Experimental Study of Spacing Ratio Effect on Multiple Cylinders Vortex-Induced Vibration Energy Converter (VIVEC) Performance

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October 27, 2020

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Abstract. Votex-Induced Vibration Energy Converter (VIVEC) is one device that utilizes current-energy. VIVEC converts the translational motion up and down from a bluff bodies (such as cylinder) attached to a slider into electrical energy. The release of the vortex that forms around the cylinder when it hit by water at a certain speed causing the cylinder oscillating. Several parameters can improve the performance of VIVEC; one of them is the addition of the number of cylinders or using the multi-cylinders on VIVEC. By using the multi-cylinders system, the distance between the cylinders needs to be considered because the vortex formed from one of the cylinders will affect the frequency of other cylinder oscillations behind it. This experiment used a multi-cylinders VIVEC with 2x2 configuration accompanied by distance variation (L / D = 2,4, and 6) and conducted with a fluid velocity of 0.67 m / s (Re = 50,000) in a towing tank. From this research, it was found that the rear cylinder had a better performance than the front with the peak of average A/D reached 0,739 for the upper-end cylinder in L / D = 2.. The power obtained and the efficiency are relatively decreased as the centre to centre spacing increases.

INTRODUCTION

In 2004, Michael Bernitsas et al. from the Dept. of Naval Architecture and Marine Engineering, the University of Michigan, had made an energy conversion device that utilizes current energy by converting vibrations in the fluid flow into electrical energy called Vortex-Induced Vibration Aquatic Clean Energy (VIVACE). VIVACE applies the hydrokinetic principle that exists in Vortex-Induced Vibration (VIV), which is a vibration generated by a vortex in a fluid, such as water or air. Research conducted on VIVACE so far focused on single-cylinder configurations. Whereas in the concept, the higher the kinetic energy, the higher the power that will be generated. As an alternative, the number of cylinders was added to VIVACE. In addition, the distance between cylinders or the Spacing Ratio (L / D) affects the force on each cylinder. Thus, it also affects the amount of amplitude that is formed (Garcia, 2008).

To design the multiple cylinders of VIVEC, it is critical to consider the interference between the cylinder, especially under the raspy operating environment. Zdarvkovich (1985, 1997, 2002) divide the interactions of multiple of two-cylinder into three types:

a) Proximity interference which occurs when the cylinders are close to each other.
b) Wake interference when one cylinder is in the wake of the other.
c) No-interference which happen when the cylinders are sufficiently apart so that they are almost fluid dynamically independent of each other.

Previous researches have been carried out using two rigid circular cylinders in tandem with the L / D variation < 3.0 which is regarded as proximity interference (Zdravkovich, 1997a; Chen 1986) and the behaviour of each spacing ratio variation is explained in Table 1.

TABLE 1. Characteristics of multicylinder in the different spacing ratio value

L / D	Charateristics
L / D ≤ 1.1	Two cylinder behave like a single bluff body and the vortex can only be found after the rear cylinder
1.1 ≤ L / D ≤ 1.6	The shear layer of the upstream alternatingly reattaches to the downstream cylinder and vortex shedding occurs on the downstream one
1.6 ≤ L / D ≤ 2.5	The shear layer of first cylinder attach to the second cylinder and again the vortex shedding only happens after the second one
2.5 ≤ L / D ≤ 3.2	Vortex shedding can be observed intermittently in the gap between two cylinders
L / D = 3.0-4.0	The critical separation of proximity interference and wake interference regions

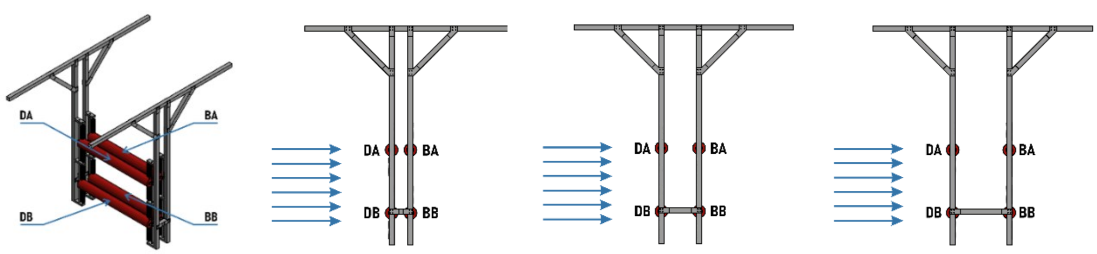
In addition, Ruseheweyh conducted an experiment in 1983 with L / D value was much smaller than ten and found out that the Significant vibrations happening in the region L / D < 5. (Shiraishi et al. [1986]) has suggested that the generation mechanism for "interference galloping" for the tandem circular cylinder was on account of the unsteady effect of the "gap flow," was initially reported by Zdravkovich (1977b).

