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Dynamics of a River Kite Power Production System with a Kinetic Energy Storage Device

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Abstract **-** Due to the rising costs and negative environmental impact of fossil fuel use, the demand for cheap, sustainable energy has increased. Dams have dominated the water power production industry, but several of them have been dismantled due to some of the negative consequences that come with their use. Dams can disrupt the flow of the river, displace people, and damage ecosystems. To avoid these negative consequences, we propose a different method of harnessing hydropower using underwater kites. Kites can harness energy from rivers and tidal flows without significantly disrupting the flow of water or boat travel. Preliminary research done on an underwater kite power production system is promising, but the results have not been as effective as expected. This reduction in performance is believed to be caused by the loss of momentum when the kite reaches the end of its stroke and changes direction. In order to improve the performance of this hydrokite system, this work examines the dynamics of a system which uses a kinetic energy storage device. This device will store and release energy each cycle via a flywheel. The results from a two-dimensional numerical simulation show that 1188.8 Watts of power can be produced from NACA0015 wing with a wingspan of 0.75 meters and a cord length of 0.125 meters in a river that has a 1 meter per second flow rate.

Keywords**:** Renewable, energy, hydropower, kites, hydrofoil, flywheel.

1. Introduction

In the past 100 years, humans have relied on fossil fuels to meet their energy needs. While fossil fuels have helped spur the industrial revolution, the negative environmental impacts caused by their combustion have gained more attention. With this increased awareness by the general population, the demand for renewable, eco-friendly power has increased as well. Currently, hydropower accounts for 2.3% of the total energy used by all humans with other forms of renewable energy claiming 1.0% (Web-1). Although these numbers represent a small portion of the total annual energy consumption, it is a significant increase when compared to previous decades. The most common renewable energy sources are wind and water. Horizontal-Axis wind turbines and dams are the dominant technologies used to harness these flows.

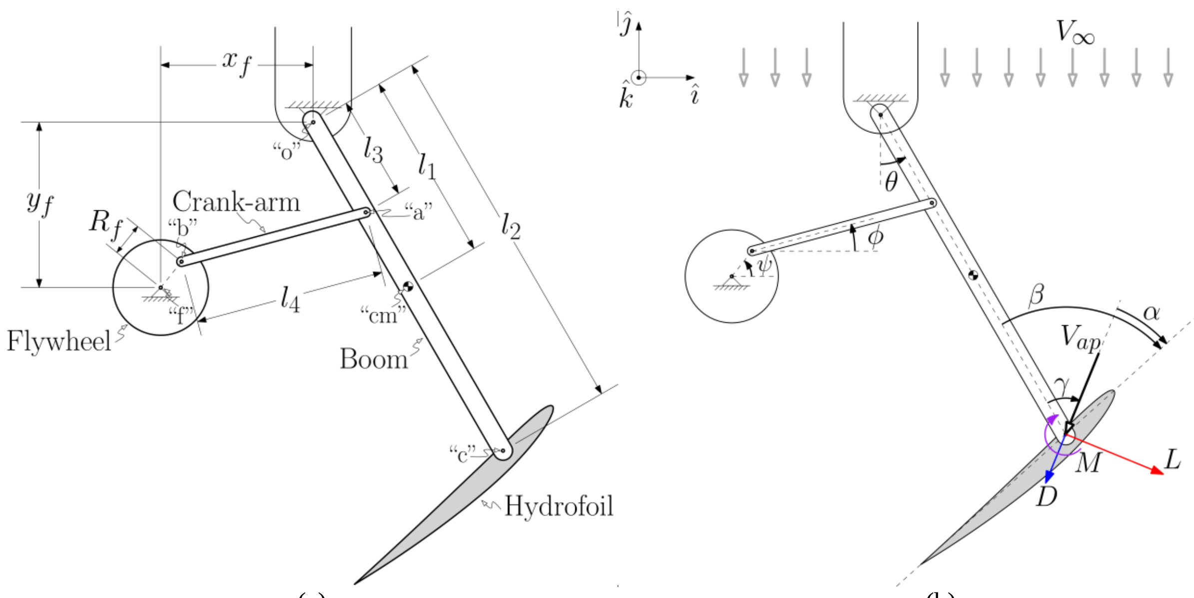
Current hydropower technology can be damaging to the nearby environment. Large reservoirs are formed when dams are built and this water can displace people, destroy homes, damage current ecosystems, and disrupt the flow of the river. Also, as dams generally are large scale and expensive, they can only be economically built in specific geographic locations. Once these locations are exploited, no new installations would be possible limiting the energy that can be harnessed from traditional hydropower plants.

