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Marine current power with Cross-stream Active Mooring: Part I

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ABSTRACT

This is the first of three papers that propose and study a new concept of mooring turbine generators with the aim of resolving key difficulties in realizing ocean current power generation. The concept of Cross-stream Active Mooring (CSAM) features a hydro sail system that allows deployment of generator turbines, from anchoring points on shore or on shallow seafloors, across current stream to access current core flowing over deep seas or over seabed not suitable for anchoring construction. The CSAM can increase system power capacity by changing horizontal positions of generator turbines to track meandering current core, and can also change system depth to avoid storms. New anchoring designs of improved efficiency and implementation methods for resolving seafloor geological issues in the Kuroshio off southeast Taiwan are also included. This first paper presents the basic concept, basic analytical model and prediction of key performance parameters, conceptual designs of the hydro sail and multiple-unit linear array, and potential benefits of the proposed system. The second paper discusses construction of the tethers, mooring of power cables and 2D formation designs. The third paper discusses anchoring designs and constructions, large scale deployment, failure mode designs and system costs.

1. Introduction

The fluid kinetic power density is proportional to the cube of the flow speed [1].

$$p = \rho V^3 / 2 \quad (1)$$

Of the two largest ocean current systems that flow by industrialized and energy needing countries, flow speed in the Kuroshio and the Gulf Stream can be over 1–2 m/s [2,3]. This is slow compared to wind speed in commercial wind farms, which typically has a mean speed of over 5.5 m/s at 30 m height, for example, according to German Renewable Energy Sources Act (see section 3.6 of [4]). However, water is about 800 times denser than air. As a result, the power density of a 1 m/s water flow is equivalent to wind at a speed of 9.3 m/s. This illustrates the potential of ocean current power generation. The cross-sectional power of the Kuroshio off Taiwan fluctuates between 4 and 10 GW with an annual mean around 6 GW [2] and that of the Gulf Stream varies between 5 and 25 GW with an annual mean of about 12 GW [5]. Another advantage of ocean current energy is that ocean currents are much more stable compared to winds and hence system capacity factor can potentially be much higher than wind power.

Despite the great potential of ocean current power generation, there are many difficulties in realizing a practical and cost-effective system. One major issue is the potentially high cost involved in marine construction, especially in deep seas. The velocity cores of major ocean currents generally flow close to sea surface, as shown in the example of Kuroshio in Fig. 1. Assuming a flow speed of 104 cm/s and above defines the core, the velocity core locates near 121°30′ E and has a depth of about 40 m and a width of about 5–7.5 km. Therefore, turbines should be placed within 50 m below water surface in order to make maximal use of the kinetic energy. However, the waters under the velocity cores are mostly quite deep. Fig. 2 shows the topography of seafloors southeast off Taiwan, the Taitung – Green Island area, where a major ocean current's velocity core flows closer to shore than any other places in Japan or in Florida, superimposed with averaged tracks of the Kuroshio. Most areas the velocity core flows over are deeper than 1000 m, some as deep as 3000 m. The undersea terrain reaches such depth within a few kilometers from shore in very steep drops. Only at the undersea ridges to the north of Green Island can seafloors less than 400 m deep be found. This area has been identified as ideal locations for possible sites for Kuroshio power generation [8,9,34]. However, experiences from offshore wind power development put an economic limit on the depth of fixed foundations to about 50–100 m

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Depth (m)							121°30' E										121°45' E										122° E
-20	###	100	100	100	100	103	108	108	104	104	95	95	98	98	98	89	89	76	76	76	81	81	76	76	63	63	63	51
-40	###	78	78	78	86	89	98	108	104	104	95	95	95	98	98	89	89	85	76	76	76	67	67	63	63	63	63	63
-60	###	###	64	64	72	81	89	98	95	95	95	85	85	89	89	89	76	76	76	76	67	67	67	67	67	63	63	63
-80	###	###	50	50	58	67	85	95	95	95	85	85	85	89	81	81	76	67	67	67	67	63	63	54	54	54	54	54
-100	###	###	36	36	45	54	76	85	85	85	85	89	81	81	72	67	67	63	63	63	63	63	63	54	54	54	54	54
-120	###	###	14	14	22	45	54	76	76	81	81	81	72	72	67	58	58	54	54	54	54	63	63	63	54	54	54	54
-140	###	###	###	0	14	32	45	58	67	67	67	67	67	67	54	45	45	45	45	45	54	54	51	51	51	54	54	54
-160	###	###	###	0	10	22	36	50	58	58	72	72	67	54	51	41	41	51	41	41	41	54	51	51	51	51	41	41
-180	###	###	###	###	0	0	14	28	36	45	45	54	54	45	41	41	40	40	40	41	41	41	41	41	41	41	41	41
-200	###	###	###	###	0	0	0	14	22	36	36	45	36	32	32	32	40	40	41	41	41	41	32	32	30	40	40	40

Flow speed (cm/s): 0 40 60 80 100

Fig. 1. Averaged Kuroshio current speed at different depths on the cross sectional plane of latitude 23° N, produced from zonal current velocity (U-V) data from 1991 to 2009 in charts published by the National Center for Ocean Research (NCOR) [6]. Horizontal distance between two adjacent grid points is about 2.5 km.

