ENERGY GENERATION FROM OCEAN CURRENTS AND RIVERS USING ELASTICALLY INTERCONNECTED CYLINDERS

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ABSTRACT

Spring-mass systems are known to experience vortex-induced vibrations (VIV) when exposed to viscous flows. These vibrations can be efficiently used for energy generation in ocean currents and rivers because significant power density can be extracted even from moderate flow velocities. The VIV generators typically include a large system of vertical or horizontal cylinders aligned perpendicular to the flow. The cylinders are connected elastically to a fixed frame and can oscillate independently. A recent comparative study shows that the VIV generators compete well with other renewable energy sources and clean technologies. This manuscript presents a new technique aiming to increase further the efficiency of the VIV energy generators by introducing some coupling between the motions of their cylindrical members. The VIV of circular cylinders is evaluated with CFD simulations. The motions of independently oscillating cylinders are compared to the motions of elastically interconnected cylinders. The numerical analysis shows that the motion amplitudes can be amplified significantly with suitable elastic interconnections between the cylinders. The proposed approach requires designing various VIV frequencies for the different members of the system, which does not allow them to synchronize their phases, and introduces instability in the motion patterns. The elastic interconnections can increase the efficiency of the green energy generation between 10% and 20% compared to previously proposed similar systems.

Keywords: VIV, blue energy, energy converter, oscillating cylinders

INTRODUCTION

A body exposed to viscous flow can shed vortices with alternating directions [1]. The vortex wake occurs for a wide range of flow velocities. The nearest to the body vortices produce uneven pressure distribution around the body surface. As a result, a mass-spring system exposed to the flow can experience vortex-induced vibrations (VIV) driven by the fluid-body interactions and the elastic restoring force. Maximum vibrational amplitudes occur when the vortex shedding frequency is near the natural frequency of the mass-spring system. It is not a simple resonance case, because large amplitudes can occur for a range of velocities where the vortex shedding frequency adjusts and synchronizes with the natural frequency of the oscillatory motion in a process known as the “lock-in” phenomenon.

VIV can be used for extracting green energy from ocean currents. For example, the VIVACE converter [2] represents a simple and efficient device for generating energy from a wide range of current velocities. The reported power conversion ratio is up to 38%. VIVACE relies on the VIV of a system of cylinders. We will demonstrate here that the mean efficiency can be increased between 10% and 20% by interconnecting the cylinders.

The VIV normally feeds back to the vortex-shedding pattern limiting the maximum motion amplitude to about one body diameter (in water). There are other factors, however, which can increase further the maximum motion amplitude. For example, an additional lift force caused by a cylinder with asymmetrical cross-section can destabilize the VIV and produce larger oscillatory amplitudes. This instability can improve the efficiency of the VIV energy converters by increasing the kinetic energy of the vibrating members. The simplest way to invoke instability is by adjusting the cylinders' geometry. The related motion pattern known as galloping, however, is sensitive to the direction and the magnitude of the flow velocity. The asymmetries may also increase the drag, making the design more challenging.

We propose an alternative method to destabilize the VIV wake pattern by interconnecting elastically the vibrating cylinders. The instability, in this case, would be due to the fact that the restoring force of each cylinder depends on the motions of its neighbouring cylinders. Such an arrangement would work proving the VIV of the different cylinders do not synchronize through the elastic connections. Therefore, the system needs to be designed to ensure significantly different VIV frequencies for the neighbouring cylinders.

MOTION AMPLIFICATION METHOD

The equation of a cylinder vibrating transversely to the flow due to vortex shedding is:

$$m\ddot{y} + b\acute{y} + ky = L(t) \tag{1}$$

where m is the mass of the cylinder, b is the damping coefficient, k is the stiffness coefficient and $L(t)$ is the force induced by the vortex shedding [3]. The cylinder locks-in and experiences largest motion amplitudes when the vortex shedding frequency

$$f_v = S_t \frac{U}{D} \tag{2}$$

coincides with the natural frequency of the mass-spring system

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m + m_a}} \tag{3}$$

where U is the flow speed, D is the diameter of the cylinder, S_t is the Strouhal number equal to 0.2 for subcritical flows, and m_a is the added mass of the water. Both frequencies depend on the fluid velocity because the drag from the flow drag usually tightens the spring system increasing its stiffness k. Large amplitudes occur for a range of reduced velocities:

$$U_r = \frac{U}{f_n D} \tag{4}$$

because the vortex shedding tends to adjust and synchronize with the frequency of the oscillatory motion.