New methods of producing hydropower that do not create as much ecological damage as dams have been created which harnesses energy from rivers and tidal flows. The concept for these methods was based off of high altitude kites, (Loyd 1980, Lansdorp *et al.* 2005) which are able to harness large amounts of power from the strong winds in the atmosphere. If a similar power production method was implemented in place of dams, ecosystems would be less damaged, river flow would remain virtually unchanged, and boats could travel unimpeded. Jones *et al.* (1999) examined the performance of a flutter type underwater kite system that allows two degrees of freedom pitch and plunge with limited translational motion.

McConnaghy (2012) analyzed two methods of producing power with a hydrokite: a Steady-State Translating Model and a Steady-State Rotating Model. These models are an extension of the kite models created by Loyd (1980) where instead of assuming constant lift and drag coefficients, the steady-state aerodynamic forces change with angle of attack and are based on Sheldahl *et al.*'s (1981) experimentally determined lift, drag, and moment coefficients. McConnaghy's Steady-State Rotating Model produces energy by having a hydrofoil connected to a single beam, which rotates about a generator. McConnaghy's models assumed instantaneous acceleration, which would cause the hydrofoil to reach maximum velocity immediately. While this provides an upper bound to the possible power production, we extend this work by creating and studying a model with a kinetic energy storage device and that is also capable of transient dynamics.

2. System Description

In order to reduce the impact of the change of momentum at the ends of each stroke, the system incorporates a flywheel, which will store and release some of the system's energy at every cycle. The system, shown in Fig. 1a, has a boom that rotates about a fixed pivot "o" and has a wing attached at the other end at "c". The angle of the hydrofoil relative to the boom is fixed for each half-cycle but can be changed at the start of each half-cycle. The flywheel is positioned off to the side of the boom and is attached by a crank-arm to a point on the boom. The hydrofoil angle, the angle between the wing's cord length and the boom, flips about the $\hat{k}$-axis once the boom has reached the end of its stroke, so the system can begin to move in the other direction. A generator is coupled to the flywheel shaft at "f". The boom is given an initial velocity so a higher power cycle can be achieved.



(a) (b)

Fig. 1 (a&b) Top view of the hydrokite/flywheel system. Water is flowing from the top of the figure which applies hydrodynamic forces to the wing. The boom rotates about its pivot point "o".

For this model, the crank-arm and wing are assumed to be massless. The boom is attached to the top of the wing and the wing is completely submerged. The rest of the system is above the water and air drag is assumed to be negligible. We assume frictionless bearings for all pin joints and the system links are assumed to be perfectly rigid. Since we use Sheldahl *et al.*'s (1981) experimentally steady-state lift, drag, and moment coefficients, to determine the hydrodynamic forces on the system, our model is quasi-dynamic since those coefficients were obtained for fully developed steady-state flow. Although this assumption clearly breaks down when our hydrofoil is flipped at the end of each half cycle, the assumption should be more accurate when the hydrofoil is away from the ends of the cycle and for systems with large boom lengths.

3. Simulation

A two-dimensional numerical simulation was created in MATLAB. The hydrodynamic forces are calculated at each time step using the apparent velocities and the hydrodynamic coefficients for a NACA0015 airfoil (Sheldahl *et al.* 1981). To determine the hydrodynamic forces for a finite wing from 2D infinite wing coefficients, we use standard induced drag and induced angle of attack modifications from Anderson (1989). The simulation uses a 4th order, variable step-size, Runge-Kutta integration method (ODE45) to calculate the positions of the boom, the crank-arm, and the flywheel. The generator is attached to the flywheel and, for simplicity, is assumed to have a constant resistive torque, in the direction opposing the boom's motion, which is a reasonable model for a friction brake. The resistive torque is modelled by Eq. (1), where $\vec{\tau}$ is the resistive torque, $\vec{\dot{\psi}}$ is the angular velocity of the flywheel, and k is the torque constant.

$$\vec{\tau} = -k \frac{\vec{\dot{\psi}}}{\left|\vec{\dot{\psi}}\right|} \tag{1}$$

The friction brake model was used for simplicity. A model which incorporate DC generator characteristics could be used and would change the system's behaviour. The instantaneous power, P, is calculated by using Eq. (2).

