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The development of the IHL wave-current turbine to convert the ocean energy from both wave and current

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Abstract. Indonesia has abundant of renewable sources of energy, among others: geothermal, solar, water, wind and marine therefore the promotion of the utilization of the renewable and sustainable energy is urgent. Since 2006 Indonesian Hydrodynamic Laboratory (IHL) BPPT has conducted research and developed a technology converts the ocean energy resources into electricity, the kinetic energy of marine current and the potential energy of wave. The prototype of marine current turbine, 2 kW and 10 kW respectively, had been installed in Larantuka Strait in 2010 and 2011 (http://www.youtube.com/user/erw4ndi). Since mostly the maximum speed of the marine current of many straits in Indonesia are in order 1.0 - 2.0 m/s, we developed the turbine prototype that can convert not only the kinetic energy of marine current but also the potential energy of the wave, called as wave-current rotor turbine, in 2013. The current usually mixes with wave height with order 0.4 - 0.8 m. A 2 kW prototype was installed under Suramadu (Surabaya - Madura) Bridge close to pier no. 56. The prototype showed a good performance especially in converting the kinetic energy of marine current. The research was continued in 2014-2016 under Ministry of Research and Technology (INSINAS RISTEK) budget scheme. Some innovations have been done to improve the performance of turbines. .

1. Introduction

Indonesia has plentiful of renewable and sustainable energy resources. Those are: geothermal, solar, water, wind and marine. Some feasibility studies of geothermal resources has been finished on 2017. On July 2018, the Indonesian Government has launched the 75 MW peak wind turbine farm at Sidrap, Sulawesi Island. Many solar power plants have being built in the islands of East Nusa Tenggara Province. However, the marine is the least exploited. As archipelagic country the sources of ocean renewable energy, theoretically, are beyond the other ones [1].

The power of hydrokinetic energy of the speed of the marine current that pass through many straits in Indonesia has attracted many investor companies to exploit it [13]. The straits in East Nusa Tenggara Province are the examples where the flow speed of the marine currents between the islands typically have strong velocities in the range of 2-4 [m/s] or more. It mixes with wind waves and swells come from the open sea surrounding the straits.

Since 2006 fiscal year, the IHL of BPPT has been establishing research on development of the turbine of the marine current. It is initiated with the predicting of the strength of the marine current in the several straits at Nusa Tenggara Province. Then a 3 blades Darrieus turbine was designed and tested in tank

facilities of IHL. Manufacturing of 2 kW prototype was started in 2009 and installed in Larantuka Strait in 2010. In 2011 the capacity of turbine was increased to 10 kW [2] [3].

In 2013 the turbine was moved to Madura Strait installed under Suramadu Bridge close to pillars no. 56. Suramadu Bridge is the bridge that connects Surabaya City and Madura Island. Since the maximum speed of tidal stream in Madura Strait is only 1.28 m/s and there is a tendency that the water under Suramadu Bridge sometimes is wavy water, we changed the blade position of Darrieus Turbine not perpendicular to the direction of the flow of tidal stream but has an angle 60° to the direction of the flow. The turbine gave a good performance especially in converting tidal stream into electricity. It is appreciated by the visitation of Minister of Research and Technology to the site to see the prototype.

The design process was continued in 2014 - 2016 under INSINAS research budget scheme managed by Ministry of Research and Technology. Some improvement designs are carried out to enhance the performance of the turbine. This paper has purpose to show the development process of the design wave-current rotor. Firstly the ocean modeling by numerical technique is utilized to predict the speed of current flow under Suramadu Bridge. Secondly the foil is designed to catch the kinetic energy of current speed. Next the physical model is tested in Maneuvering Ocean Engineering Basin (MOB) of IHL. The prototype is built and installed in Suramadu Bridge. The turbine can work well with cut-in speed 0.6 m/s.

2. Materials and Methods

This research follows the following method: firstly mesoscale numerical simulation is conducted to predict the velocity of tidal stream at Madura Strait, secondly based on the mesoscale numerical results, the foil of the wave-current rotor is designed with assumption that the category of current speed is slow. Next the prototype of wave-current rotor is tested in MOB basin of IHL, furthermore the prototype of wave-current rotor is manufactured and finally it is installed under Suramadu Bridge close to pillar no. 56.

