Resource Assessment of Tidal Current Energy in Hangzhou Bay Based on Long Term Measurement

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Abstract: Compared with other marine renewable energy, tidal current energy benefits a lot in high energy density and good predictability. Based on the measured tidal current data in Hangzhou Bay from Nov 2012 to Oct 2012, this paper analysed temporal and spatial changes of tidal current energy in the site. It is the first time measured data of such long time been taken in tidal current energy analysis. Occurrence frequency and duration of the current of different speed are given out in the paper. According to the analysis results, monthly average power density changed a lot in different month, and installation orientation of tidal current turbine significantly affected energy acquisition. Finally, the annual average power density of tidal current energy with coefficient $C_P$ in the site was calculated, and final output of a tidal current plant was also estimated.

1. Introduction
Tidal current energy refers to kinetic energy in horizontal movement of seawater under the action of tidal force. The kinetic energy can be transformed into electric energy through tidal current turbine. Tidal current energy has a unique superiority in that it does not produce any waste as clean renewable energy. Compared with other marine renewable energy, tidal current energy benefits a lot in high energy density and good predictability, etc. China has conducted survey and assessment on national tidal current energy \cite{1}, \cite{2}, as well as assessment of tidal current energy in certain regions \cite{3}, \cite{4}. These assessments are mainly based on short-term observations or 2-D numerical results, whose purpose is to understand resource conditions in a larger range, and provide a reference for site selection of tidal current energy. It is the first time measured data of such long time been taken in tidal current energy analysis. It will be useful in tidal current turbine design and economic analysis for tidal current energy extraction.

At present, the study of tidal current turbine is becoming the focus of tidal energy research \cite{5}, \cite{6}, which need detailed analysis of tidal current characteristics and temporal and spatial distribution at alternative tidal energy extraction site. On the one hand, it is important to choose laying depth and installation orientation of the turbine; on the other hand, it is to grasp occurrence frequency and duration of the current of different speed through long term measurement, so as to better determine design current velocity for tidal current turbine, and estimate its output precisely.

Hangzhou Bay is known for its strong tide, and its energy density of tidal current is one of the highest in China. In this paper, we analyzed from the above two aspects with one year data measured in the central area of Hangzhou Bay, to provide reference for tidal current turbine design, estimation of generating hours of high flow velocity and output of single set.
2. **Data source**

The data used in this paper was provided by a bottom-seated observation system located in central area of Hangzhou Bay where water depth is about 10m. Specific location is shown in Table 1 & Figure 1. The system was installed with a 600kHz Acoustic Doppler Flow Profiler (ADCP), which emit sound waves upwards to measure flow velocity, flow direction from 1 to 9m above seabed with layer thickness of 1 m. And it recorded velocity and direction data every half hour from November 2012 to October 2013. The accuracy of the ADCP measured velocity is 1% of measured value, and the accuracy of direction is ±1°. The velocity range is ±10ms-1, and the direction range is 0 to 360°.

*Table 1. Location of the observation system in Hangzhou Bay*

| Station A | Longitude | Latitude | Water depth |
|-----------|-----------|----------|-------------|
| 121°28.2′E | 30°28.6′N | 10m      |

*Figure 1. Location of the observation station*

At present, most current turbine was designed to be installation a fixed depth below the lowest tide level [5], [7]. That means the surface velocity is usually not used during high tide period. Therefore, the analysis in this paper focused on the current energy of the layers below the lowest tide level, which is in the range of 1m to 6m above the seabed in this site. We call those effective layers.

3. **Analysis and discussion**

3.1. **Basic characteristics of tidal current in the area**

The basic characteristics of the tidal current in the station are as follows: The tidal current of Hangzhou Bay is semidiurnal tide. And it has a feature of standing wave for its relation between tide and tidal current. The maximum current velocity basically appears near half-tide level time; while turn of tidal current mostly occurs at high and low tide moments (Figure 2). The flood current direction is about 300°, while ebb current direction is about 120°. Both flood and ebb currents have concentrated directions, and the feature of reciprocating current is in evidence.
Table 2. Hours of depth average velocity at all levels

| Velocity Range   | Hours | Proportion |
|------------------|-------|------------|
| U≤0.5m/s         | 1631  | 18.6%      |
| 0.5<U≤1.0m/s     | 2096  | 23.9%      |
| 1.0<U≤1.5m/s     | 2949  | 33.7%      |
| 1.5<U≤2.0m/s     | 1731  | 19.8%      |
| U>2.5m/s         | 353   | 4.1%       |

