Energy harvesting from the flow induced motion of flexible mangrove root-type models with different flexibilities.

Amirkhosro Kazemi (Purdue), Eduardo E Castillo Charris (Turabo), Daniel Gomez (Turabo), Humberto Bocanegra Evans (Texas Tech) , Oscar M Curet (FAU), Luciano Castillo (Purdue)

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Abstract

- Red mangroves, *Rhizophora mangle*, in coastal areas comprised of rigid and flexible roots (*Pneumatophores*) oscillating in the water. The oscillations of the flexible root provide a new source of renewable energy. These oscillations can essentially be harvested as electrical power from tidal currents of the shallow coastal water in the form of pollution-free energy by converting the kinetic energy of the moving fluid into voltage. Understanding and quantifying an optimal regime in vortex induced vibrations (VIV) and energy harvesting is a major challenge and objective of this research. We present an elastically mounted rigid circular cylinder as simplified flexible mangrove roots attached to a coil and magnet to understand the role of flexibility on the vortex-induced vibration phenomena for energy harvesting. In a series of experiments, we performed kinematics measurements inside a water channel for the cylinders limited to a transverse oscillation (one degree of freedom) at constant velocities ($200 \le Re_d \le 1400$) . We tested three different flexibilities, and found that the optimal range for the middle flexibilities is $4 < U_r < 6$.

Introduction

- Mangroves are salt-tolerant species of trees that can live along the intertidal coastal zones in tropical and sub-tropical regions [1,2].
- Some unique flexible mangrove roots and branches can oscillate in the water. The oscillations provide great opportunity to harvest energy from the flow in riverine currents.
- We designed a energy harvesting device including a magnet and a coil attached to a rigid circular cylinder which was elastically mounted to a flexible steel plate.
- **Questions:**
  - How do the root flexibilities and water flow velocity affect the energy harvesting from the oscillations?
  - How does the wake respond to a motion of the root that causes the wake?
  - What it the optimum range of efficiency and amplitude for this osculation?