The Geophysical Fluid Dynamic Navier Stokes equations and continuity equation are discretized with staggered grid system. First order upstream differencing scheme is applied to the advection term, second order centered differencing scheme is applied to diffusion term. Equations are integrated by forward-backward scheme [7].

At the open boundaries, the tidal constituent data at Karang Jamuang (North Madura Strait) and Karang Kleta (East Madura Strait) produced by DISHIDROS Indonesian Navy are fed to computational domain [8]. The sea elevations calculated by the tidal components are given at every time step. Velocity gradient normal to the open boundary is assumed to be 0.
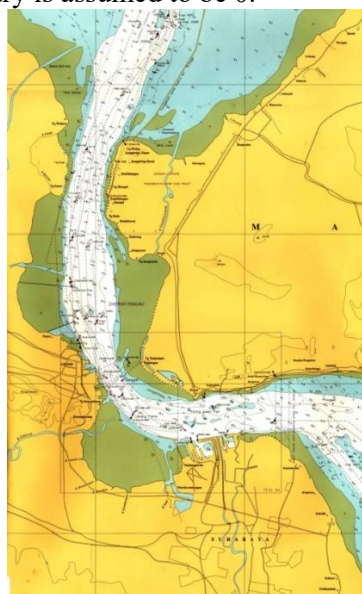

Figure 1. Madura Strait

2.1. Numerical Prediction of the Current Speed at Madura Strait

The MEC Ocean Model (Ocean modeling program of Marine Environment Committee of the Society of Naval Architects of Japan) [4] has been utilized as the initial approach for the prediction of the strength of the marine current at Madura Strait. Madura Strait (Selat Madura) is situated between East Java and Madura Island, as shown in Figure 1. In the east of Madura Strait there is Suramadu Bridge, the longest bridge in Indonesia. Numerical prediction was carried out intensively using variable mesh. Erwandi [5][6] showed the variable mesh technique to predict the speed of current distribution in Alas Strait.

2.2. Grid Generation of Madura Strait

The MEC-Model uses the orthogonal constant grid system and variable grid system. Since the bathymetry data are very coarse, , for the first approximation, the 50 meter accuracy in horizontal direction and 0.5 meter accuracy in vertical direction of the orthogonal constant grid system is generated to discretize the bathymetry contour of the strait. The variable mesh is concentrated in the site where the Suramadu Bridge exists. The variable mesh in bird view is shown in Figure. 2.
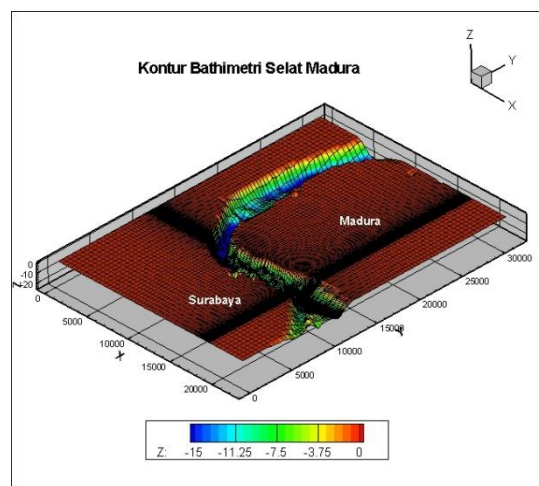

