A Pilot Project on Ocean Energy Generation by Tidal Currents on the Northern Coast of Taiwan

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***Abstract*-Keelung Sill is a seamount-like formation, located between the Keelung Harbor and Keelung Island on the northern coast of Taiwan. Due to its shallow depth, the sill constricts the waterway and accelerates tidal currents. It was preliminarily identified that the tidal current speed is as large as 5 knots in some tidal periods. A project was approved to assess the actual capability of the tidal current energy and to develop a 3kW marine current turbine prototype. This project, starting from December 2009, is a part of the National Science and Technology Program. In 2010, a prototype turbine will be designed and tested in a large cavitation tunnel. In addition to the turbine development, assessments of tidal current power by in-situ measurements, satellite images, and numerical model simulation will be carried out. These assessments will also help us to determine suitable sites for the 2011 field test. Long term typhoon wind and wave data will also be collected to study the extreme forces acting on the planned structure. This is a fundamental project on the research and development of tidal current energy generation in Taiwan. The results of this project may provide the government a base for its future energy policy on the development of the tidal current energy generation.**

I. Introduction

People believe that the burning of fossil fuels (coal, oil and gas) is causing our climate to change dramatically. Clean, renewable forms of energy are essential if we are going to undertake the mitigation of climate change. In the recent decade, significant developments have taken place within the field of ocean renewable energy, including the energy converted from ocean waves, tide difference, tidal or ocean currents, ocean temperature difference and wind energy at the coastal ocean. In addition to the installation of land-based wind turbines, several offshore wind farms have been in operation recently in the European countries such as Denmark, United Kingdom (UK) and the Netherlands. They can be found at this homepage [1]. Most of them are situated in shallow waters, having a water depth of less than 20 meters and are relatively close to shore (< 10km). Wave power devices extract energy directly from the surface motion of ocean waves or from pressure fluctuations below the surface. Some wave energy converters have been raised to an industrial level and installed at sea and produce electrical energy, such as the Pelamis device [2]. The first full scale prototype was successfully installed and generated electricity at the European Marine Energy Centre (EMEC) in UK in 2004. The wave farm consisting of three Pelamis that located off the coast of Portugal was officially opened in Sept. 2008 but closed two months later because of water leakage [3]. More and more places where full scale or intermediately sized wave energy converters can be tested in the real sea states have been specially developed during the past years. The full scale experimental facilities allow for a better understanding of the wave energy device's response and energy conversion and production. In addition to Pelamis, the Wave Dragon overtopping device for wave energy extraction has been tested in the Danish inlet since 2003 [4] and [5], the Wave Hub off the northwestern coast of Cornwall in the UK, the SEM-REV under development in South Brittany in France [6] and the Portuguese Pilot Zone in the west coast of Portugal [7]. There has been a rapid rise in worldwide interest in the use of tidal currents for electricity generation although there are still only a limited number of actual installations. Periodic changes of water levels, and their associated tidal currents, are due to the gravitational attraction by the Sun and Moon. Tidal motions are more predictable than the wind flow. At present, the largest commercial, grid connected tidal current power generation machine is the twin rotor horizontal axis tidal turbines system, installed by Marine Current Turbines in 2008 at Strangford Lough, Northern Ireland (UK), The system has a rated power of 1.2MW [8]. Open-Hydro installed a 6m diameter driven rim ducted machine which was connected to the electrical supply grid in 2008 at the EMEC. In 2009, a 1MW commercial tidal current turbine was deployed in the Bay of Funny in Canada [9]. Although there are still many challenges for marine energy technology, the ocean energy community did have some developments in the past few decades and started to be commercialized.