Consider a simple interconnected two-cylinder system restricted to oscillate in the perpendicular to the flow direction *y*; see Figure 1. The spring stiffness *k* is selected to be the same for all springs.

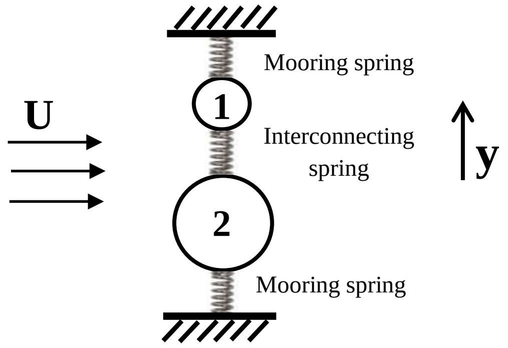

Figure 1. A two-cylinder interconnected system.

The coupled system of equations in this case becomes:

$$\begin{vmatrix} m_1\ddot{y}_1 + b_1\dot{y}_1 + k(2y_1 - y_2) = L_1(t) \\ m_2\ddot{y}_2 + b_2\dot{y}_2 + k(2y_2 - y_1) = L_2(t) \end{vmatrix} \tag{5}$$

The spring restoring force for each cylinder now depends on the motion of the other cylinder, as can be seen from the third term of the equations (5). The motion pattern destabilizes within time intervals when the sign of the restoring force is the same as the sign of the displacement

$$(2y_1 - y_2)y_1 > 0 \text{ or } (2y_2 - y_1)\, y_2 > 0 \tag{6}$$

leading to motion instabilities; see Figure 2.

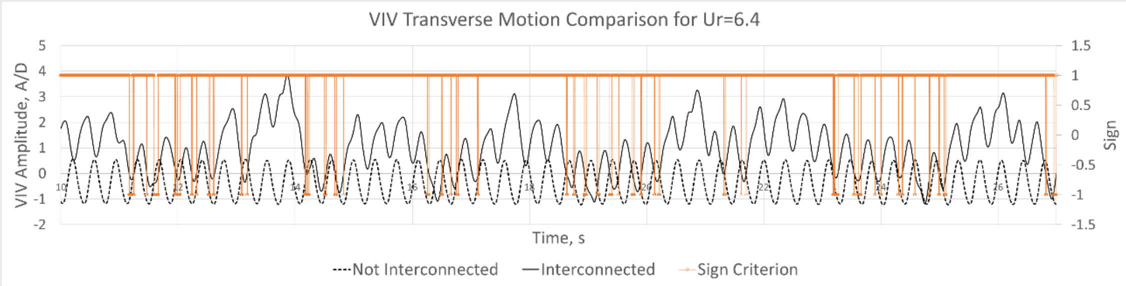

Figure 2. Instability sign criterion (6) demonstration.

The expectation is that optimal amplitude amplification would be achieved by designing system members satisfying the following requirements as close as possible:

- To prevent phase synchronization, select the diameter parameters so that the vortex-shedding frequencies (2) of the neighboring cylinders are sufficiently different. The frequency ratio should exceed a certain threshold (e.g. 1.5), taking into account the ability of the vortices to adapt to the motion pattern.

- To ensure that the cylinders will oscillate in the same flow velocity range, design members with similar reduced velocities. According to formulas (3) and (4), the spring stiffness and the mass parameters should be selected to achieve similar f_nD terms for the different cylinders.

- The highest VIV amplitudes typically occur in the lock-in regime and this is where the energy converters are most efficient. The lock-in corresponds to reduced velocities U_r in the range of 6 to 9 approximately. To maintain lock-in for a given cylinder diameter D, the natural frequency f_n needs to grow with the flow velocity U according to (4). There are active and passive methods to accomplish that. The active ones may use U-feedback and vary f_n by adjusting the pretension of non-linear mooring springs. A passive method may rely on the natural tightening of the mooring spring system caused by the drag force when the cylinders are exposed to flow. For example, consider a cylinder supported by four linear mooring springs (Figure 3). It can be calculated that the drag force would produce an offset that increases the transverse stiffness k_y with U in a non-linear way. The non-linearity depends on the geometrical asymmetry of the system exposed to the flow. Therefore, to maintain f_n roughly proportional to U, we need to use longer mooring springs, which minimize the asymmetry for the expected offsets.