By adapting the work concept to VIVACE, a study was made using Vortex-Induced Vibration Energy Converter (VIVEC). VIVEC converts the translational motion up and down from a bluff bodies (such as cylinder) attached to a slider into electrical energy. The release of the vortex that forms around the cylinder when it hit by water at a certain speed causing the cylinder oscillating. Several parameters can improve the performance of VIVEC; one of them is the addition of the number of cylinders or using the multi-cylinders on VIVEC. By using the multi-cylinders system, the distance between the cylinders needs to be considered because the vortex formed from one of the cylinders will affect the frequency of other cylinder oscillations behind it. This experiment used a multi-cylinders VIVEC with 2 x 2 configuration accompanied by distance variation (L / D = 2,4, and 6) and conducted with a fluid velocity of 0.67 m / s (Re = 50,000) in a towing tank.

RESEARCH METHOD

VIVEC is a structure that consists of an oscillating part (cylinder) held by a spring that is attached to the ends of the cylinder, which utilizes vibrations affected by fluid flow. In this experiment, the cylinder used consisted of PVC with a diameter of 2.5" and 0.85 m length, which was given an iron plate as an additional mass to achieve the desired buoyancy. The oscillating cylinder made of stainless steel cylindrical with a diameter of 12 mm serves as a buffer plate iron.

The frame and slider system of the oscillating cylinder is needed to support the system. This frame functions as a barrier to the oscillating cylinder, placed in the test train on the towing tank. The frame used made of square hollow stainless steel which can be set based on variations in the distance between cylinders.



(a) (b) (c) (d)

FIGURE 1. (a) The design ssembly of VIVEC, (b) The side view design for spacing ratio (L / D) 2, (c) The side view design for spacing ratio (L / D) 4, (d) The side view design for spacing ratio (L / D) 6.

VIVEC tests were performed using towing tanks at ITS Laboratory and placed on the towing tank train then pulled at the speed 0.67 m / s. This speed selection was based on previous research, which shows that the efficiency that can be harnessed by the VIVEC is in the range Reynolds number $10^4 - 10^5$ (Zdravkovich, 1997c).

In order to calculate the efficiency of VIVEC, several parameters are required both from the measurement process and calculation. Equation (1) describes the natural frequency formula, where k is the spring stiffness and m_{app} is the sum of the mass of the pipe and added mass.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m_{app}}} \tag{1}$$

Then, the velocity as a function of time v(t) for each cylinder in all variation of L / D is determined by differentiating the equation (3), where F_L is a lift force is the result of the multiplication of spring stiffness (k) and the displacement obtained from the experimental results and it described in equation (2). Meanwhile f_s is the karman vortex frequency of the cylinder during the experiment, and ζ is the damping ratio which is assumed to be 0.6 from the previous studies (Hall-Stinson, 2011).

$$F_L = k \times A \tag{2}$$

$$\text{v(t)} = \frac{d}{dt}y(t)$$

$$\text{v(t)} = \frac{F_L \omega_n \cos(\omega_n t + \frac{\pi}{2})}{k\sqrt{(1-(\frac{f_s}{f_n})^2)^2 + 4\zeta^2(\frac{f_s}{f_n})^2}} \tag{3}$$

Power as a function of time is obtained by multiplying the maximum velocity with the lift force experienced by the cylinder as shown in equation (4).

$$\text{P(t)} = \text{v}(t)F_L \sin\omega_n \tag{4}$$

Mean power P_{RMS} is calculated using the maximum power *P(t)* using the equation (5), whie P_{MAX} obtained from the maximum power for each cylinder from previous calculation using equation (4).

$$\text{P}_{RMS} = \frac{P_{MAX}}{\sqrt{2}} \tag{5}$$

Based on the Bernoulli's equation, the upper limit of power in fluid P_{fluid} can be defined as

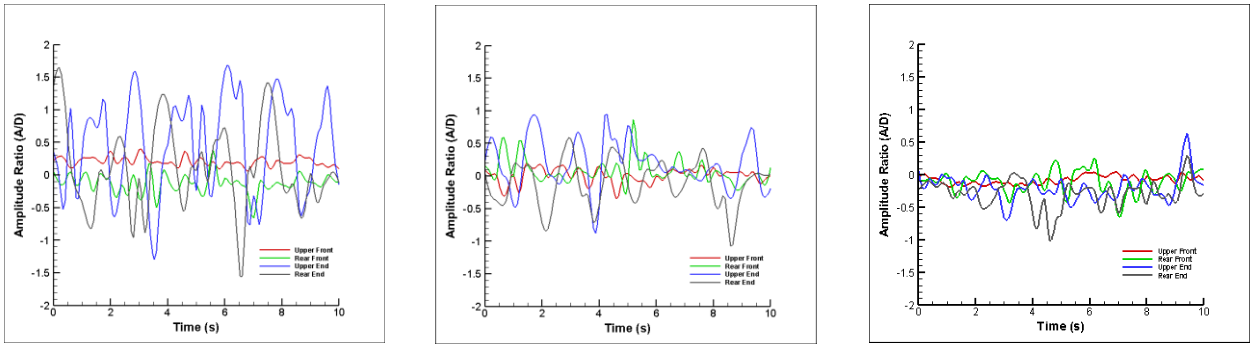
$$\text{P}_{fluid} = \frac{1}{2}\rho_{fluid}U^3 DL \tag{6}$$