During the observation period (September 2012 to October 2013), the maximum flood current velocity in effective layers (1 to 6m above seabed) was 2.73 m/s at 6m layer; the maximum ebb current velocity in effective layers was 2.55 m/s at 6m layer. The maximum depth-average flood velocity is 2.32 m/s, and the maximum depth-average ebb velocity is 2.10 m/s. Flood current lasted an average of 5 hours 55 minutes, while ebb current lasted 6 hours 30 minutes.

During the observation time, depth-average residual value was 0.11 m/s, and the direction was about 130°. The residual value decreases from the surface to the bottom, the direction is deflected counterclockwise, and the residual value near seabed is 0.02 m/s, the direction is about 100°. Figure 3 shows depth average velocity rose based on measured data of one year. It can be seen that tidal current of the site is mainly concentrated in WNW, while ebb current is mainly concentrated in ENE direction. Flow velocity is mainly in the range of 1.0~1.5 m/s, which accounts for 33.7%, followed by the range of 0.5~1.0 m/s, which accounts for 23.9% (Table 2).

Flow velocity of one year is analyzed statistically, and velocity value of each guarantee rate is shown in Figure 4. As can be seen, flow velocity beyond 0.5 m/s occurred in 7010 hours, with guarantee rate of 80%; flow velocity beyond 1 m/s occurred in 4406 hours, with guarantee rate of 50%; flow velocity beyond 1.5 m/s occurred in 1113 hours, with guarantee rate of 13%.

Figure 2. curves of tide and tidal current (September 14 ~ 17, 2012)

Figure 3. Roses of depth average Tidal current over a year
Figure 4. Flow velocity for each guarantee rate

3.2. Vertical distribution of tidal current energy
As we all know, tidal current velocity shows significant vertical variation. During the observation, flow velocity of the station was small at the bottom, but significantly larger at middle and surface layers. The power law is often used for vertical structural description of flow velocity as follows:

\[
\frac{U}{U_0} = \left( \frac{Z}{Z_0} \right)^\alpha
\]  

(1)

\(Z_0\), sea surface measured from the seabed, m
\(Z\), water depth measured from the seabed, m
\(U_0\), current velocity at sea surface, \(\text{ms}^{-1}\)
\(U\), current velocity at \(Z\) depth, \(\text{ms}^{-1}\)
\(\alpha\), power law exponent

The vertical distribution of measured flow velocity is compared with that of the theoretical curve in Figure 5. The measured data is between \(\alpha=1/2\) and \(\alpha=1/7\) theoretical curves, and does not exactly match one certain curve.

In order to avoid trouble of tidal current flow vertical structure variation, and to visually reflect distribution of tidal current energy in each effective layer (1 to 6 m above seabed), the average power density of the tidal current energy of each layer during the observation was calculated using the 30 min interval tidal current data during one year. The calculation is as follows:

\[
P = \frac{0.5 \sum_n \rho U_i^3}{n}
\]  

(2)

Figure 5. Vertical distribution of velocity
According to the calculation results, vertical distribution of average power density of tidal current energy during observation is shown in Figure 6. Annual average power density of each level is between 401 and 1195 Wm$^{-2}$. Average power density was lowest at the bottom and highest in surface layer. In shallow water, average power density of tidal current energy decreases obviously to the bottom. The power density drops about 150 Wm$^{-2}$ per meter depth in this site.

In view of the above analysis, more energy can be captured if the tidal current turbine is installed as high as possible until the lowest tide level.