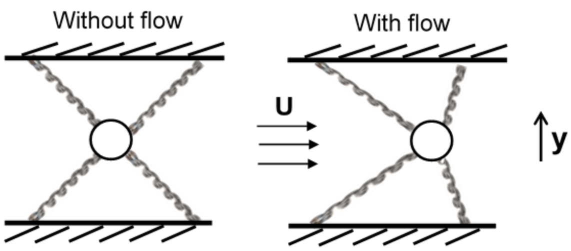

Figure 3. Transverse mooring stiffness increases for higher flow velocities

A theoretical case matrix is presented next based on the requirements above. To verify the proposed VIV amplification method, we will study two-cylinder systems. The cylinders are constrained with horizontal linear mooring springs in *X* and *Y* directions. Tables 1 and 2 present the parameters and the case matrix for the two-cylinder problem.

Table 1. Parameters of the two-cylinder problem

Parameters	**Ratio**
Diameters	1:2
Lengths	1:1
Mass	1:4
Mooring Stiffness	1:1
f_n , f_v	2:1
Connector Stiffness / Mooring Stiffness	1:10, 1:1, 10:1
U_r	1:1

The connector stiffness was selected based on $U_r=3.2$, and the rest of the flow velocities were simulated only for the selected stiffness ratio of 1:1. The decision was made because the stiffest connector (10:1) forces the smaller cylinder to follow the larger cylinder, while the softest connector (1:10) case is similar to the disconnected state where the cylinders oscillate independently. Only the stiffness ratio of 1:1 produced the desired motion amplification.

Table 2. Case matrix for the two-cylinder problem

Parameters	**Cases**
Connector Stiffness / Mooring Stiffness	1:10, 1:1, 10:1
Connectors	0 or 1
Vr	1.6, 3.2, 4.8, 6.4, 8.0

A Volume-of-Fluid (VOF) technique was used in ANSYS Fluent to simulate the flow around the cylinders. We have benchmarked extensively the numerical analysis for cylinder VIV phenomena [4]. The moving hybrid (quad/tri) meshes used in this study are shown in Figure 4. They consist of 300,000 elements. The DES (Detached Eddy Simulation) approach [5] was used for turbulence modeling. The unsteady RANS model was implemented in the boundary layer, while the LES treatment was applied to the separated regions. Appropriate turbulent length scales of $k^{0.5}/\omega$ and $k^{1.5}/\varepsilon$ determined the RANS/LES boundary. Figure 5 shows a computed distinct VIV pattern for $U_r=3.2$.

The time discretization was selected to maintain the Courant number below 1.0 according to the turbulence modeling requirements.

The numerical results summarized in Table 3 show that the highest efficiency gain could be achieved in the lock-in regime. This is also the regime where the VIV converters are