Figure 2. Variable mesh at Madura Strait

2.3. Designing the Foil of Wave-Current Rotor Turbine

Since the rate of tidal stream characteristic under Suramadu Bridge is slow, then special design of foil should be considered. We had been designed special foil named as LHI 166 [9]. LHI is abbreviation of Laboratorium Hidrodinamika Indonesia (Indonesian Hydrodynamic Laboratory) and 166 is the thickness code, means 16.6% of chord length. LHI 166 foil is designed for special purpose. It gives high lift in low Reynolds Number. The full inverse and mixed inverse formulation panel method was employed to design the shape of the foil. The lift and drag force of LHI 166 was calculated numerically using commercial CFD program with angle of attack 0° - 358°. Fig. 4 shows the mesh when CFD is utilized to find the lift and drag force coefficient.
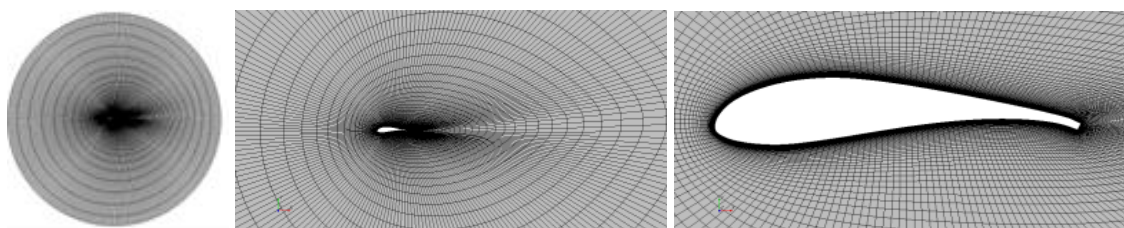

Figure 3. Mesh generation of LHI 166 foil

2.4. Design and Hydrodynamic Test of Wave-Current Rotor Turbine

Three blades wave-current rotor turbine ver. 1.0 was designed originally from the research of performance Darrieus Turbine designed in IHL. The blade position was changed. In Darrieus turbine the blade position is perpendicular to the direction of the stream flow of marine current whilst the wave-current rotor turbine has angle 45° and 60° to the direction of the flow. Figure 4 shows the shape of wave current rotor turbine.

Three aluminum model of wave-current rotor turbine blade with sectional area foil LHI-166 shape was manufactured using CNC machine. The length of the blade and the length of the chord were 1 meter and 10 cm respectively. The blade can move freely up to -20° at a hinge close to the leading edge of the foil. The passive variable pitch is applied to control the movement of the blade. The hydrodynamic test showed that this application can increase the efficiency of turbine up to 38%. However there are disadvantages of it, the torsional vibration increases when the velocity of marine current increases [11]. The wave-current rotor turbine was tested both in towing tank and wave tank (Maneuvering and Offshore engineering Basin / MOB). Figure 5 showed the testing process in MOB.
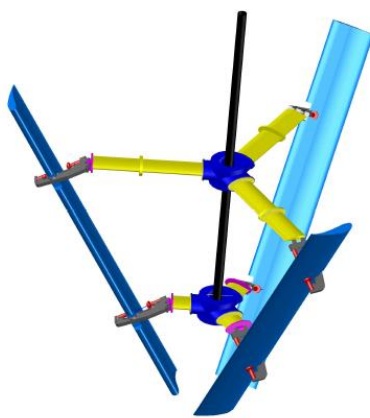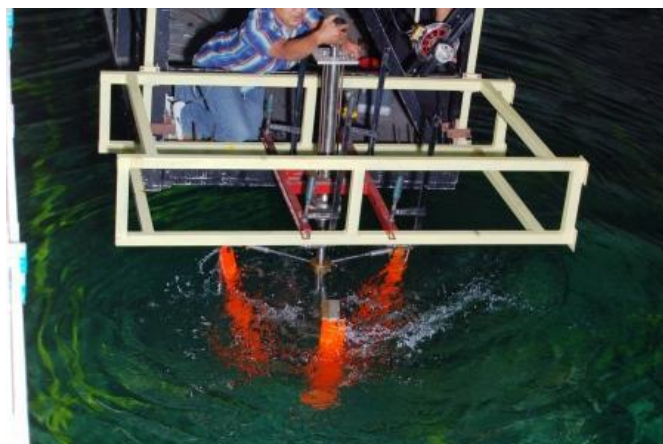

Figure 4. Wave-current rotor turbine   **Figure 5.** Testing of wave-current rotor turbine at MOB

2.5. Wave-Current Rotor Installation at Suramadu Bridge

A 3.5 kW wave-current turbine prototype was manufactured between two floating pontoon of fiber reinforced plastic. The length of the pontoon is 8 meter, the width is 1 meter, and draft is 0.5 meter. Total width of the prototype is 6 meter. The blade of the turbine has length 2.6 meter and diameter 3.6 meter. Four nylon mooring ropes diameter 7 cm and length 80 meter were connected to each bow and aft of the pontoons respectively. The two pontoons are connected with a cremona bridge where one of the edge of cremona can be raised and lowered easily using hoist and leverage at the other edge as a hinge. Figure 6 shows the schematic view the system to raise and to lower the wave-current rotor turbine. Figure 7 is the drawing of the prototype of wave current-rotor.