3.3. Direction distribution of tidal current energy
The tidal current turbines being studied or experimented are mostly direction-fixed Horizontal axis turbines[5,7], but tidal current flow changes in a range. So that, the maximum energy that turbine can capture will be limited by angle between the flow direction and turbine orientation. Flow directions at this site are mostly in the range of 240° ± 20° for flood current, and 60° ± 20° for ebb current. The direction modified power density of tidal current energy was calculated when the turbine is oriented in the range of 220-260°. The calculation is as follows:

$$P_c = \frac{0.5}{n} \sum_{i=1}^{n} \rho U_i \cos \theta$$

(3)

$P_c$, direction modified power density of tidal current energy, Wm$^{-2}$
$\rho$, sea water density, 1025 kgm$^{-3}$ is taken
$U_i$, flow velocity at 30min interval, ms$^{-1}$
$\theta$, angle between flow direction and turbine orientation
$n$, number of observations, 17520 in one year

The annual average power density of tidal current energy in effective layers (1 to 6m above seabed) is 820 Wm$^{-2}$ regardless the limitation of the angle between flow direction and turbine orientation. In view of limitation of the angle, when the turbine orientation is 299°, direction modified power density
reaches a maximum of 802 Wm$^2$. When the turbine orientation turns left or right by 10°, the power density drops 5% to 759 Wm$^2$ (Figure 7).

![Figure 7. Achievable power for different turbine orientation](image)

3.4. **Tidal current energy variation over time**

Significant regularity is an important feature of tidal current energy. In semidiurnal tide sea area, it has twice flood time and twice ebb time of high flow speed every day. And there’s low speed time between flood and ebb. Flow velocity is also affected by the spring-neap tide cycle. Figure 8 shows a spring-neap cycle in November 2012. In which maximum velocity during spring tide is 2.55 ms$^{-1}$ and the maximum velocity during neap tide is 1.45 ms$^{-1}$. The daily average power density of current is 1377 Wm$^{-2}$ in spring tide time which is 1.7 times of annual average, and it’s 344 Wm$^{-2}$ in neap which is 0.4 times of annual average. Table 3 shows that monthly average power density changes between 648 and 965 Wm$^{-2}$ in different month. The fluctuation range is ±20% of annual power density, which reminds us to note the unavoidable estimation error using the monthly data in estimating the power density.

3.5. **Annual reserve of tidal current energy**

The annual average power density calculated by measured date is 820 Wm$^{-2}$, and direction modified annual power density is 801 Wm$^{-2}$. However, not all the kinetic energy of tidal current can be captured due to Betz’ law and other theory. Efficiency coefficient $C_p$ is developed to calculate the final output of tidal current energy. It is defined as the ratio between captured power and original power. The $C_p$ reported or used by many researchers is usually between 0.3 and 0.5\[8\]-[10]. In this site, the final annual average power density is 240 Wm$^{-2}$ with a $C_p$ of 0.3. That means the final output will be 59.4MWh by a plant with a 6m-diameter turbine rotor.

**Table 3. Monthly average power density from Nov 2012 to Oct 2013(Wm$^{-2}$)**

|       | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $P$   | 847 | 743 | 721 | 778 | 906 | 823 | 784 | 874 | 1009| 869 | 763 | 652 |
| $P_c$ | 839 | 736 | 712 | 765 | 892 | 815 | 779 | 848 | 965 | 849 | 757 | 648 |
4. Conclusions
The tidal current is semidiurnal tide in Hangzhou Bay, and it belongs to standing wave. Maximum velocity in effective layers (1 to 6m above seabed) was 2.73 m/s at 6m layer, while maximum depth-average velocity is 2.32 m/s. For one year, flow velocity beyond 0.5m/s occurred in 7010 hours, with guarantee rate of 80%; flow velocity beyond 1m/s occurred in 4406 hours, with guarantee rate of 50%; flow velocity beyond 1.5 m/s occurred in 1113 hours, with guarantee rate of 13%. Monthly average power density changes a lot in different month, and the fluctuation range is about ±20% of annual power density, which reminds us to note the unavoidable estimation error using the monthly or shorter data in estimating the power density. Average power density of tidal current energy decreases obviously to the bottom. More energy can be captured if the tidal current turbine is installed as high as possible. The direction modified annual average power density is 802 Wm$^{-2}$. When the turbine turns left or right by 10 °, the power density drops 5% to 759 Wm$^{-2}$. The final annual average power density with efficiency coefficient $C_p$ of 0.3 is 240 Wm$^{-2}$. That means the final output of a plant with 6m-diameter turbine rotor will be 59.4MWh in this site.

5. References
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