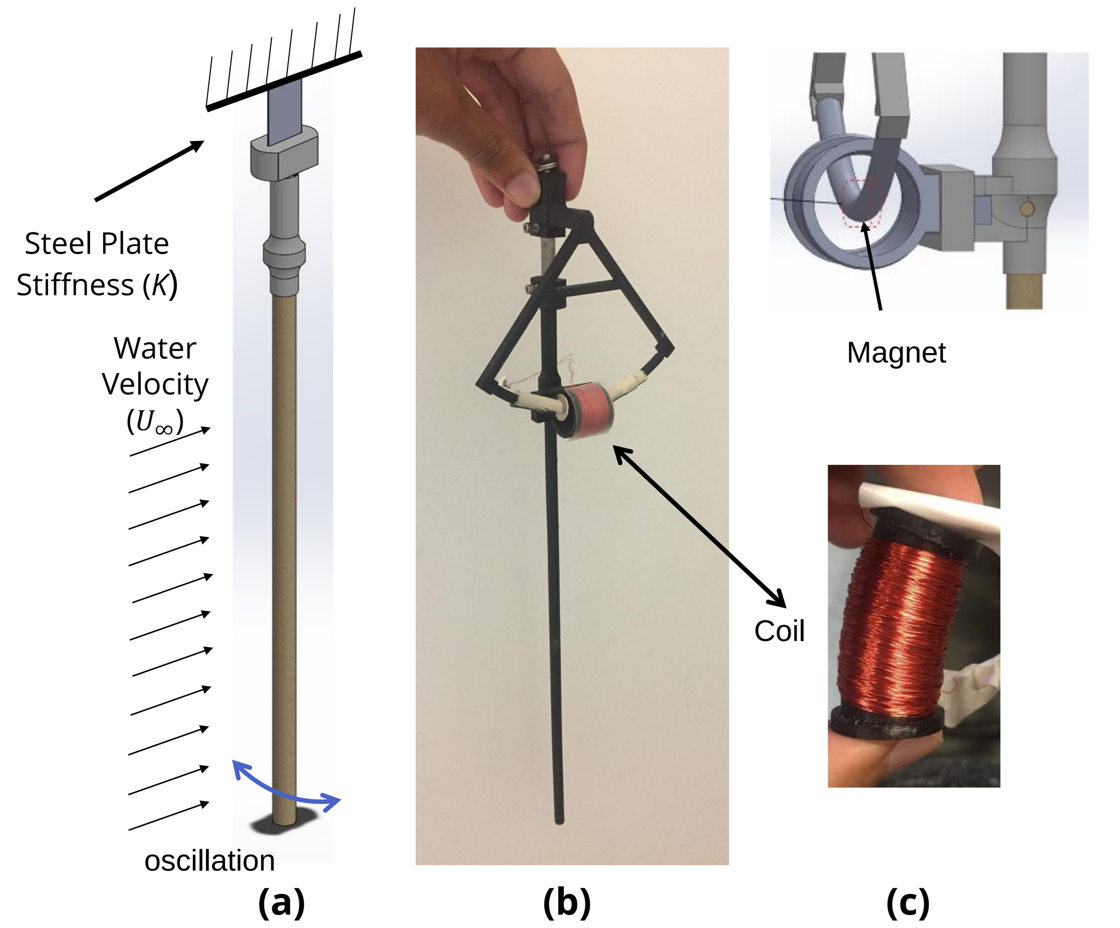
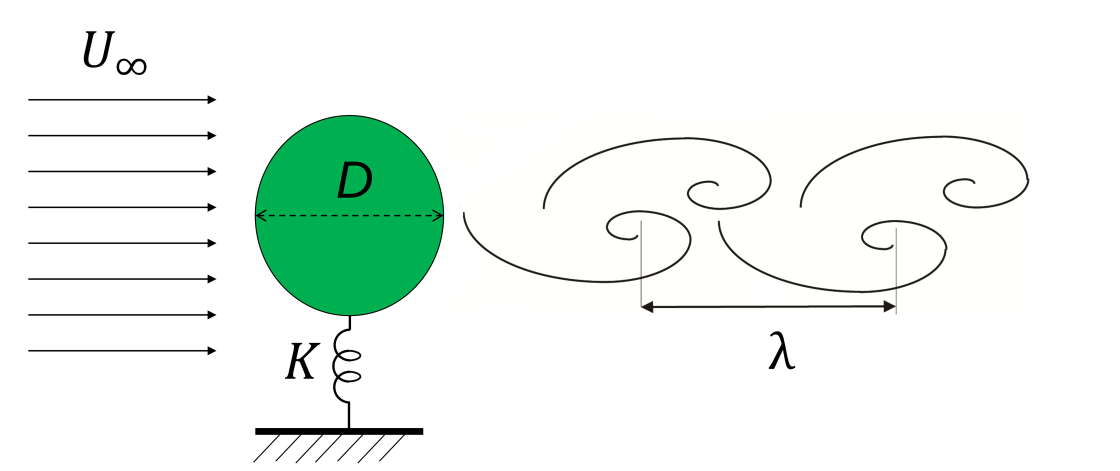


Fig 1. Simplified mangrove root model (*d=6.35 mm*) oscillating in the water current with single cylinder attached to a flexible steel plate (b) Energy harvesting device assembly that was tested with three different flexibilities (c) coil and magnet used to convert kinetic energy into electrical power from the VIV of the cylinder.

Methodology

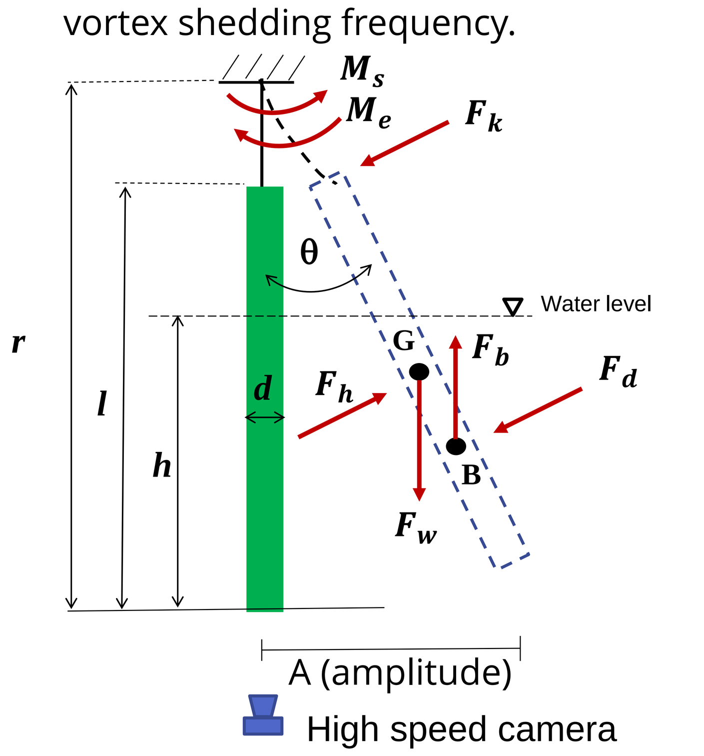


$$T_{Fluid} = \frac{D}{U_\infty} \qquad T_{Vortex} = \frac{\lambda}{U_\infty} \qquad U_r = \frac{T_{Solid}}{T_{Fluid}}$$

