

# Concept of Energy Extraction from Sea Waves Using Flapping Foils Operating as Biomimetic System

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## ABSTRACT

Oscillating hydrofoils in presence of waves under the free surface as new systems for energy extraction is a hybrid renewable marine energy sources. In this system energy extraction is associated with oscillating hydrofoils operating as biomimetic systems in harmonic waves and currents in coastal regions using active pitch control. Another way of energy exploiting is used by installation of foils under the hull of the ships. Flapping foils located beneath the hull of the ship are investigated as unsteady thrusters, augmenting ship propulsion in rough seas and offering dynamic stabilization. In this system the foil undergoes a combined oscillatory motion in the presence of waves. For the system in the horizontal arrangement, the vertical heaving motion of the hydrofoil is induced by the motion of the ship in waves. The survey shows that exploiting of energy from sea using these techniques can be proposed for Iranian hybrid ships for their propulsion as secondary source of energy. Particularly North part of Persian Gulf has a proper situation for installation and operation as marine energy device in coastal regions.

## 1. Introduction

Rising energy bills and intensifying pressure to reduce CO<sub>2</sub> emission have caused increasing demand for alternative energy sources for many sectors including marine propulsion. The ocean waves have long been considered as a substantial source of energy for marine propulsion. However, utilization of wave energy has not been studied extensively because of the complexity of nonlinear oscillatory hydrodynamics. Several experiments have been performed to examine the possibility of utilizing the energy from ocean waves for marine propulsion. In their concept, one or two hydrofoils were fixed to the ship through a spring system, in a manner that the angle of the hydrofoils could be adjusted as the direction of incoming water is changed. In the meantime, the ship and the hydrofoils are heaving and pitching with incoming waves and produce forward thrust on the hydrofoil. The corresponding problem with the moving foil oscillating in an unbounded fluid has been studied for several decades. Swimming of slender fish has been treated by Lighthill [1], and the waving motion of a two-dimensional flexible plate has been calculated. Later, based on the potential flow approach (the perturbation potential is governed by Laplace's equation) [2, 3], a series of researches was performed

to optimize the oscillating motion and shape parameters for two-dimensional flat plates. Furthermore, several theories of an oscillating foil have been developed. Bose has developed a time-domain panel method for analysis of an oscillating foil in unsteady motion [2]. Kubota et al. and Kudo et al. [4] developed two dimensional linear and nonlinear theories which can estimate propulsive performance of partly flexible as well as rigid oscillating propulsors. They also showed that an aft-half elastic foil reveals 8% higher efficiency than a rigid foil [4].

## 2. History and concept

Understanding the interaction of water waves with varying currents in near shore and coastal areas is important for a variety of engineering applications, including interaction of waves with structures, coastal management and harbor maintenance, as well as design and development of systems for exploitation of marine renewable energy resources. In particular, the effects of inhomogeneous currents on wave transformation in the near shore and coastal environment are significant, since they are responsible for Doppler shifting and additional wave refraction, reflection, and breaking, completely changing the wave energy pattern. In particular, the characteristics of surface waves present significant variation as they

propagate through non-homogeneous ambient currents, in the presence of depth in homogeneities in variable bathymetry regions. Thus, large amplitude waves can be produced when obliquely propagating waves interact with opposing currents. This phenomenon could be further enhanced by inshore effects due to sloping sea beds, and has been reported to be connected with the appearance of giant waves. Extensive analyses concerning the subject of wave-current interaction in the near shore region have been presented by various authors. Recent information can also be found in the corresponding sections of reviewing articles.

Extensive research has been performed in the area of flapping wing aerodynamics and also hydrodynamics. In order to absorb the energy the basic understanding of subject matter, the simple case of rigid hydrofoil / aerofoil in two dimension must be investigate. The vertical structure formed behind these moving foils have a strong link between the motion and the thrust or generated drag. Advanced level of investigation lead to high propulsion efficiency.