$$P = \vec{\tau} \cdot \vec{\dot{\psi}} \tag{2}$$

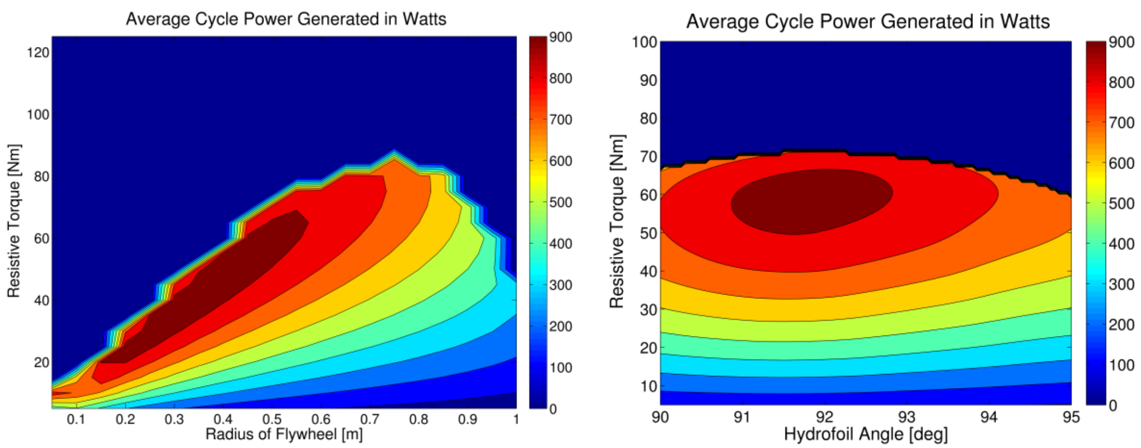
Once our numerical solution has been obtained, the average power per cycle can be determined using Eq. (3), where $\bar{P}$ is average cycle power, t is time, and T is the total cycle time.

$$\bar{P} = \frac{\int P dt}{T} \tag{3}$$

The system, for the set of parameters and initial conditions we studied, is capable of stable periodic motions. Various parameters of this system were analysed to understand their effects on the average power per cycle. These parameters, see Fig. 1a, are position of the flywheel with respect to the origin (x_f, y_f), radius of the flywheel (R_f), moment of inertia of the flywheel (I_f), location of attachment of the crank-arm on the boom (l_3), length of the boom (l_2), and hydrofoil angle (β). These parameters were first determined using a brute force method to obtain an initial understanding of the effects of each parameter, and then improved using a simple hill climbing optimization routine which sought to increase the average cycle power of the system.