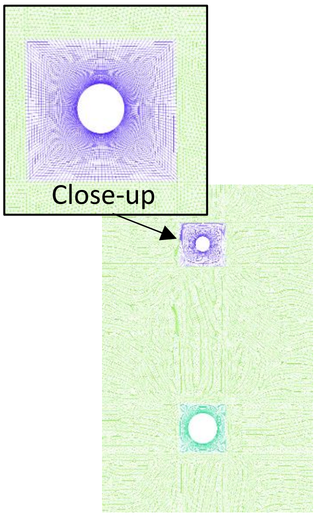

Figure 4. CFD mesh

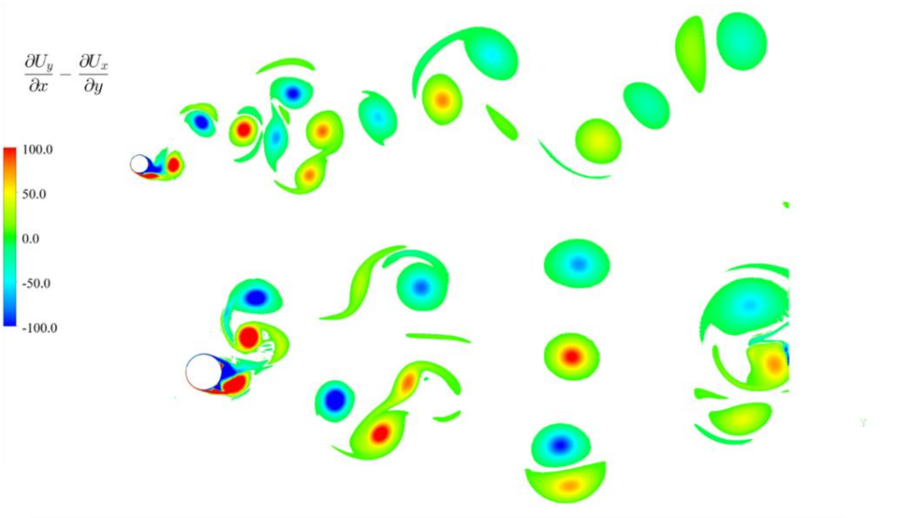

Figure 5. A computed VIV pattern behind the two cylinders

most efficient reaching the highest amplitude oscillations (*A/D* ratio). There is a discussion in the previous section on how the converter can be designed to stay in a lock-in regime for a wide range of flow velocities. Figures 6-10 compare motions and energies for the lock-in case. It is clear that the elastic interconnection between the cylinders destabilizes the vibration pattern and produces significantly higher amplitudes and kinetic energies; see Table 4.

Subcritical flows ($Re<10^5$) were used everywhere.

Table 3. Interconnection effect

U_r	Amplitude Increase (St Dev)	
	Large Cylinder	**Small Cylinder**
1.6	4%	12%
3.2	-23%	14%
4.8	16%	22%
6.4 (Lock-in)	**65%**	**58%**
8.0	28%	97%

Table 4. Efficiency improvement

$U_r = 6.4$	Energy Increase	
	Large Cylinder	**Small Cylinder**
Max	83%	164%
St Dev	17%	55%
Mean	10%	20%

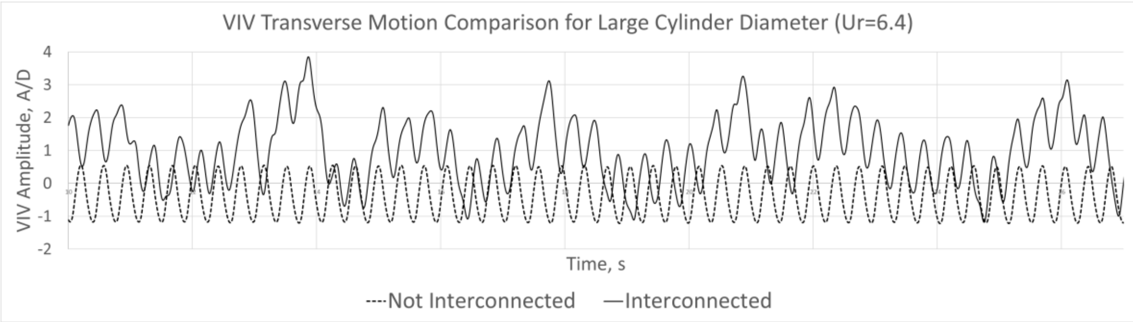

Figure 6. The St Dev of the large cylinder diameter motion increased 58% due to the elastic interconnection

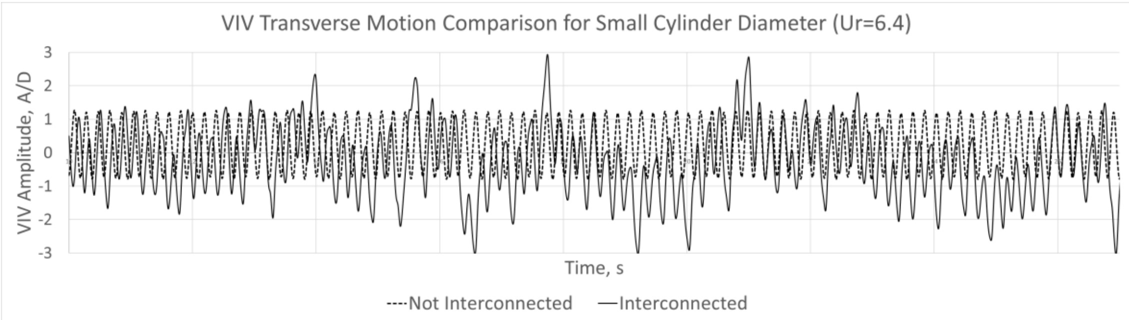

Figure 7. The St Dev of the small cylinder diameter motion increased 58% due to the elastic interconnection