Fig 2. Time-scales for VIV; T_{Fluid} corresponds to the time for convection of a particle across the length D, T_{vortex} is period of vortex shedding, T_{solid} is the period of cylinder oscillations and U_r (reduced velocity) is used to compare the dynamics of fluid and of the solid.

Strouhal law: $T_{Vortex} = \frac{T_{Fluid}}{St}$ ⇒ $\frac{T_{Solid}}{T_{Vortex}} = St \times U_r$

- ✓ When $St \times U_r = 1$, shedding of the vortices and motion of the solid happen at the same time-scale and resonance (locked-in) occurs.
- ✓ In the locked-in region the mass-spring system doesn't follow the Strouhal law and the oscillation frequency is fixed with vortex shedding frequency.



h=229 mm
l=254 mm
r= 358 mm
d=6.35 mm
F_k :Torsional spring force
F_b :Buoyancy force
F_w :Gravity force (weight)
F_d: Damping force
F_h: Hydrodynamic force
M_e:Electromagnetic moment
M_s:Support moment

Fig 3. Schematic of free-body diagram of a single root model in VIV in a half cycle oscillation. The oscillation motions were captured with a high speed camera at 256 frame per second at different flow speed from $0.02\,\frac{m}{s}$ to $0.18\,\frac{m}{s}$. We performed image processing to analyze the kinematics of oscillations.

- Static equilibrium of the system

$$M_s - M_k - M_e + \boldsymbol{F_b} \sin\theta\, r_B - \boldsymbol{F_w} \sin\theta\, r_G - k\theta - I\ddot{\theta} = 0$$

$$\omega = 2\pi f_n = \sqrt{\frac{K}{I}} \qquad I = I_a + I_b \qquad K = K_{flexible\ plate}$$

I_a: Added inertia due to cylinder oscillations in water
I_b: Inertia of a hanging root

- Dynamic response of the system

$$I\ddot{\theta} + k\theta = \frac{1}{2}\rho U_r^2 l C_L \sin\left(\frac{2\pi t}{T_{vortex}}\right)$$

$\boldsymbol{\theta(t)}$:Dynamics of the cylinder $\quad$ $\boldsymbol{F(t)}$: Forcing by the wake