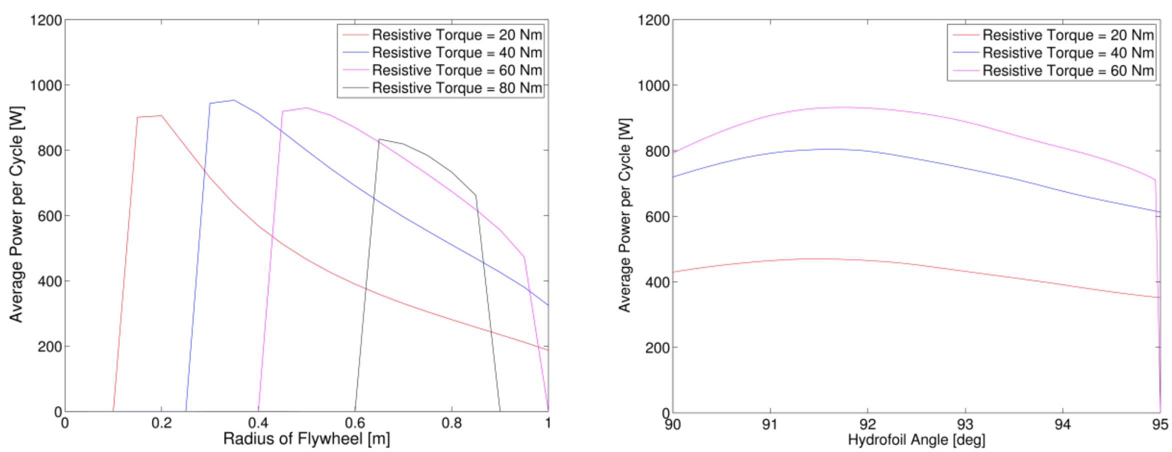
4. Results

The brute force optimization examined the effect of two parameters on average cycle power and typical results are shown in Fig. 2a&b. These contour plots show two dimensional slices of the average cycle power landscape. Fig. 2a shows that the average cycle power has a distinct average power peak as the radius of the flywheel and resistance torque change. The steep drop in average cycle power at larger resistance torques is a result of the resistance torque being so high that the system can no longer complete a cycle, effectively stopping the motion of the system entirely. Fig. 2b shows the average cycle power as the hydrofoil angle varies with the resistance torque. We see in Fig. 2b that, for the range of parameters examined, there is a single clear average power peak for these two parameters. Note that we see the same sharp drop in average cycle power for high resistive torques which is again due to the large braking torques completely stopping the system from moving. Similar to the results from McConnaghy (2012), the hydrofoil angles which produce the largest average cycle power is close to perpendicular to the boom. For all of the 2D parameter searches, only two parameters were varied at a time and all other parameters were kept constant (and are listed in Table 1 for reference). Although we cannot know if there is a single average power peak when one examines the higher dimensional parameter landscape we do see a single peak in the these two parameter slices. For clarity Fig. 3a&b show one-dimensional parameter variations for the average cycle power. Fig. 3a shows that at, over a small range of flywheel radii, the peak average cycle power is relatively insensitive to changes in the radii, *i.e.* the peak is flattened near the top. Fig. 3b shows that the peak is smoothly increases and the average cycle power smoothly changes in response to changes in the hydrofoil angle near the peak.



(a) (b)

Fig. 2 (a&b) Average cycle power contour plots.



(a) (b)

Fig. 3 (a&b) Average cycle power as a function of (a) Flywheel radius and (b) Hydrofoil angle for several braking torques

Table 1. Parameters used in parameter study for Figs. 2 and 3.

Parameter	Symbol	Fig. 2&3 (a)	Fig. 2&3 (b)	Units
River Velocity	V_∞	1	1	m/s
Water Density	ρ	1000	1000	kg/m^3
Hydrofoil Angle	β	92	Varies	Deg.
Resistive Torque constant	k	Varies	Varies	N·m
Horizontal Position of Flywheel	x_f	3	3	m
Vertical Position of Flywheel	y_f	1	1	m
Radius of Flywheel	R_f	Varies	0.5	m
Moment of Inertia of Flywheel	I_f	1	1	$kg{\cdot}m^2$
Length of Boom	l_2	2.5	2.5	m
Crank-Arm Attachment Location on Boom	l_3	1.25	1.25	m
Wingspan	b	0.75	0.75	m
Cord Length	c	0.125	0.125	m
Mass of the Hydrofoil	m_w	0	0	kg
Mass of the Boom	m_b	1	1	kg

The hill climbing optimization found what appears to be a local maximum for the average power per cycle of 1188.8 Watts for the parameters listed in Table 2. The hydrofoil angle, resistive torque, horizontal position of the flywheel, vertical position of the flywheel, radius of the flywheel, and moment of inertia of the flywheel were allowed to vary and all other variables were constant. It appears that the system is attempting to reduce the flywheel inertia to values that are much lower than we would have predicted. These low values of flywheel inertia essentially remove it's dynamics from the system, while retaining the kinematic constraint.

Table 2. Results from hill climbing optimization for the hydrokite model.

Parameter	Symbol	Result
River Velocity	V_∞	1 m/s
Hydrofoil Angle	β	91.7°
Resistive Torque constant	k	30 N·m
Horizontal Position of Flywheel	x_f	5.6 m
Vertical Position of Flywheel	y_f	1.26 m
Radius of Flywheel	R_f	0.25 m
Moment of Inertia of Flywheel	I_f	0.01 $kg{\cdot}m^2$
Length of Boom	l_2	2.5 m
Crank-Arm Attachment Location on Boom	l_3	1.25 m
Wingspan	b	0.75 m
Cord Length	c	0.125 m
Mass of the Hydrofoil	m_w	0 kg
Mass of the Boom	m_b	1 kg
Average Power per Cycle	$\overline{P}$	1188.8 W

5. Conclusion

The results show that 1188.8 Watts of power were able to be produced for a wing with a cord length of 0.125 meters and a wingspan of 0.75 meters in a river with a flow rate of 1 meter per second. These initial results are promising and larger wings could be used to harness more energy from a river. Future work remains to explore how a more realistic model for an electrical generator would affect system performance. It is still unknown how other parameters affect the average cycle power and if other local maxima exist. Other optimization methods could be used to determine if other local maxima exist that generate more average cycle power than the result shown here. It is interesting to note that our initial optimization sought to minimize the dynamics of the flywheel when seeking to maximize average cycle power. Further examination of the effect of the flywheel on the system performance would be interesting. Since some energy must be used to flip the hydrofoil at the end of each half cycle, and that amount is considered negligible in our model, our result should be considered an upper bound to the amount of power which could be obtained by a physical prototype. In addition, further study of the stability of the system's periodic motions would determine the robustness of the motions to perturbations in flow velocity or impacts due to river debris.

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