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Application of Vortex Induced Vibration Energy Generation Technologies to the Offshore Oil and Gas Platform: The Preliminary Study

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Abstract**—**The global demand for continuous and eco-friendly renewable energy as alternative to fossils fuels is large and ever growing in nowadays. This paper will focus on capability of Vortex Induced Vibration (VIV) phenomenon in generating alternative energy for offshore platform application. In order to maximize the potential of energy generation, the effects of lock in phenomenon and different geometries of cylinder were studied in this project. VIV is the motion induced on bluff body which creates alternating lift forces perpendicular to fluid flow. Normally, VIV is unwanted in order to prevent mechanical failure of the vibrating structures. But in this project, instead of eliminating these vibrations, VIV will be exploited to transform these vibrations into a valuable resource of energy.

Keywords**—**Vortex Induced Vibration, Vortex Shedding, Renewable Energy

I. Introduction

A. Problem Statement

NOWADAYS, most of the oil and gas companies used Normally Unmanned Installation (NUI) platform to remotely monitor another offshore platforms operating conditions for oil and gas exploration. NUI is known as a type of automated offshore platform which is designed to be operated remotely and only to be visited irregularly by work crew to perform routine maintenance work [1]. NUI which is shown in Fig. 1, used in shallower water, is a relatively simple and economical option as compared to the cost using subsea wells [2]. However, such unmanned offshore platforms required continuous electrically power driven service to remain operational at all times maintenance work which required higher power consumption [3]. Continuing burning of these conventional fuels will produce higher total of CO_2 emission to the environment. Thus, offshore platform will face a problem to operate their activities in an environmentally manner. Therefore, alternative sources of energy must be harvested from sources that are not only renewable but also environmental friendly.

Currently, great efforts have been taken to discover the renewable of energy to lessen the current rate of fossil fuel usage and their ensuing effects of climatic changes and global warming. Some of the unmanned offshore platform started to exploit a renewable energy sources such as solar and wind to generate power supply to lessen consumption of fuels as shown in Fig. 2.

Fig. 1 NUI platform

Fig. 2 Solar panel on unmanned platform

Unfortunately, solar energy technologies existed currently are unable to meet the continuous energy demand due to their self-limitation. Solar energy is dependent on the availability of the sun [4]. Newer and less ecologically technology needs to be developed to make power generation on offshore platform not only renewable, but also pollution-free.

One viable solution that meets these criteria is the hydroelectric power extraction system based on Vortex Induced Vibration (VIV) in ocean flow. Ocean which is affected by winds and density difference will create the ocean current flow circulation known as Marine Hydrokinetic (MHK) and can be captured to create electricity [5].

Vortex Induced Vibration (VIV) is a phenomenon when shedding of irregular vortices behind bluff body results in the oscillation of hydrodynamic forces and thus leading to its vibration as shown in Fig. 3. For decades, engineers have been trying to minimize the present of vortex induced vibration in order to prevent mechanical failure of the vibrating structures as shown in Fig. 4. In this project, instead of minimizing these effects, VIV will be maximized and exploited in order to

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transform these vibrations into a valuable resource of energy [6].

