting energy from wave-generated VIV

In this paper, vibration energy harvesting is being considered as a potential methodology to extract energy from waves. Vibration is usually seen as an undesirable feature during the design of WECs. In fact, Farez M'zhougi [26] used real measured experimental data for a machine-learning-based diagnosis in wave power plants and found that a certain turbine on an OWC WEC plant was reported to suffer from a resonance problem that caused an excess in vibration. The paper shows the outcome of collected data on vibration in turbines recorded for 24 hours, depicting a surpass in vibration levels with a conclusion suggesting these heavily impact the system's performance. Since resonance problems can be anticipated, it can be proposed that they can be designed into the system to positively utilise an unwanted phenomenon.

Fig. 4. (Left) The Tacoma bladeless Wind VIV device in operation in Spain ; (Right) The 2012 second open water testing for the VIVACE tidal device. Deployed in the St. Clair River, Port Huron, Michigan. [27] [31]

As far as research has dictated, there are only two small scale wind and tidal devices that are currently on the market utilising renewable resources as input to convert and harvest energy via vibrations. These two device systems utilise either wind-induced or marine currents-induced VIVs. For wind, the company Vortex Bladeless [27], have implemented a wind generation device based on VIV resonance and wind powered oscillations from a cylindrical mast that oscillates freely perpendicular to the wind direction, see Figure 4. Once the wind speed reaches a critical value, the VIV frequency matches the device's structural vibration frequency, which is exploited to harness energy. The phenomenon consisting in vortices detaching from the mast is called vortex shedding. The other device utilising VIV energy harvesting is a tidal energy device called the *VIVACE*. This tidal system was developed and patented by the University of Michigan [28] and exclusively licensed by Vortex Hydro Energy [29]. Similarly to the *Vortex Bladeless* wind device, the *VIVACE* does not use propellers, dams, or turbines. The water currents induce transverse motion that initially made them heave up and down, and these were found to be successful for slow flows such as rivers [30]. The deployments were publicized as seen in Figure 4, which shows the Vortex Tacoma pictured during operation in Spain (left) and the VIVACE tidal device being deployed in the St. Clair River Michigan (as slow as 3 knots flow speed) at its second installation open water test in 2012.

1) The Gap - Potential for wave: However, when it comes to harnessing wave energy, there are no known devices that apply this principle to waves, and this is expected since waves, in general, induce oscillatory, and not unilateral flows. Depending on the relative dimension of the wave with respect to the harvesting device, high Keulegan-Carpenter (K-C) numbers can be achieved, which lead to vortex shedding and potentially VIV: these conditions can be achieved by properly sizing the harvesting device.

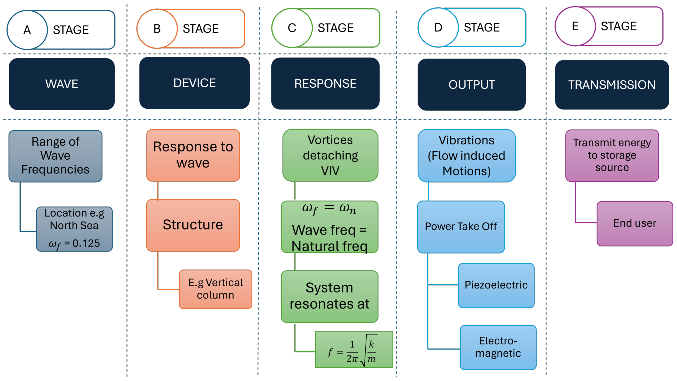


Fig. 5. The overall principle highlighting the lifespan development from stages A to E

B. Study - VIV Generation Concept

This potential concept for generating wave energy based on VIV and the basic stages involved will be outlined in Figure 5.

Stage A begins by selecting a location of the sea where waves have significant periods and frequencies in the range encountered by offshore devices and structures so that vibration can occur due to resonance effects. Stage B would channel the oscillatory waves, which need to be transformed into unilateral flow. This is the most critical stage of the concept. At this stage, it is required to design a structure or structural member that will respond to the wave excitation. A typical non-floating example can be a vertical cantilever mounted on the seabed, and vibration would be excited by waves with a significant natural frequency close to the natural frequency of the cantilever. The structures can be installed in the identified offshore location, and in practice, there can be as many vertical cantilevers as the amount of energy required. However, in the case of a floating device, this can be placed further offshore independently. Alternatively, it can be hybridized into a floating wind system by attaching the device to the floating wind mooring lines, which can also offer stability opportunities to the connected floating wind platform. Stage C would tune the response of the VIV detachments, and stage D would extract the energy from the vibrating structures, with a suitable power take-off system. Finally, stage E would transmit the energy to a storage source for the end users. The present paper focuses on Stage B by examining how best to achieve the unilateral flow.