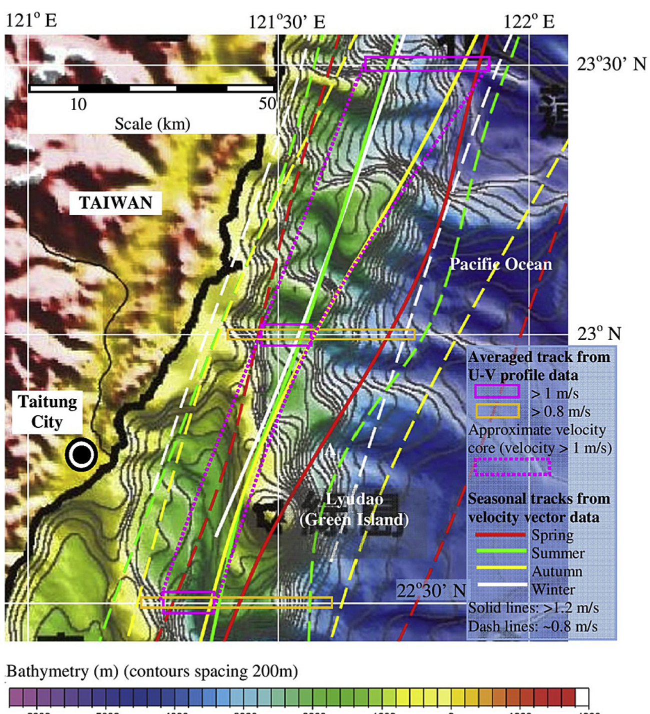

Fig. 2. Averaged tracks of the Kuroshio at 30 m depth over topographic map off southeast Taiwan. Averaged tracks from U-V profile data were approximation based on zonal composite current velocity profile diagrams at the indicated 3 different latitudes published by the NCOR [6]. The diagrams were marked as "all" time and "made 2009.04". Tracks from velocity vector data, showing seasonal variations, were consolidated from composite flow velocity vector diagrams from 1991 to 2008, also published by the NCOR. The topographic map is a cut out from a digital map also published by the NCOR.

[7]. This may be used as a guideline for marine current power as well. Accordingly, moored floating systems will have to be used. However, these ridges are likely of hard andesite and have almost no sediments on their top surfaces [8]. As a result, embedment anchors are not likely to be applicable and piling at this depth will be very expensive.

Anchoring difficulties aside, the comparatively shallow hill tops in the undersea ridges have limited areas. This limited footprint cannot moor the large number of turbines needed for a mass scale power system if traditional distributed, downstream-type mooring methods are used.

In the case of the Florida Current, the seafloor in the Florida Straits gradually inclines from shore to over 500 m deep under the velocity core of the current at a distance of about 30 km from the shore. Fig. 3 shows the topography of the Florida Straits superimposed with approximate tracks of the Florida Current. The terrain is relatively flat, except for the area of Miami terrace in the southern part, and many areas are covered with mud, sand or sediments [10]. However, anchoring in this area may face a different problem: deep sea coral. Biological studies have found wide presence of coral on the seafloor of the Florida Straits [11]. It turns out that when this benthic information is combined with geological data, areas suitable for anchoring become quite limited, as suggested by maps in Ref. [10]. Fig. 3 consolidates the results of siting study reported in Ref. [10] with deep reef information from Ref. [11] and tracks of the Florida Current in one map. It can be seen that the fast core (averaged current velocity >1.8 m/s) at depth of 50 m actually flows outside of the few areas identified as suitable for anchoring. The significance of placing the turbines in the speed range of >1.8 m/s rather than 1.6 m/s is a power capacity increase by at least 42%, referring to numbers in Table 1.

Another issue that can impact the efficiency of an ocean current power system is the variation of the track of an ocean current. This "meandering" of ocean currents has been a research subject in the community of oceanography, for examples, referring to Refs. [12,13,15–19]. Analysis of satellite altimetry shows that, between 22° and 23°N, the central position of the Kuroshio surface current locates around 122°09′ to 122°18′E and deviates with a standard deviation of 0.2–0.25°, or about 20–25 km, at various periods with the most significant around 60 and 180 days [19]. This positional variation, apparently coupled with seasonal transport fluctuation, affects the meandering of the velocity core to the west. As shown in Fig. 2, along 23° N, the averaged current axis (flow speed > 1.2 m/sec) deviates about 3 km from summer to winter, with the shortest distance to shore of about 21 km. In spring, the axis deviates outward from land by about 16 km. The averaged 0.8 m/s flow speed boundary also deviates by about the same amounts. In the Florida Current, ocean model simulation suggested a seasonal deviation of the current velocity core of about 10 km at 50 m depth near 27°N, as indicated in Fig. 4. This is consistent with measurement results from Ref. [13]. Considering that power capture is proportional to the cube of flow speed, the ability to accommodate current meandering can increase system capacity factor significantly.

Still another issue, also associated with geographical locations, is that typhoons or hurricanes occur frequently in those waters. A power system must also resist any potential damage by rough sea conditions caused by typhoons.

Various ocean current power system concepts and designs have been proposed or discussed by commercial companies as well as in academic researches. In the 1970's, a project called the Coriolis Program, with power turbine concept featuring a special catenary rotor in a large diffuser duct anchored at three points on seafloor,