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With limited indigenous energy resources, developing independent renewable energy resources in the island of Taiwan is thus of priority concern for the government [10]. Taiwan is surrounded by the Pacific Ocean. It has enormous potential to develop ocean renewable energy. The development of sustainable energy in Taiwan started in the 1980s, and now some wind turbines are in operation along the coast and on the offshore island. The government has also been examining the possibility of drawing on ocean energy recently. The Bureau of Energy (BOE) under the Ministry of Economic Affairs is now working to increase the capacity of renewable energy up to more than 10% of the island's energy capacity by 2025. Taiwan is one of the favorable places for Ocean Thermal Energy Conversation (OTEC) development. It was estimated that the sea off Taiwan's east coast presents the right conditions to produce thermal power that could be converted to generate 600 GW to 900 GW of electricity, enough to cover 2% of the island's annual power needs [10]. Beginning off Taiwan's east coast and flowing northeast toward Japan, the Kuroshio is the world's second-largest warm current after the Gulf Stream in the Atlantic Ocean. It was estimated that the Kuroshio could be an enormous source of energy that could be converted to generate power in the GW range. In addition to the power generation by ocean current, there are some areas with strong tidal current in the Taiwan Sea, such as at Penghu waterway and Keelung Sill. Therefore the National Science Technology Project (NSTP) is funded to do further studies on the development of ocean energy extracted from tidal currents starting from 2010. It is the purpose of this article to present the framework of the project and some preliminary results.

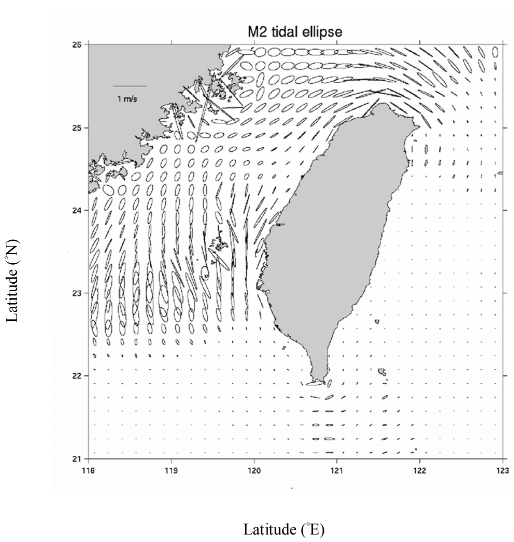

Fig. 1 Tidal current simulation (M_2) in the sea near Taiwan

2 Study area

Taiwan is in the tropical to sub-tropical western Pacific. At east of Taiwan, where the shelf is narrow and the water is deep (> 5000m). West of Taiwan is the Taiwan Strait, which has a mean depth of 60m. The current that affects Taiwan most is the Kuroshio which passes by Taiwan's east coast. The tidal currents are a result of the rise and fall of the water level due to the tides. Shown in Fig. 1 are the M_2 tidal ellipses for the sea surrounding Taiwan. It can be seen that at the northern offshore of Taiwan, the M_2 tides are comparatively large, although diurnal tides here are also significant. The coastal water between the Keelung Harbor and Keelung Island (Fig. 2) is particularly of interests, since behind the island there is an underwater seamount-like formation, called Keelung Sill. The water depth at the location surrounding the sill is about 60m, and the depth of the sill ranged from 5m to 40m (Fig.2). The tidal current speed at the coastal water of northern Taiwan is around 1-3 knots (0.5~1.5 m/s). But when the tidal current approaches the Keelung Sill, it can go up to more than 5 knots, due to the contraction of the flowing section. This makes the area on Keelung Sill a potential site for tidal current energy studies. Keelung Island is merely 3.5 km north of the Keelung coast.

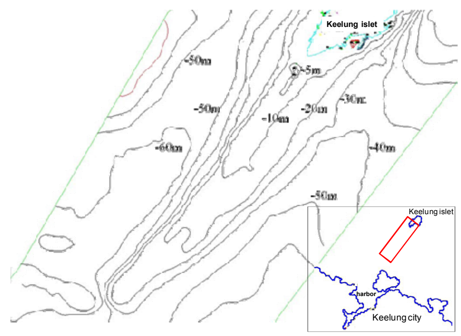

Fig. 2 Location and topography of the water on Keelung Sill

3 Framework of the proposed project

The present study consists of 5 inter-related projects, including numerical simulation of tidal current, in-situ current measurement, tidal current assessment using satellite remote sensing, turbine blade design and assemblage of the power generator, and assessment of natural forces on the generator structure by typhoon wind and waves. Figure 3 is a simple diagram of our working projects and Fig. 4 provides a view of the Keelung Sill site.