Plenty of researches shown that biomimetic systems inspired by hydrobionts not only could produce high thrust but also has a high degree of efficiency. For instance, Bose and Lien [5] estimated that the maximum hydro mechanical efficiency of a whale is about 85%. Furthermore, Triantafyllou, Triantafyllou and Gopalkrishnan [6] and Triantafyllou, Triantafyllou and Grosenbaugh [7] shown that optimal propulsive efficiency occurs at non-dimensional frequencies corresponding to the maximum growth of the jet flow behind the foil.

High efficiency is not the only advantage of a flapping-foil biomimetic system. As Gursul and Ho [8] mentioned, unsteady vortex control creates very high lift coefficients for maneuvering. Additional work on underwater vehicle propulsion and maneuvering has been performed by Bandyopadhyay et al. [9] and Kato [10]. Experimental evidence by Read et al. [11] and Scouveiler et al. [12] also, demonstrates that when flapping foils perform undergoing nonsymmetrical flapping, extraordinary maneuvering capacity occurs. Finally, the three dimensionality of flapping wings and fins has also been studied experimentally by Hart et al. [13], Dickinson et al. [14], and Drucker and Lauder [15].

On the other hand, evolution of air and sea creatures, through million years of natural selection/optimization, arrived to the flapping wing as their single propulsion system. The main difference between a biomimetic (flapping wing) propulsor and a conventional propeller is that the former absorbs energy by two independent motions, the heaving and the pitching motion, while for the propeller there is only rotational power feeding.

Yamaguchi and [16] Bose extended the work of Kubota et al. and Kudo et al. [4] to design rigid and aft-half elastic oscillating foils for a large-scale ship. Their results showed that both oscillating foils can give higher propulsive efficiency than an optimal screw propeller, and the elastic foil gives 5–7 % higher propulsive efficiency than the screw propeller. Early hydrodynamics models were restricted to potential flow assumption [3]. But with the advancement of computers, more sophisticated numerical models have been introduced to analyze the performance of an oscillating foil [2]. Pedro et al. and Guglielmini and Blondeaux [17] have investigated the performance of a low Reynolds number oscillating foil based on a computational fluid dynamics (CFD) approach and promising results have been reported. Other studies (Lai et al. [18], Anderson et al. [19] and Triantafyllou, Triantafyllou and Gopalkrishnan [6]) have addressed the thrust producing capability of an oscillating hydrofoil by experimental work. They have shown that the potential efficiency of the oscillation hydrofoil propulsor can compete with that of a conventional rotating propeller. However, an oscillating hydrofoil has not been considered as a practical replacement because of the mechanical complexity even with the improvement of efficiency up to some extent. Because of that, some of them extended their studies on oscillating foils to consider propulsion by using wave energy as described in the following paragraphs. For the first time in history Wu introduced the theory for extracting energy from surrounding flows by a two-dimensional hydrofoil oscillating through gravity waves in water. According to his theory, it has been found that the energy extraction is impossible if the flow is uniform and only feasible when the primary flow contains a wave component which has vertical velocity normal to the mean free stream and the wing span. Finally, he was able to obtain the best mode of heave and pitching for extraction of wave energy by passive type wave devouring propulsor. Later, Isshiki [20] employed Wu's theory of an oscillating hydrofoil and extended it by introducing a free surface effect for investigating the possibility of wave devouring propulsion by a passive type oscillating hydrofoil. Further, not only theoretically, but also experimentally, Isshiki and Murakami [21] studied the basic concept of passive type wave devouring capability of an oscillating hydrofoil. In addition, to illustrate the unsteady foil motions and wave devouring capabilities, Grue et al. [22] developed a theory for a two-dimensional flat plate near the free surface using a frequency-domain integral equation approach. The theory in both head and following waves was in good agreement with the experiment conducted by Isshiki and Murakami; however, with lower wave numbers there were systematic discrepancies between the theory and the

experimental results as nonlinear effects and free surface effects were not fully accounted for in the theory. Despite these inviting results by several independent studies, a significant commercial success is yet to be seen. The drawbacks of the concept have added resistance in calm seas as well as mechanical complexity. Although the oscillating foil propulsor is mechanically complex, if the gain by recovering the wave energy is considerable, it may be more attractive

than the conventional screw propeller. In the present study, therefore, we propose a new concept of wave energy recovering through a powered oscillating foil propulsor, which is designed to replace the conventional screw propeller "Figure 1". The objectives are to develop a numerical model which can predict the oscillating foil performance in a wave field and to elucidate the physical mechanisms.