1) Obtaining unilateral flow: The flow diagram of the working principle is described in Figure 5 shows the need to obtain a unilateral flow. This needs to be for a certain period to enable the flow time to develop vortices detaching from the structure. Although limited, the time needs to be sufficient so that the wave can be exploited for vibration. The problem is therefore illustrated as per Figure 6.

To obtain unilateral flow, the Keulegan–Carpenter number (Kc) needs to be tuned appropriately. Usually, vortex shedding is initially studied by numerical solutions of two-dimensional unsteady Navier-Stokes [32] and continuity equations along with the application of the Morrison's model on a uniform flow, as the Kc is related to the Navier-Stokes equation but not a direct derivation from the equations. Nonetheless, since assessments will be made numerically, the governing fluid behavior is by continuity equation 1, momentum equation 2, and energy equation 3.

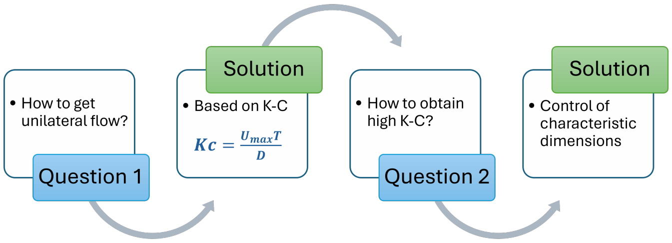


Fig. 6. The problem - A working principle

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial[\rho u_i u_j]}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i \tag{2}$$

$$\frac{\partial(\rho e)}{\partial t} + (\rho e + p)\frac{\partial u_i}{\partial x_i} = \frac{\partial(\tau_{ij} u_j)}{\partial x_i} + \rho f_i u_i + \frac{\partial(\dot{q}_i)}{\partial x_i} + r \tag{3}$$

Where ρ is (mass) density, u is flow velocity, p is pressure, t is time, τ is stress tensor and (i or j) are the sub-indices. Note, equation 1 may be used as an assumption that density changes are so negligible, and the derivative can be assumed to be $\frac{\partial \rho}{\partial t} = 0$. The equations are presented without manipulating complex equations, which allows multidimensional Cartesian quantities to be simplified in a compact manner. However, the sub-indice (i or j) is repeated in the same equation and can be summed across the n-dimensions [33]. For the three terms spacial Navier-Stokes, such as $1, 2, 3$ or x, y, z, the equation is a shorthand representation of: $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_1)}{\partial x_1} + \frac{\partial(\rho u_2)}{\partial x_2} + \frac{\partial(\rho u_3)}{\partial x_3} = 0$. Equation 2 is a superposition of 3 separable equations which could be written in a 3-line form: one line equation for each i in each of which one sums the three terms for the j sub-indice. Using the $\longrightarrow, \otimes, \nabla$ notation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \tag{4}$$

$$\frac{\partial(\rho \vec{u})}{\partial t} + \vec{\nabla} \cdot [\rho \overline{\overline{u \otimes u}}] = -\vec{\nabla} p + \vec{\nabla} \cdot \overline{\overline{\tau}} + \rho \vec{f} \tag{5}$$

$$\frac{\partial(\rho e)}{\partial t} + \vec{\nabla} \cdot ((\rho e + p)\vec{u}) = \vec{\nabla} \cdot (\overline{\overline{\tau}} \cdot \vec{u}) + \rho \vec{f} \vec{u} + \vec{\nabla} \cdot (\vec{q}) + r \tag{6}$$

Whereby the variables are as per equations 1, 2, 3 and ∇ is divergence with f gradient vector field of the function. For more comprehensive multivariable calculations on Navier-Stokes, see [34].