Results

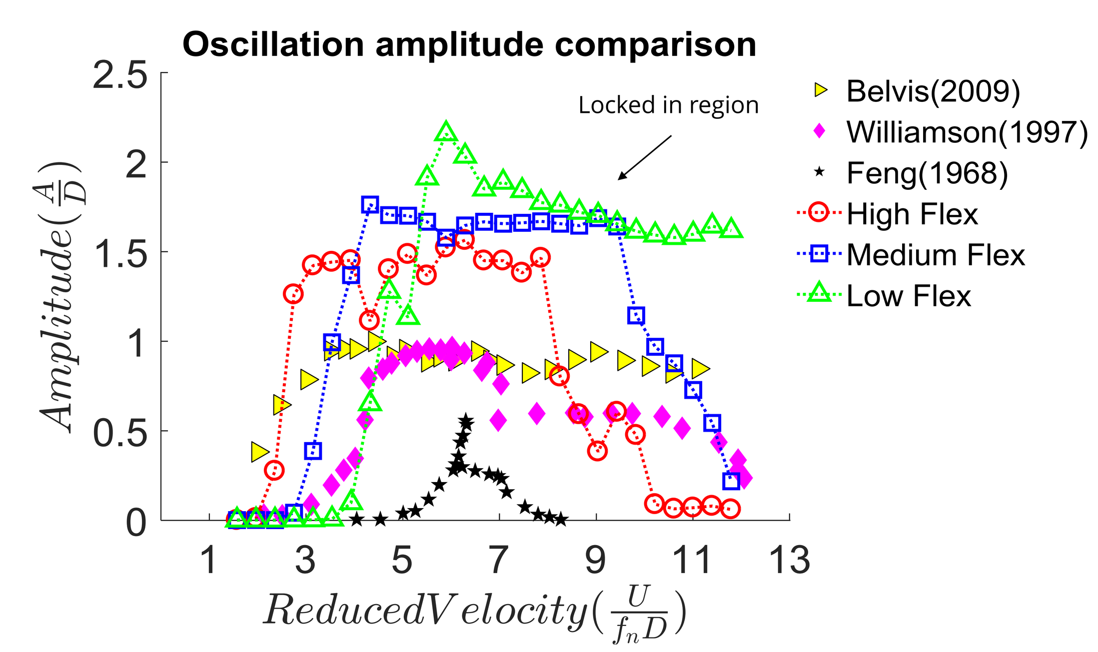
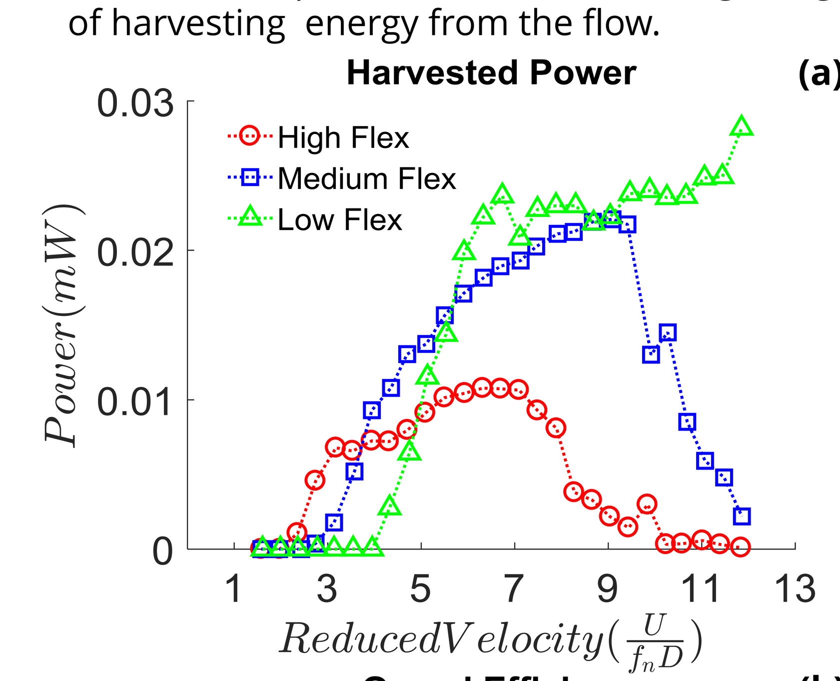


Fig 4. Comparison of normalize amplitude of oscillations versus reduced velocity with different flexibility. It is observed that lower flexibility has the largest region of locked-in (Synchronization).

- ✓ For the low flex, oscillations start at higher kinetic energy of the flow (higher velocities), however, the oscillation amplitude reaches greater values compare to the high flex.
- ✓ It is observed that for higher flexibilities, the oscillation decays with increasing reduced velocity (Reynolds number), however, for the low flex, the region of synchronization increases and remains almost plateaued.
- ✓ The oscillation amplitudes for the present study is considerably higher than the canonical case of cylinder oscillation in previous works, indicating a higher possibility of harvesting energy from the flow.