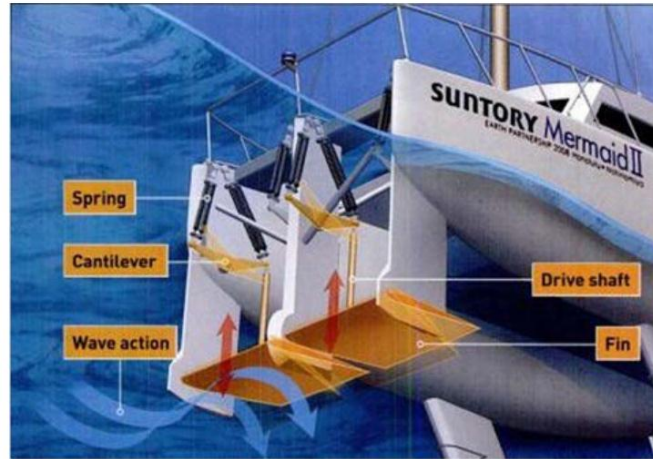


Figure 1: The Suntory Mermaid II which sailed from Hawaii to Japan in 2008 (Popular Science, 2008) [23]

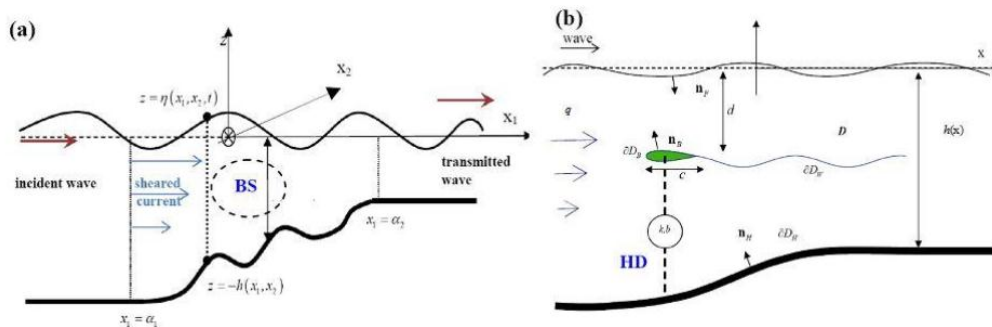


Figure 2: a) Interaction of waves with vertically sheared currents over variable seabed topography. b) Flapping hydrofoil biomimetic system (BS) operating as energy device in waves and sheared currents.

### 3. Motion of flapping foils

The flapping motion of large aspect ratio wings with two-dimensional foils in harmonic pitch and heave motion has been studied intensively in response to the demand for faster and simpler simulation. The NACA0012 hydrofoil is the benchmark model. Others have used conformal mapping Joukowski or elliptical foils. Moreover, more complex unsteady motions are studied, starting with simple forward and heaving motion or forward and pitching motion and finally flapping motion. The latter consists of forward, heaving and pitching motion

### 4. Pure heave motion

A Combination of reduced frequency and normalized heave amplitude has been found to be a good parameter to predict the drag-thrust wake pattern. Heave amplitude is normally defined divide by chord length. Lai and Platzer find that a drag-producing wake behind a pure heaving NACA0012 foils changes to a thrust-producing jet as soon as ratio of maximum heave velocity to free stream speed or the non-dimensional heave velocity "Figure 4(a)".