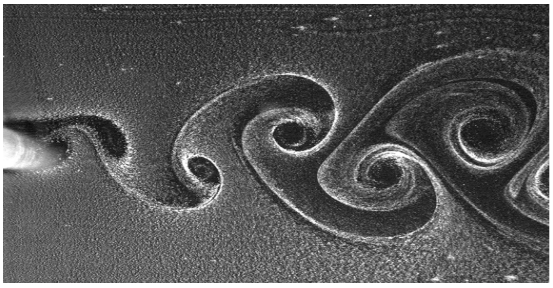

Fig. 3 Vortex shedding periodic pattern

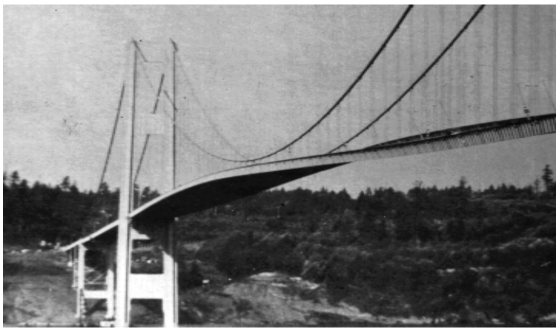

Fig. 4 Tacoma bridges collapsed due to VIV

This technology works by placing cylinder bodies in cross fluid flows. Flow over this cylinder will generate an irregular vortex pattern which created alternating high lift forces on the body and pushing it up and down perpendicular to fluid flow [7]. The alternating movement of this body will produce fluctuating kinetic motion which can be converted into electricity [8].

B. Previous VIV Design Technology

The energy converter device based on VIV is originally designed by Prof. Michael Bernitas from University of Michigan in 2008 which is known as VIVACE. The system works by placing cylinder horizontally in a fixed frame and allowed alternating movement to the direction of water flow. The cylinder is attached to cylinder's housing where magnetic sliders move up and down over a rail containing a coil and generate DC current which can be stored into the grid [6]. The current project aims to further enhance the energy generation from this VIV application (i.e. bluff body design variation). Thus, proper understanding on the fundamental of vortex induced vibration and its related design will be studied and improved.

C. Background

1) VIV Theory

VIV is a result of vortex shedding phenomenon which generally occurs nearly on any bluff body when submerged into fluid flow. Normally, irregular vortex shedding will occur in flow behind the body resulting in the fluctuating pressure differential which produces lift force perpendicular to the direction of the flow. The oscillating motion on the body is due to alternating lift forces [8].

2) Reynolds Number

In general, flow parameter that affects the behaviour of vortex shedding has been observed to be the Reynolds number of flow as shown in (1).

$$Re = (UD)/v \qquad (1)$$

U is the free-stream velocity, D is the cylinder diameter and v is the fluid kinematic viscosity. The regime that is targeted in this project is known as the "fully turbulent vortex street", with Reynolds number in the range of ($300<Re<3\text{x}10^5$) [9].

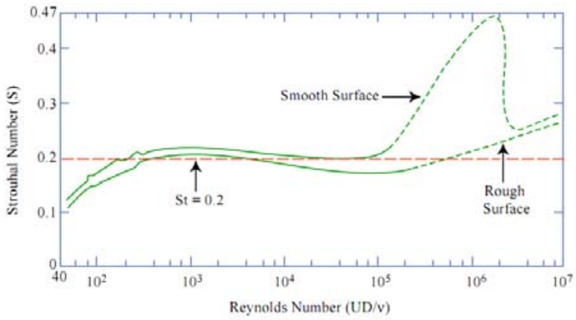

Fig. 5 Strouhal Number vs. Reynolds Number

3) Strouhal number

The Strouhal Number, St is a non-dimensional parameter that describes the vortex shedding frequency to the oscillating flow mechanism.

$$St = (f_s D)/U \qquad (2)$$

f_s is vortex shedding frequency. Strouhal number will be used as a constant value in this project as the Reynolds number falls in the middle of constant Strouhal number region which is 0.2 for subcritical flow as shown in Fig. 5 [10].

4) Lock In Phenomenon

A phenomenon known as "lock in" is a condition when the vortex shedding frequency becomes close to the natural frequency of the body. It has the potential to enlarge the amplitudes of bodies' oscillation which is similar to linear resonance. It is essential to find the range of shedding frequency that match with natural frequency, f_n to design energy harnessing device;

$$f_n = (1/2\pi)\ (\sqrt{(k/m_{app})} \qquad (3)$$

k is spring stiffness and m_{app} is mass applied to the cylinder. The non-dimensional parameter used to measure vibration of amplitude is known as reduced velocity, U^*;

$$U^* = (1/St) = [U/(Df_s)] \qquad (4)$$

Several studies showed that within the range of (3<U*<8), shedding frequency can lock in and shift to match the natural frequency [11].