As a result, the efficiency of VIVEC in the fluid per unit length is

$$\eta_{VIVEC} = \frac{\text{P}_{RMS}}{\text{P}_{fluid}} \times 100\% \tag{7}$$

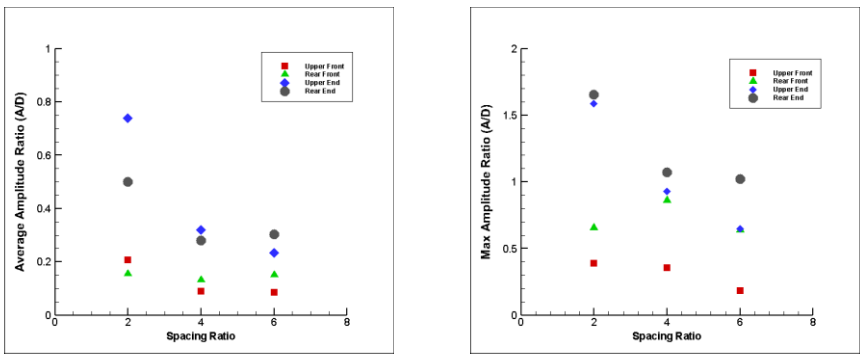
RESULT AND DISCUSSION

Based on the experimental conducted, the result of the amplitude ratio (A / D) in dependence on L / D value is shown in Fig. 2. In this discussion, the non-dimensional value for the amplitude ratio is used to simplify the further research.



(a) (b) (c)

FIGURE 2. Amplitude Ratio (A / D) respons of each at (a) L / D = 2, (b) L / D = 4, (c) L / D = 6



(a) (b)

FIGURE 3. (a) Average A / D of each cylinder in dependence on L / D value, (b) Maximum A / D of each cylinder in dependence on L / D value

Fig. 3 describes the relation between average and maximum A / D and changes in L / D value. It can be seen that the rear end cylinder always obtains the highest maximum A / D in all variations with a value reaching 1.653. Followed by the upper end, rear front cylinders, and finally, the upper front cylinders with a value of 0.388. This sequence trend occurs in all variations of the spacing ratio.

However, this does not apply to the average amplitude ratio relationship in the variations of A / D 2 and A / D 4; the upper-end cylinder obtains the highest value with the difference reaching 0.238 to the rear-end cylinder. Also, on this graph, the rear-front cylinder owns the smallest average A / D value in variations A / D 2 and upper-front A / D 4 and 6.

TABLE 2. Performance Result Calculation for L / D = 2

Cylinder	***Upper Front***	***Rear Front***	***Upper End***	***Rear End***
Lift Force, F_L (N)	1.74	1.30	6.23	4.23
Maximum Power, P_{max} (W)	0.17	0.53	2.92	4.24
Average Power, P_{RMS} (W)	0.12	0.37	2.06	3.00
Power in Fluid, P_{Fluid} (W)	9.56			
Efficiency, η (%)	1.27	3.96	21.60	31.39
Efficiency Total, η (%)	58.24			

TABLE 3. Performance Result Calculation for L / D = 4

Cylinder	*Upper Front*	*Rear Front*	*Upper End*	*Rear End*
Lift Force, F_L (N)	0.75	1.10	2.69	2.39
Maximum Power, P_{max} (W)	0.15	0.27	0.32	1.20
Average Power, P_{RMS} (W)	0.10	0.27	0.32	1.20
Power in Fluid, P_{Fluid} (W)			9.56	
Efficiency, η (%)	1.14	2.92	3.43	12.54
Efficiency Total, η (%)			20.05	

TABLE 4. Performance Result Calculation for L / D = 6

Cylinder	*Upper Front*	*Rear Front*	*Upper End*	*Rear End*
Lift Force, F_L (N)	0.72	1.27	1.96	2.56
Maximum Power, P_{max} (W)	0.05	0.27	0.16	1.41
Average Power, P_{RMS} (W)	0.03	0.19	0.11	1.00
Power in Fluid, P_{Fluid} (W)			9.56	
Efficiency, η (%)	0.37	2.01	1.19	10.46
Efficiency Total, η (%)			14.05	

Tables 2, 3, and 4 compare four characteristics in terms of lift force, maximum and average power, and efficiency obtained from each cylinder in all spacing ratio variations. It is evident that both end-cylinders have a better performance than the two cylinders in front of it.

The rear-end cylinder obtains maximum power in all variations of the spacing ratio, namely 4.24 watts at the spacing ratio 2, 1.69 watts at the spacing ratio 4, and the 1.41 watts the spacing ratio 6, while the upper front cylinder obtains the lowest performance.

CONCLUSIONS

The VIVEC application as an alternative to renewable energy is a viable option given its ability to produce energy at low currents. One important parameter that determines the performance of VIVEC with multiple cylinders is the spacing ratio, where based on the experiments that have been carried out, the smaller the L / D value, the better the performance. This result corresponds with several experiments that have been carried out previously where the characteristics of the vortex flow can interfere with the cylinder behind it in a specific L / D range. In addition, overall, the performance of the rear cylinder is better than the two cylinders in front.

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