If the non-dimensional forms of these equations are defined, various non-dimensional numbers appear, such as Strouhal number (St) 11. The St number is significant in tuning the vortex shedding frequency at stage C of the development, as shown in Figure 5. However, as mentioned, the Kc number is empirical. It is not based on a complete derivation from the Navier-Stokes equation, but for a mathematical understanding of its formation, see Keulegan and Carpenters 1958's seminal work [35].

Regardless, Kc can be derived from looking into the characteristic scales and dividing the acceleration terms to have a ratio between the convective acceleration, equation 7, and local acceleration, equation 8.

$$\text{Convective Acceleration:} \quad \frac{\partial u}{\partial t} \tag{7}$$

The convective acceleration is the effect of acceleration of a flow with respect to space and is a feature of the Cauchy and hence continuum equation 1.

$$\text{Local Acceleration:} \quad u\frac{\partial u}{\partial x} \tag{8}$$

The ratio of the two yields the Kc number as represented in equation 10.

$$\text{Therefore:} \quad Kc = \frac{\frac{\partial u}{\partial t}}{u\frac{\partial u}{\partial x}} \tag{9}$$

Written in the direct form as

$$Kc = \frac{UT}{L} \tag{10}$$

where U is the characteristic flow velocity, T is the characteristic time scale, and L is the characteristic length scale.

2) Obtaining and tuning for high Kc number: Once the Kc is obtained, the flow can be exploited for vibrations via vortices detaching. Vincenc Strouhal observed vortex shedding and notably discovered that fluid flowing over a cylinder will shed vortices at a frequency proportional to the fluid velocity and the diameter of the cylinder. This is the shedding frequency as demonstrated by equation 11.

$$St = \frac{fst.D}{U} \tag{11}$$

Whereby St is the Strouhal number, f_{st} is the Strouhal frequency, D is the body diameter of the device, and U is the fluid velocity. The shedding response has been evidenced to show a specific formation behind a cylinder called the Von Karman Street [36]. This must be attained before vibration can be observed on the structure. It is these shedding formations that have a relationship with the Kc number, equation 12, since Kc is the ratio between inertia and drag forces in an oscillatory flow of period T and is widely used in ocean engineering to take into account viscous effects with a reference length of the structure (e.g. a cylinder diameter) [37].

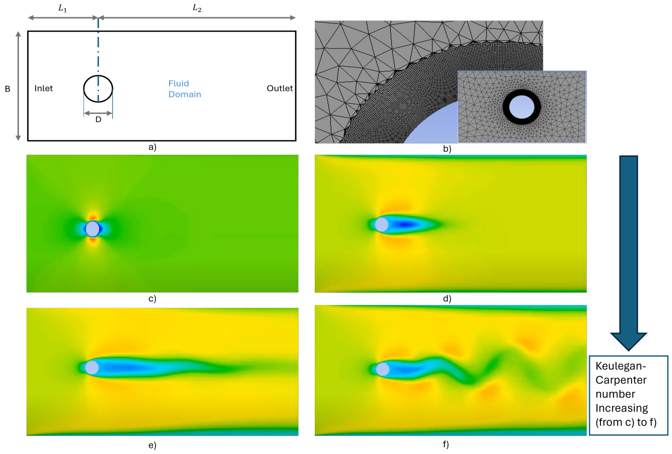


Fig. 7. Simulation - a) Fluid domain schematic, length and breadth varied as per simulation b)Meshing around cylinder c)Beginning of simulation (0s) d)Steady separation being observed e)Unsteady oscillating flow f)Separated flow with Von Karman street

Since the Kc number is significant in assessing vortex shedding phenomena and has been observed to increase as the vortices develop, to attain an appropriate Kc, a sensitivity study of the diameter of the structure is carried out from rearrangement of the Kc equation as per equation 12. This is done with the maximum flow velocity of the water particles U_{max} because for a resonant frequency of a given wave, the amplitude is maximal. Therefore the diameter of the structure is derived from

$$D = \frac{Umax.T}{Kc} \tag{12}$$

Equation 12 allows for the dimensions and characteristics of the structure's diameter to be controlled and to obtain a desired high Kc to enable vibrations. A high Kc number is required to cause unsteady separation of flow appropriately. Additionally, lock-in condition was discovered during vortex shedding [38]. It was demonstrated that under certain conditions, the vortices shed by a structure become ”locked on” to the structure and synchronize the oscillations [38]. The lock-in suggests that the shedding frequency and its force have a frequency close to the natural frequency of the system itself, possibly becoming coupled.