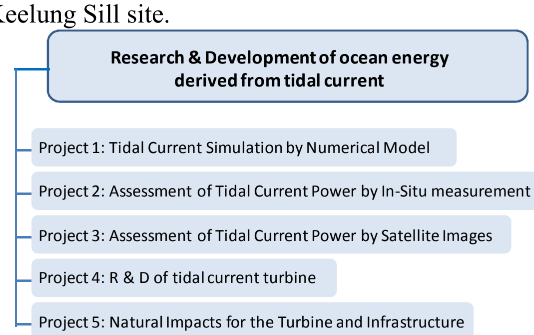

Fig. 3 Contents of the project

Fig. 4 A view of the Keelung Sill from NTOU

3-1 Tidal current simulation

For the numerical simulation of tides, a finite difference method is used to solve the control equations. The tides at open boundaries of model are the driving forces for tidal flow inside the model. The tides at domain boundaries are calculated by means of Japan NAO model.

We used vertically integrated continuity equation and equations of motion in the x and y directions. In the procedure of vertical integration we have used the hydrostatic equation to determine the pressure at depth z and incorporated the corresponding boundary conditions. The atmospheric pressure at sea surface is neglected in this model, and the bottom stresses are included in the model.

A measure of water velocity is obtained by averaging the volume transport over depth, thus

$$\bar{u} = \frac{U}{\zeta + H} \quad \text{and} \quad \bar{v} = \frac{V}{\zeta + H}.$$

where (U,V) is the volume transport vector, ζ is the free surface displacement from the undisturbed state and positive upward. Because the surface displacement ζ is much smaller than the water depth H, we take $(\zeta + H) = H$.

Shown in Fig. 5 is the preliminary result of our simulation using a 50m × 50m grid spacing. The figure clearly shows the strong current on the Sill. However, the computed strongest current in a 24-hr cycle is about 1.0 m/s, which is lower than the measured value. It may be due to the lunar phase of simulation day different from the measured time. Our next step is to use a finer 10m × 10m grid spacing. For model verification, we need current measurements made on the Sill.

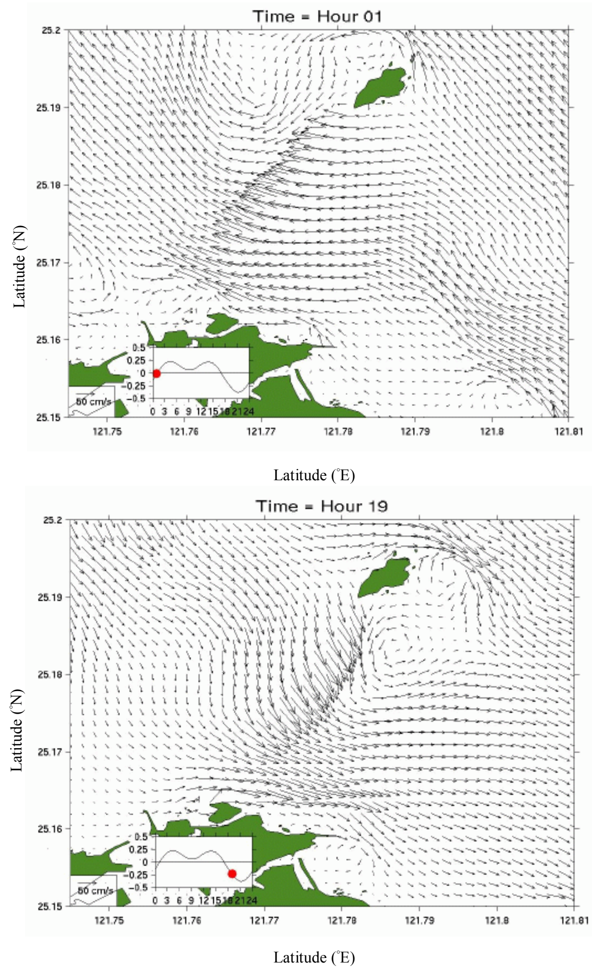

Fig. 5 Tidal current simulations at for the Keelung Sill Site, at flood tide (upper) and ebb tide (under)