In the deck, we placed bevel gear from vertical axis to horizontal axis, the hydraulic brake, a 1 : 20 horizontal gearbox, and permanent magnetic generator (PMG). The maximum rotation rate of PMG is 250 rpm. The fluctuated AC electric current as output of PMG is converted to DC electric current through rectifier and then goes to inverter where the standard voltage and frequency are produced. A handmade system of dump load is utilized to transfer the electricity when the electricity produced by PMG is bigger than the load. Figure 8 is the prototype of wave-current rotor turbine when it was assembled at Pantai Ria Kenjeran Surabaya. The total displacement of the prototype is 8 ton.

The prototype was installed close to the bridge pillar no. 56, the anchor and concrete block for mooring system was not needed. The rope was directly tied to the pillar. Figure 9 showed the prototype installed in bridge pillar no. 56. The installation system of the prototype is well known as floating type

installation system. Since it is floated then the performance of the turbine in converting the potential energy of the wave cannot be measured and observed. The prototype only works to convert the kinetic energy of tidal stream.
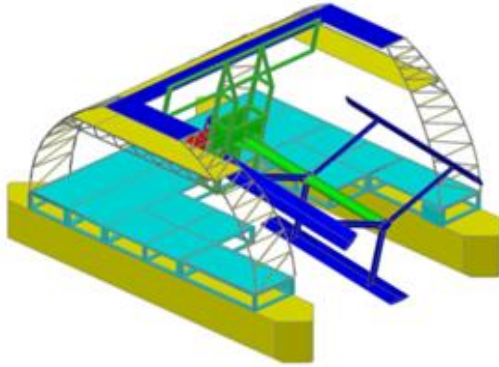

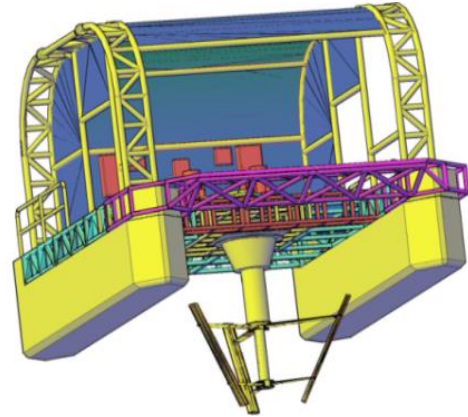**Figure 6.** System to raise & lower the turbine

Figure 7. The drawing of wave-current rotor

Figure 8. Prototype of wave current rotor

Figure 9. Prototype installed in bridge pillar no. 56

3. Results and Discussions
3.1. Results of Numerical Simulations

The tide type of the Madura Strait is mixed predominant semi-diurnal, therefore we assumed only semi-diurnal tide at the open boundary and we considered the amplitude of sea elevation is the summation of the amplitude of the tidal constituents M2, S2, K1, and O1. Phase lag is set by M2 tide. The variability of spring-neap cycle is reproduced by using amplitude M2+S2 for mean spring tide, and M2-S2 for mean neap tide. Both cases use phase lag M2. Fig. 11 (a) and (b) show the vector and power distribution of current velocity at high tide and low tide respectively. The position of Suramadu Bridge is indicated in rectangle box. The maximum velocity of current at high tide at point where the Suramadu Bridge pillar no. 56 is 1.38 m/s whilst the maximum velocity of low tide current at same position is 1.1 m/s. The prediction of those maximum values using numerical simulation was confirmed to the direct measurement reported by Haryo Dwi Atmono et. al. 2005 [10]. They have a good agreement between numerical results and direct measurement.