C. Preliminary Results - A summary

Initially, a fluid flow past a cylinder was computed for the structure to undergo vibrations. Computational Fluid Dynamics (CFD) provides a tool to analyze scenarios with detailed visuals of the patterns, as shown in Figure 7. Initially, simulations for a "fixed" cylinder with cross flow were reproduced on ANSYS and then adjusted to the desired specific case. Figure 7 presents the resulting simulation.

Result 1 - A stable vortex pattern was achieved as shown in Figure 7 c), d), e) and f), whereby an animation showed shedding of the vortices from the cylinder, eventually expected to achieve turbulence. The simulations showed that past the beginning where the flow is transient, the particles will begin to shed. The stages go from steady flow 7c), separated vortex 7d), unsteady vortex shedding 7e) and fully developed vortex shedding 7f). The simulation study presented

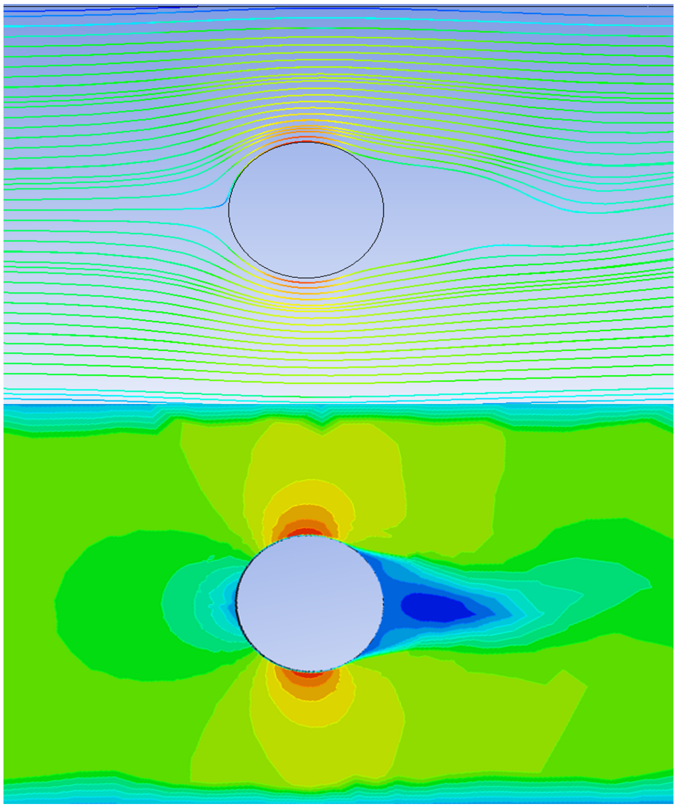


Fig. 8. Velocity streamline and corresponding flow in the simulation, at early steady separation stage (10s)

in Figure 7 was the first step to analyzing fluid behavior for the structure to vibrate.

Result 2 - Separation started to be observed from the highest velocities, followed by an adverse pressure gradient and insufficient momentum. This can be seen in Figure 8, whereby the streamline highlights the velocities. Additionally, as expected, lifting coefficient C_L, was seen to start at zero as there is no lift to begin with, and then proceeded to fluctuate.

Result 3 - From a modification on the fixed cylinder, a frequency of force exciting the device is noted and utilised to add a motion. This is done by the equation of motion 13 for a WEC in the frequency domain expressed as

$$m\ddot{\eta} + c\dot{\eta} + k\eta = F(\omega) \tag{13}$$

Where m, c, and k are the coefficients of the mass, damping, and stiffness, and F is the external force in the frequency. This allows for the system to mimic the structure (device) movements. To visualize the differences in the fluid behavior experienced, the fluid domain is specifically adjusted in various simulations with L_1, L_2, and B being varied as per schematic a) on Figure 7. However, changes to flow velocity are seen as change patterns in the vortices. A more in-depth analysis is required to study this next step.