3-2 Assessments of tidal current power by in-situ measurements

To have a clear picture of the tidal current at the Keelung Sill Site it is necessary to conduct in-situ measurements. From the measurement we can assess the power generation potential by the tidal current. Moreover, the data obtained can be used to calibrate our numerical simulations. For this we have planed a three deployments of current meters, each one last at least one month. The current measurements are to be carried out using Aquadopp Profilers (acoustic current meter by Nortek), an Aquadopp (single point) and a RCM-7 rotary type current meter (by Aanderra). These instruments are to be deployed at 5 stations along the Sill at nominal depths of 20m, 15m, 10m, and 5m (Fig. 6). The first measurement has been done during February 9 and March 12. Our preliminary results show that in the measurement period, the highest current speed at the 15m deep site is about 2.2m/s, measured at the -5m level. This occurred on March 1, about 2 days after the largest tidal range in that fortnight period and exactly on the New Moon date. Our results also shows that current speed was 2.4 m/s for the measurement obtained at the 20m station when the 2.2 m/s speed was clocked a the 15m deep station. Also, at the same station, the near bottom current speed was lower than that of the surface layers.

The power, P (Watt), of the tidal current with a speed v (m/s) can be calculated by the following:

$$P = 0.5\ C_p \rho A v^3$$

where C_p is the efficiency coefficient, ρ water density in kg/m^3, and A the blade sweep area in m^2.

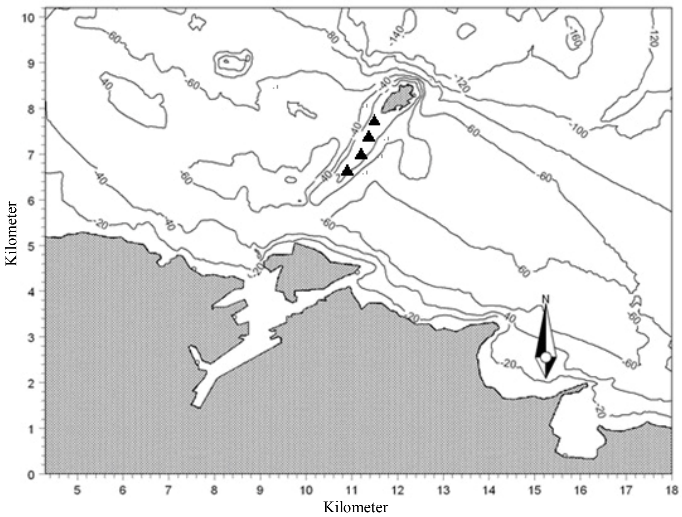

Fig. 6 Locations (▲) of the bottom-mount current meters: Aquadopp (5m deep station), Aquadopp profilers (10m, 15m and 20m) and RCM-7 (20m).

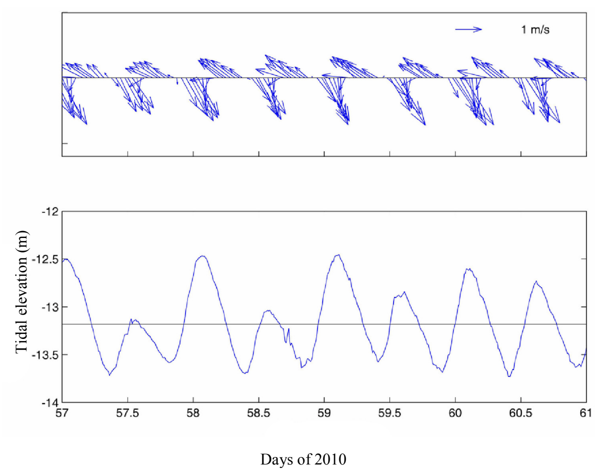

Fig. 7 Stick diagram of near surface (-5m level) tidal current measured by an acoustic current meter at the 15m station on the Keelung Sill. The maximum current speed is 2.2 m/s, which occurred at 12:50 on March 1 (Day 59).