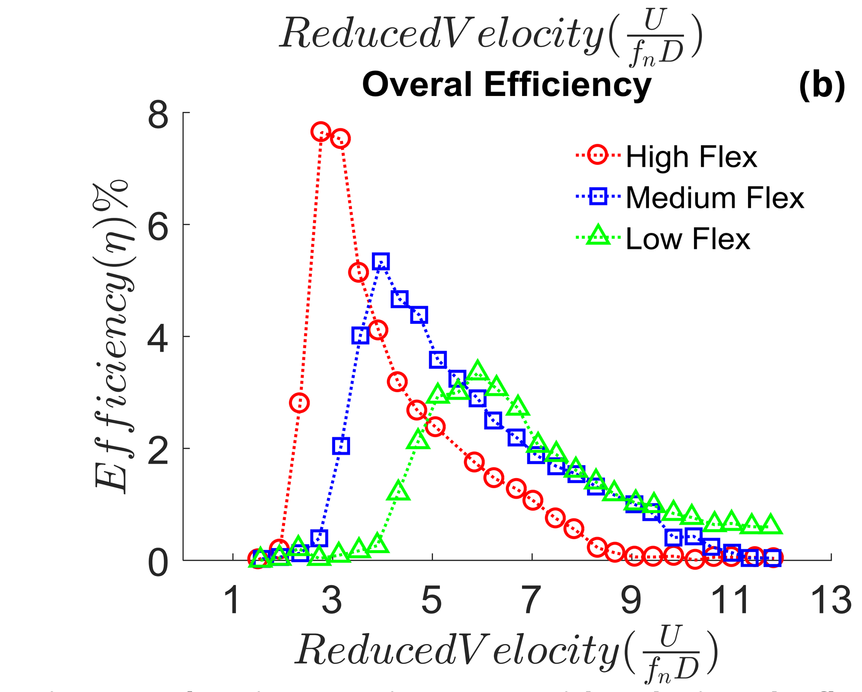


Fig 5. (a) Electric power increases with reducing the flexibilities. (b) overall efficiency ($\eta = \frac{electrical\ power}{fluid\ power}$), where fluid power $= \frac{1}{2}\rho U^3(dh)$.

- It is observed that for the low flex, the electrical power is considerably high at $U_r = 9$, eventhough the efficiency is quite low.

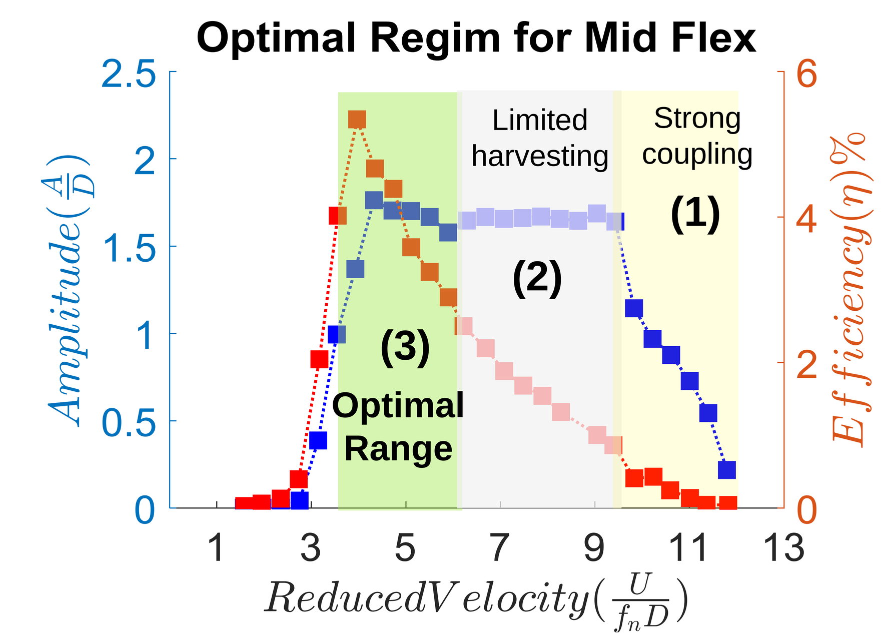


Fig 6. Working range of the system for the middle flexibility. Three distinctive working region can be observed. The optimal range is about $4 < U_r < 6$.

- ✓ **(1) Strong coupling:** vibrations are damped out which reduced the harvested energy and efficiency.
- ✓ **(2) Limited harvesting:** The vibration amplitude is large, however the harvesting efficiency is very limited. Basically, the solid does not see we are taking energy out from it and the cylinder dynamics are marginally impacted.
- ✓ **(3) Optimal range:** The optimum regime the vibrations are modified due to energy extraction but not completely mitigated

Conclusion

- We introduced a new energy harvesting device consist of a rigid cylinder attached to a flexible plate with a coil and magnet. We investigated the effect of root flexibilities and reduced velocity on the range of the achievable amplitude, power, and efficiency. We found that higher flexibility resulted in increasing the frequency of oscillations with a reduction in the reduced velocity. We obtained the optimal range of the working system which the region of both high oscillation amplitude efficiency. This bio-inspired design has potentials for future electricity generations from tidal currents. The proposed work can be used in arrays of cylinders to work as a collaborative system and possibly increase the system efficiency.

Acknowledgements

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