Result 4 - It was noted from simulations that the further upstream separation occurs, the more drag the cylinder experiences. Thus, this satisfies the VIV theory stating that a high Kc number allows water particles to travel a relatively large part relevant to the structure's diameter. As evidenced, high Kc equals higher vortex shedding with oscillations of fluid around the structure shedding enough to create vortices, and if the Kc keeps increasing, then even larger vortices shed with increased contribution from viscous drag to the total force felt by the body. This is then resulting in vibrations.

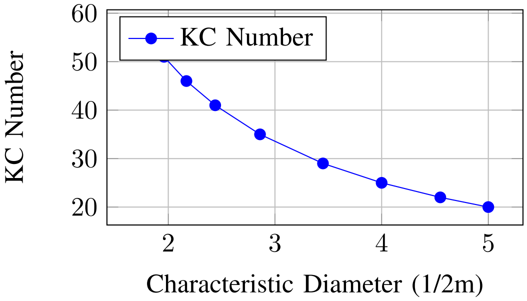


Fig. 9. Relationship between KC Number (dimensionless) and Characteristic Diameter (Length)

The study to obtain a high Kc also focused on geometry and determining the most effective device dimensions to secure unilateral flow from the waves long enough for a given typical North Sea wave. The main result is summarised and presented in Figure 9.

The diameter, which is the relative dimension of the structure with respect to the dimension of the wave, was varied up to 0.5 m, as shown in Figure 9. The Kc number was seen to increase as the characteristic diameter decreased. The shape is cylindrical to achieve an omni-directional device that is capable to vibrate from any direction it is induced. Additionally, the study shows that making the dimensions small enough that even if the wave period is not very long, will still create a unilateral flow from the wave. This is suggestive that a smaller scale device is more suited to maximising VIV in the system.

Regardless, the flow has to have a sufficiently long period (T) to create a unilateral flow for adequate time for vortices and vibrations to develop. Hence a study is required to find a limited encompassing period where this will happen for a specific location.

V. DISCUSSION

A. Future areas for research and challenges associated with practical implementation

The existing systems for extracting wave energy can be enhanced by improving their efficiencies and increasing the number of units, however, there are limits to what can be achieved, and the following areas require research:

a) In the case of wave and other renewable energy systems, the portion of wave energy contribution is not negligible, given the global power demands. A focus on wave centered systems is on the rise. As well as the more popular wind and wave hybrids, exploration is needed for other possibilities, whereby research should focus in particular on both the feasibility and viability of such a concept.

b) On the case of a VIV-WEC: The topics of Wave Energy Harvesting and Vibration Energy harvesting are both well established and extensively researched within their respective disciplines. However, the combination of renewable energy and vibration can be said to be of emerging interest demonstrated with expertise from companies such as VIVACE and Vortex Bladeless, who are combining VIV with tidal and wind energies. As for combining wave energy and vibration, this is a completely new area of interest. Relevant to work done in this paper regarding a potential VIV-WEC system, research can look to develop a mini device induced by waves to create vibration capabilities, and studies combining all desired movements in one model and effectively managing the resulting non-linearity feedback will be fundamental for the scope of work. This will be significant after the system is proved to be able to resonate creating flow induced movements, as linear resonance will occur, then non-linearity will pick up and the motion of cylinder will start to change the frequency of vortex generation. The primary challenge for practical implementation revolves around wave theories, which dictate that the input wave must be unilateral. This ties back to the device dimension requirement to be small scale. However, research has shown that these are clear commonalities of VIV device design.

c) On the case of utilising methodologies to enhance a WEC system: Integration offers several advantages, such as efficient resource utilisation and enhanced reliability. However, it also highlights potential concerns regarding systems capable to harness together in a complementary manner. It is a challenge when two or more systems are required to cooperate or integrate because each system may be individually designed to deliver as best outputs as possible based on most suitable hardware and software. The integration process seeks compatibility which often cannot be achieved cost effectively. For future effective practical implementation, research is therefore imperative for combined systems with little or no operational experience.

VI. CONCLUDING REMARKS

The potential contribution of wave energy to offshore renewable energy is extensive and is based on the principles of using water motions and responses of operating structures in waves. However, research is needed to ensure that the outputs can be extracted in sufficient quantity that can aid towards meeting society's demand. The study has shown that solutions based on renewable energy resources and VIV have been incepted recently, but there are no similar designs for wave energy yet. For wave energy to contribute similarly, considerations need to be given to enhancing the WEC arrangements with connection to other energy generation concepts.

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