As shown in Fig. 11, the power produced from the kinetic energy of the marine current speed can be determined by following equation:

$$P = 0.5\rho A V^3 \eta \quad [\text{W}] \tag{1}$$

Where:

P: power [watt]

ρ : density of water [1024 kg/m3]

A : turbine cross sectional area [m2]

V : current speed [m/s]

η : the efficiency of the turbine (0.593)

The efficiency value that is set to 0.593 is theoretical efficiency. The real efficiency of the turbine, actually, is lower than 0.593, however in this study it is assumed that the mechanical turbine efficiency is 1. Since the fastest current speed in vertical direction is near the surface thus the turbine should be installed close to the surface. The cross sectional area A is set to 1 m2.
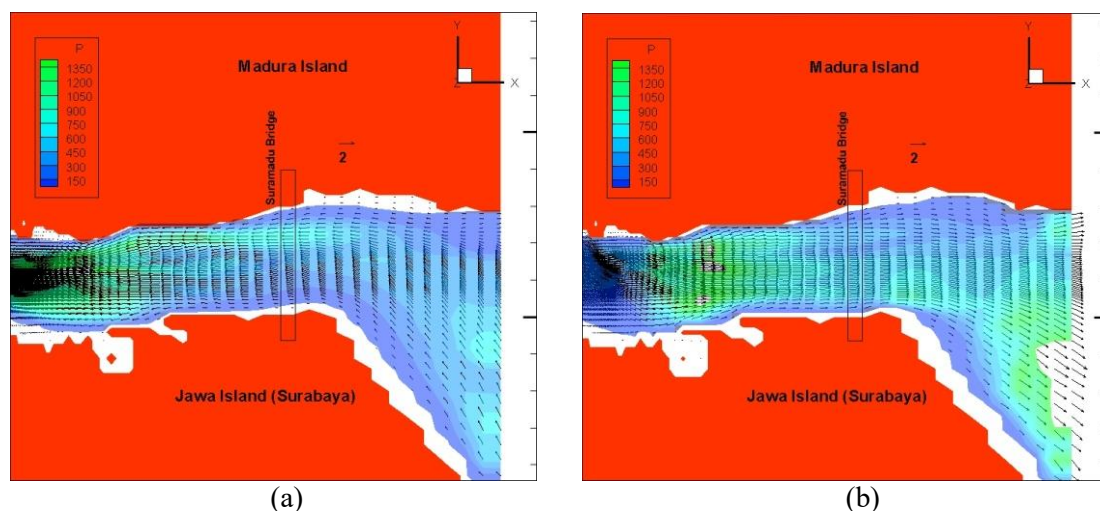

Figure 10. Vector distribution of Marine Current Speed at Suramadu Bridge Madura Strait (a) High tide (b) low tide

3.2. Results of Wave-Current Blade Foil Numerical Simulations

Based on the mesoscale numerical simulation, two dimensional detail numerical simulation was carried out. Figure 11(a) shows the sample result numerical calculation of LHI 166 at angle of attack 14° whilst Figure 11(b) is the pressure coefficient distribution of Figure 11(a). The knowledge of flow characteristic at every position in the certain angle of attack will give a fruitful information to design the performance of turbine when the foil passes upstream and downstream area. Since the tangential force produced by foil is very essential to rotate the turbine system then a careful design of passive variable pitch will increase the efficiency of the turbine. The results of numerical analysis is then verified by testing the physical model not only in towing tank but also in MOB. The foil LHI 166 gave a good performance since the average efficiency is 38.8%. It worked well at tip speed ratio (TSR) 2.25. The passive variable pitch can remove the phenomena of negative torque and give a high efficiency at slow velocity of the stream. It provides the very low cut-in speed of the turbine. The turbine started rotating at 0.25 m/s.

However the application of passive variable pitch gave disadvantage when the towing speed was increased. The turbine system started shaking at towing speed 1.3 m/s. The passive variable pitch produced very high lift force in higher speed. High lift force means high tangential force. Since the resultant of tangential force is bigger than normal force perpendicular to radial arm, then the radial arm will experience fluctuated bending moment. The fluctuated bending moment is conveyed to the shaft and the whole turbine system [11][12].