II. Approach and Methods

A. Initial Model Calculation

This section will express the result for one testing cylinder length based on calculation. A simple calculation of cylinder parameters is important to describe the fluid-oscillator interaction in order to set up the estimation of the possible dynamic performance of a VIV. The Reynolds Number targeted in this project is within the range of ($300<Re<3\text{x}10^5$) which is known as fully turbulence regime. At this range Strouhal number is about 0.2 for smooth surfaces, which correspond to the fully turbulence vortex range. The cylinder and flow parameters investigated are listed in Table I.

TABLE I
CYLINDER AND FLOW PARAMETERS

Cylinder pipe (schedule 40)				
Nominal Bore [inch]	0.5	1	1.5	2.0
Diameter [m]	0.0158	0.0266	0.0409	0.0525
Length [m]	0.2			
Density [kg/m]	0.476 kg/m (3.4mm thickness)			
Water				
Velocity [m/s]	0.5 m/s (minimum ocean current in Malaysia, as in [12])			
Density [kg/m^3]	997 kg/m^3			
Kinematic viscosity [m^2/s]	9.0x 10^{-7}			

For ($300<Re<3\text{x}10^5$), the vortex street behind the cylinder is known to be fully turbulence. The Strouhal number which is related to the function of Reynolds number is calculated on (5) to validate the initial estimation of Strouhal number discussed previously [10].

$$St = 0.198\,[1-(19.7/Re)] = 0.20 \quad (5)$$

For lock in phenomenon to happen it is a must to match the vortex shedding and natural frequency to provide large amplitude vibrations of cylinder. The vortex shedding frequency is then calculated on (4).

$$f_s = (St.U)/D = 3.76/s$$

To calculate the natural frequency of cylinder, the following cylinder properties were determined.

$$M_{add} = 0.0\,kg \quad (6)$$

$$M_{pipe} = \rho_{cyl} \times L + M_{add} = 0.095\,kg \quad (7)$$

$$Volume = (\pi/4) \times D^2 \times L \quad (8)$$

$$M_{dis} = \rho_{water} \times volume = 0.111\,kg \quad (9)$$

$$M_{app} = M_{pipe} + M_{dis} = 0.206\,kg \quad (10)$$

By matching the natural frequency with shedding frequency for lock in condition [$f_s = f_n$], spring stiffness, k value is calculated by (3).

$$k = [f_s \times 2\pi]^2 \times M_{app} = 115\,N/m$$

Spring stiffness 115 N/m will be used to create the lock in phenomenon in the experiment (future work).

The periodic force $F(t)$, applied on cylinder is assumed to be sinusoidal function with frequency equivalent to natural frequency of cylinder and given by (11). Coefficient of lift force C_L is assumed to be 0.6 based on previous study [8].

$$F_L = 0.5\,\rho_{fluid} U^3 D L C_L = 0.199\,N \quad (11)$$

The amplitude of the cylinder as a function of time $y(t)$ is given by (12) below where damping coefficient, ζ is assumed to be 0.06 [8].

$$y(t) = [\,F_L \sin(\omega_n t + (\pi/2))\,/[k\sqrt{(1-(f_s/f_n)^2)^2 + 4\zeta^2 (f_s/f_n)^2}] \quad (12)$$

Then, the velocity of the cylinder $v(t)$ is determined by differentiating (12) as shown in (13) below.

$$v(t) = (d/dt)y(t)$$

$$v(t) = [\,F_L\,\omega_n \cos(\omega_n t + (\pi/2))\ /[k\sqrt{(1-(f_s/f_n)^2)^2 + 4\zeta^2 (f_s/f_n)^2}] \quad (13)$$

Power is calculated by the result of the maximum velocity multiplied by the force of lift experienced by the cylinder. The frequency of $P(t)$ is doubled the frequency of velocity or lift force since it contains product of sine [13].

$$P(t) = v(t) \times F_L \sin(\omega t) = 0.049\,W \quad (14)$$

Mean power for cylinder is calculated on (15).

$$P_{RMS} = P_{max}/\sqrt{2} = 0.035\,W \quad (15)$$

The theoretical upper limit of power in fluid is calculated on (16) below.

$$P_{fluid} = 0.5\,\rho_{fluid} U^3 D L = 0.33\,W \quad (16)$$

Efficiency η is calculated as (17) below.

$$\eta = P_{RMS}/P_{fluid} = 0.105 \quad (17)$$

III. Result and Discussion

Based on calculation obtained, the theoretical results are tabulated in Table II [14].