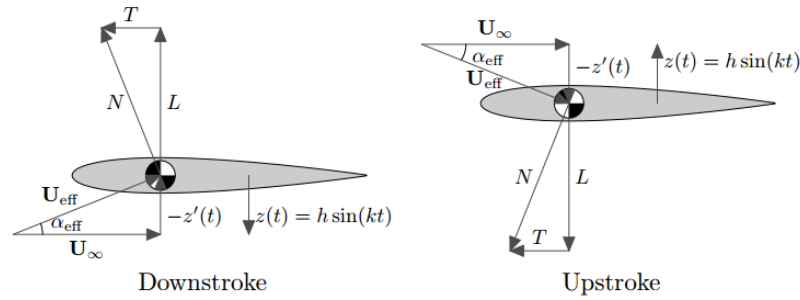


Figure 3: Explanation of thrust generation by pure heave motion

### 5. Pure pitch motion

pure pitch motion is the only case where thrust is generated when there is no forward velocity. A strong influence on the corresponding wake patterns of the amplitude, frequency and the shape of oscillation waveform was also identified. The reduced frequency for vortex roll-up is found to decrease as the oscillation amplitude increases "Figures 3 and 4(b)".

### 6. Combined heave and pitch

The case of combined heave and pitch is often found in flapping wing propulsion in nature. The flapping motion to be a better strategy than the pure heave and pitching alone as it is more efficient and higher thrust can be generated [24]. The complexity of coupling the two motions, heaving and pitching, means that two more parameters are needed to add to the current set. They are the additional amplitude and phase angle between heave and pitch "Figure 4(c)".

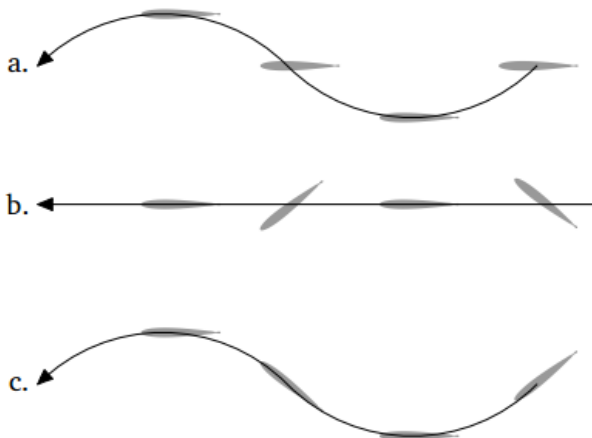


Figure4:a) Pure heaving and forward motion b) Pure pitching and forward motion c) Combined heaving and pitching and forward motion

### 7. Results and Discussion

The current flow is assumed to vary very slowly as it is in the case of tidal and low frequency environmental flows, so that it may be considered steady at the scale of wave evolution. The current is

characterized by a vertical variation will be stronger than the horizontal one, so that the vorticity associated with the background flow is essentially horizontal like the current itself. The current flow velocity is small and thus, the associated mean free-surface elevation (set-down) is also small. The wave flow perturbing the background current flow, is generated by an incident wave system coming from the far up-wave region. One of the application of flapping hydrofoil biomimetic system is extraction of energy from sea in harmonic waves and current in coastal regions using pitch control [25]. Interaction of waves with vertically sheared currents over variable seabed topography. One of the most important factor is geometry of coastal regions because of interaction of wave and seabed. This specification of geometry of sea is related of north part of Persian gulf where along of coast depth of water has a proper situation "Figure 2".

### 8. Conclusions

Oscillating hydrofoils in waves and currents are investigated as novel biomimetic systems for extraction and exploitation of this kind of marine renewable energy. The effects of the wavy free surface through the satisfaction of the corresponding boundary conditions, as well as the velocity component due to waves and vertically sheared currents on the formation of the incident flow were investigated. After validation, it could be found that it is useful for the design and optimum control of such biomimetic systems operating in the near shore/coastal region and extracting energy from waves and ambient currents.

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