The performance of turbine can be represented in Figure 12. The maximum rotation rate of the turbine transfer to PMG was 167 rpm. The maximum electric power produced by PMG was 2003 Watts

at 1.21 m/s. The electricity generated by PMG was fluctuated depend on the turbulent flow fluctuation of the tidal stream and the shaking phenomena of wave-current rotor turbine system. In Figure 12 the electricity output measured by power meter is in blue symbol, whilst the red dot represents the rpm power diagram taken from the PMG technical specification sheet.

From Figure 12, we also conclude that the selection of the gearbox rate seems too low. The gearbox installed in wave-current rotor turbine has rate 1:20. The analysis of the power generated by PMG, the torque in the shaft is still bigger than the torque of PMG. The change of gear box rate will increase the power produced by PMG since the maximum power of PMG is 3500 Watts at 250 rpm.

The prototype was installed for 6 months. As continuation of the research, we are designing new turbine called wave-current rotor turbine ver. 2.0 to enhance the performance of the turbine in converting the potential energy of the wave height.
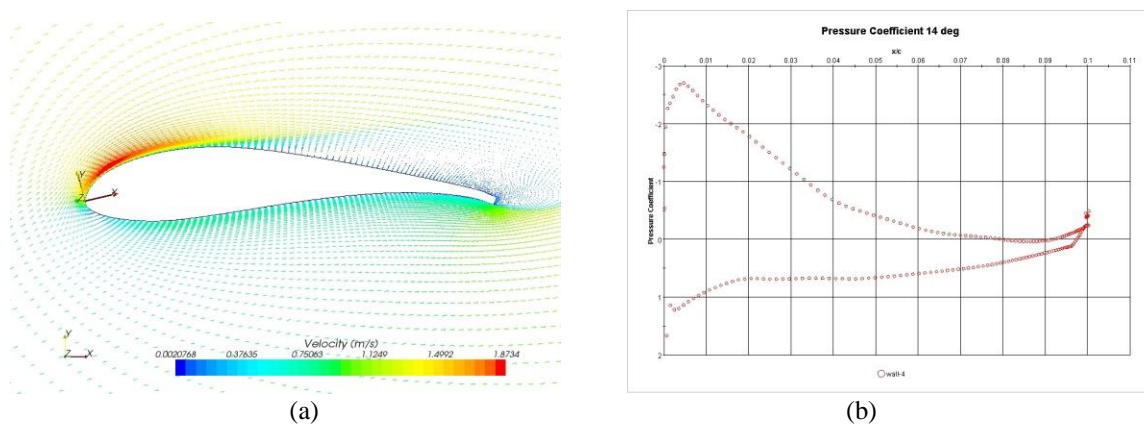

(a)   (b)

Figure 11. Sample result of LHI 166 foil at angle of attack 14°
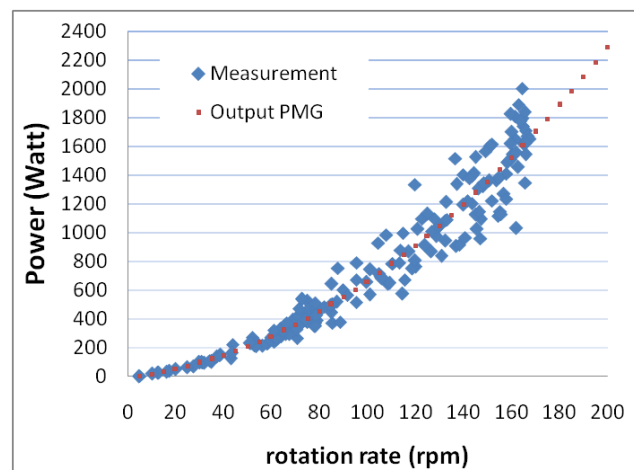

Figure 12. Rotation rate and power diagram

4. Conclusion

The numerical ocean modeling (MEC model) is very useful to predict the power of the hydrokinetic energy from marine current speed in Madura Strait and the tidal current under Suramadu Bridge. Moreover the detail numerical simulation can also predict the performance of the foil LHI 166. Finally the prototype of wave-current rotor can work well in converting kinetic energy of tidal current under Suramadu Bridge.

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