3-3 Satellite image application

In this project, the satellite visible images will be used to calculate the water depth around the Keelung Sill, and then to estimate the tidal elevation and tidal energy around there. The Formosa-2 satellite contains a multi-spectral sensor, which includes 3 visible and 1 near infrared band, with spatial resolution of 8 m and a swath width of 24 km. It is an operational satellite with sun-synchronous orbit and repeat cycle of 1 day. The visible light is the only electromagnetic wave which can penetrate beneath the sea surface to see directly down to the depth of several meters and even to the sea bottom if the water is clear enough. Therefore, a series of cloud-free Formosa visible images around the Keelung Sill can be applied to compute its temporal-variable water depth and then tidal elevation and tidal energy. The high-frequency satellite-derived tidal elevation in this study can be compared with the in-situ data.

3-4 Research and development of tidal current turbine

One of the major tasks of the whole power generation project is the design or the turbine blades and the assembly of the turbine with a commercially available power generator. The objective of the turbine blades design is to find an optimal configuration—camber and pitch—for the blades to provide maximal power output for the operational current speed. Since the tidal current changes direction with time, the turbine should be able to face into the current at all time. We are trying to come up with a design so that the turbine can do that passively, without active control to change the turbine direction. Then, we will design and manufacture necessary gear system, and other parts for the power generator. Once this is done, the whole assembly will be tested in the laboratory to verify our blade design. The National Taiwan Ocean University has the world third largest cavitation tunnel, which has a test section with 10m in length, 2.6m in width, and 1.5m in height (Fig. 8). Test speeds can reach as high as 12m/sec. The cavitation tunnel is often used to test propeller, and which is uniquely suited for testing of underwater turbine. Power generation capacity will also be verified in the tunnel. Our initial prototype generator is a 3 kW one. After successfully tested, the current generator will be installed at the Keelung Sill Site for field tests.

Fig. 8 The cavitaion tunnel in the National Taiwan Ocean University.

3-5 Natural forcing on the device

The development and assessment of the ocean energy converters are closely linked to the fields of coastal and offshore engineering. Steel monopole/multipole structures and concrete gravity foundations are possible substructures for tidal current converters. The major difference between the converters with traditional fixed offshore structures is the dominant dynamic response behavior and the combined action of wind, waves and currents which govern the response. Currently, there are very few references and data in pubic domain relating to the actual dynamic behavior of the converters especially by a full-scale machine in the field. It is likely that the blade will experience the most extreme load variations. To assess the design loads for the structure in the sea, hydrodynamic models or site specific statistics of the waves, wind and current can be used. The first phase of this project is to investigate the magnitude of the force from natural factors, including wind, wave and current forces. Field data in the study area will be collected. Statistical approach, the frequency analysis based on the best fit distribution model will be applied to estimate the loadings of various return periods. Static analysis using Morison equation and dynamic analysis under irregular waves and non-uniform currents in time domain will be carried out in the second phase project period. It is anticipated to understand the dynamic responses of the tidal current energy converter.

4 Summaries

In this article, we report an on-going power generation project, a part of the National Science Technology Project and funded by the National Science Council. This project selects a near coast region where tidal current can run as high as 2.5 m/s to study and develop tidal current power generation devices. Our team will study the tidal current at the site using numerical simulation, in-situ measurement, and remote sensing techniques. We will also design the turbine for the power generator. Our initial aim is to install a 3 kW current generator at the site, after successful tests in the laboratory. We also will study extreme forces from the current, wind and wave on the power generator blades and structure, particularly those during typhoon conditions.

Acknowledgements

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