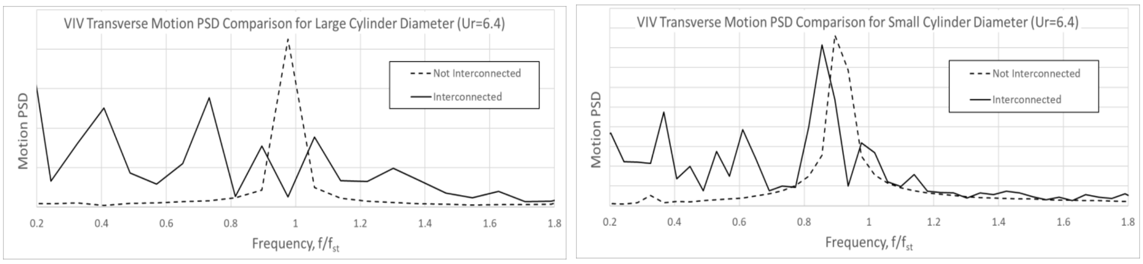

Figure 8. Power Spectral Density (PSD) motion comparison for the large and small cylinders

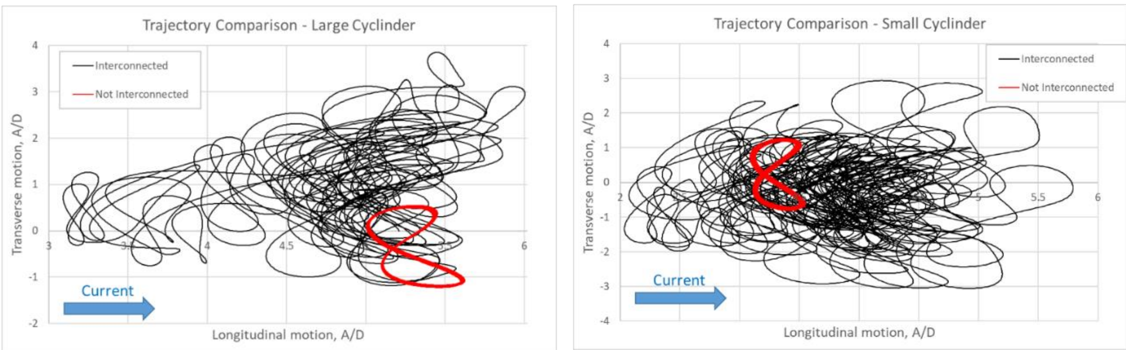

Figure 9. Trajectory comparison for the large and small cylinders (U_r=*6.4*)

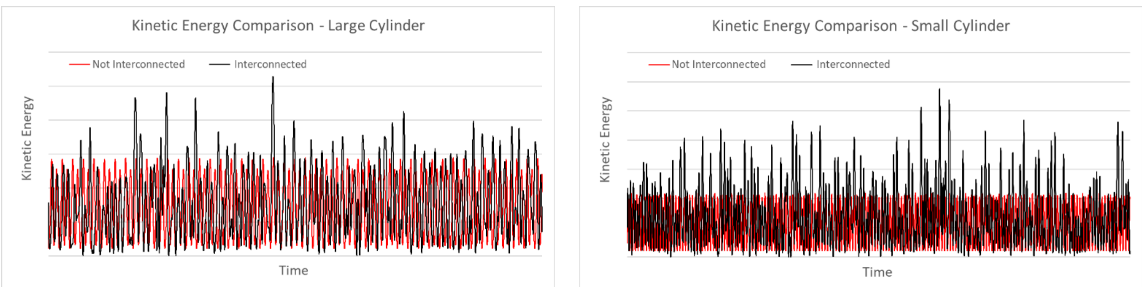

Figure 10. Kinetic energy comparison for the large and small cylinders (U_r=*6.4*)

CONCLUSION

The presented CFD results imply that the efficiency of VIV-based energy converters can be improved significantly by introducing suitable elastic interconnections between their cylindrical members. The advantages of the new method are especially pronounced in the lock-in regime. Interconnecting springs with stiffness close to the mooring stiffness tend to perform better. The increase in motion amplitudes and velocities is due to instability caused by the interconnections. The expected instability in the motion pattern was predicted analytically and confirmed with CFD analysis. The motion amplitudes increase by up to 97%. The kinetic energies show a 10% - 20% increase in the mean values and up to a 164% increase in the maximum values.

The findings from the numerical analysis will be experimentally verified during the next study. Tests with cylinders in a cavitation tunnel are being planned. The motion amplitudes and velocities of independently moving cylinders will be measured and compared to the motion of identical interconnected cylinders.

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