TABLE II
THEORETICAL RESULTS CALCULATION

PVC [Inch]	0.5	1	1.5	2.0
Diameter [m]	0.016	0.027	0.041	0.053
Re	$8.9x10^3$	$1.5x10^4$	$2.3x10^4$	$2.9x10^4$
Stiffness [N/m]	212	115	84	75
$y(t)$ [m]	0.003	0.006	0.009	0.010
$v(t)$ [m/s]	0.14	0.31	0.45	0.51
P_{max} [W]	0.021	0.049	0.073	0.083
P_{RMS} [W]	0.015	0.035	0.052	0.057
P_{fluid} [W]	0.197	0.332	0.510	0.654
Efficiency, η	0.076	0.105	0.101	0.087

It is important to find the range of shedding frequencies that matches with natural frequency design energy harnessing device. As the lock in condition is the main goal of this project, the stiffness of springs for each testing cylinder diameters is varied in order to match the shedding frequency with natural frequency. It showed that spring stiffness decreases when the diameter of cylinder is increased. The different in stiffness of springs are due to the different of mass applied for each of the cylinders. Lock-in condition has the potential to enlarge the amplitudes of bodies' oscillation which can result in higher power generation rate.

From Table II, it showed that *Re* generally increases with an increase of cylinder diameter (other parameters are constant) which can result in higher cylinder amplitude. Velocity of cylinder is found by differentiating the equation of displacement, $y(t)$ with respect to time. As the range of Reynolds number targeted in this project is within ($300<Re<3x10^5$), the diameter of tested cylinder need to be chosen within this range of *Re*. It also clearly showed that as the diameter of cylinder is increased, the maximum power of the system increases. This is due to the increase of *Re* which is related to the cylinder diameter. The increase of *Re* will result in higher cylinder velocity. Thus, it will increase the power generation rate of cylinder.

The highest efficiency showed in this result is on the 1'' tested cylinder. It showed that power efficiency of cylinder is reduced as the diameter cylinder increases. This could due to complex interaction between the turbulent flow and the structure. The random and fluctuating motion of the turbulence quantities affects the efficiency of the power generation [14], [15]. It becomes much harder to control the cylinder motion thus reducing the power efficiency. The efficiencies were lower for the larger diameter of cylinders and higher *Re* except for the cylinder 0.5". This might be P_{max} produce by the 0.5" cylinder is too small compared to P_{RMS} which results in the lowest power efficiency.

Maximum power generated by the each cylinder is quite small due to lower cylinder amplitude obtained. Thus, a single unit of VIV system is insufficient to provide power supply to offshore platform. However, this VIV application can be installed in multiple units of cylinders in order to generate sufficient power supply to NUI offshore platform. Although this single system may not capable to generate enough power supply to the offshore platform, VIV can be integrated to the current renewable energy application system such as solar, wind and tidal energy.

IV. Conclusion

The VIV application in generating alternative energy is a viable solution of the current energy extraction problem for offshore application. Although some technologies based on solar and wind energy sources are currently being developed for offshore platform application, not all these technologies are suitable for Malaysian offshore platform areas due to their self-limitation. Further research on maximizing VIV phenomenon will be done to increase energy extraction rate based on the geometries of cylinder. Different design of VIV system will be numerically and experimentally researched to trigger more rigorous vortex shedding activities thus enhancing energy generation. VIV also has the potential to be integrated and applied on the offshore platform with the other renewable energy technologies such as solar, wind and tidal.

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