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Experimental Parametric Investigation of an Oscillating Hydrofoil Tidal Stream Energy Converter

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Abstract

There has been significant commercial interest in the use of oscillating foil energy converters (OFECs) to extract renewable energy from tidal streams. The majority of research into OFECs has focused on a foil undergoing a prescribed pitch and heave and does not take into account the complex fluid-structure interaction found in commercially developed elastically supported OFECs. To address this need, an experimental investigation was conducted of a model OFEC undergoing a prescribed pitch with a heave determined by the response of the mechanism to unsteady hydrodynamic forcing on the foil. The aim of the tests was to investigate the influence on power generation and efficiency of key dimensionless parameters; reduced frequency (k), and pitch amplitude (α_0).

For a fixed dimensionless damping coefficient of $C' = 29.5$ the device achieved an efficiency of 23.8%. This occurred at a high pitch amplitude of $\alpha_0 = 58^\circ$ and a reduced frequency of $k = 0.1$ which is in agreement with numerical simulations of OFECs undergoing a prescribed pitch and heave.

Nomenclature

U = flow speed [ms^{-1}]
α_0 = pitch amplitude [°]
$\alpha(t)$ = pitching motion [°]
θ_0 = angular heave amplitude of foil [°]
$\theta(t)$ = angular heave of foil [°]
$h(t)$ = translational heave of foil [m]
h_0 = translational heave amplitude of foil pivot location [m]
$h_{\text{T.E.}}$ = translational heave amplitude of foil trailing edge [m]
f = pitching frequency [Hz]
k = reduced frequency [-]
C = damping rate [Nmsrad^{-1}]
C' = dimensionless damping coefficient [-]
ρ = fluid density [kgm^{-3}]
c = chord length [m]
s = foil span [m]
a = foil pivot location from leading edge [m]
r = length of lever arm [m]
$\eta_{\text{T.E.}}$ = efficiency based on foil's trailing edge [-]
$C_{P\text{out}}$ = coefficient of output power [-]
$C_{P\text{in}}$ = coefficient of input power [-]
ϕ = phase angle [°]

Introduction

Tidal In-Stream Energy Converters (TISECs) being developed to harness tidal energy promise lower environmental impacts than traditional tidal barrage power plants. One such class of TISEC receiving commercial interest is the oscillating foil energy converter (OFEC). This type of device operates by passive or active pitch manipulation of one or several hydrofoils to generate lift forces to drive an oscillating heave of the foil(s). This heaving motion may be coupled to a generator to extract energy from the flow.

The feasibility of using an oscillating foil to extract energy from a flow was first demonstrated by McKinney and DeLaurier whose Wingmill achieved an efficiency of 16.8% [6].

Recent numerical 2D simulations of an OFEC undergoing prescribed pitch and heave over a greater parametric range achieved an efficiency of 34% [4]. A high efficiency of 40% has been demonstrated by a 2kW tandem foil prototype [4]. In these cases both the pitch and the heave of the foil is prescribed; the heave amplitude is set and the foil heaves sinusoidally at a set phase angle to the foil's pitch.

Isogai [2] was the first (non commercial) researcher to model an OFEC as an elastically supported foil where only the pitching motion was prescribed and the heave was dependent on system response. Isogai's 2D RANS simulation achieved an efficiency of 33%.

Commercial developments in OFECs included the 150kW Stingray demonstrator installed in Yell Sound in 2003 [7], the 100kW Pulse Stream 100 prototype commissioned in the Humber River in 2009 [9] and the 250kW bioStream demonstrator being developed for installation in Australia [1]. Both the Stingray and bioStream involve a single elastically supported hydrofoil on a lever arm undergoing a prescribed pitch.

Definition of OFEC

Figure 1 presents an analytical model of the OFEC under investigation. The foil is pitched about its quarter chord ($\frac{a}{c} = 0.25$), its pitching motion is defined by:

$$\alpha(t) = \alpha_0 \sin(2\pi f t) \tag{1}$$

The pitching frequency f is converted to the non dimensional reduced frequency k by:

$$k = \frac{fc}{U} \tag{2}$$

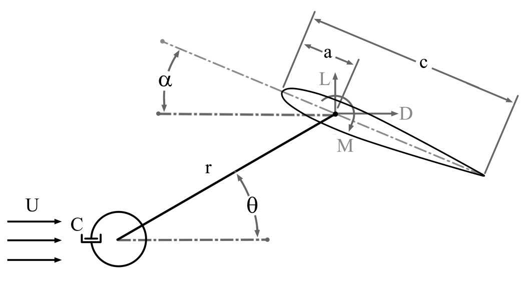


Figure 1: Schematic of OFEC analytical model

The foil undergoes an angular heave $\theta(t)$ about its lever (or swing) arm of length r. This is converted to a translational heave by:

$$h(t) = r\sin(\theta(t)) \tag{3}$$

The hydrodynamic input power $P_{\text{in}}(t)$ required to pitch the foil is defined as the total power measured on the input shaft $P_{\text{in}_{\text{total}}}(t)$ minus the power required to drive the pitching mechanism $P_{\text{in}_{\text{mech}}}(t)$. The power output $P_{\text{out}}(t)$ of the device is defined as the product of the angular heave velocity of foil and the torque applied by the hydrodynamic forces acting on the foil to the output shaft. The heave of the foil is restricted by a rotary damper with a damping rate C [Nm rad^{-1} s], the dimensionless damping coefficient is defined by:

$$C' = \frac{C}{1/2\rho U s c^2 r} \tag{4}$$

The non dimensional coefficients for input power and output power are defined by:

$$C_{P\text{in}} = \frac{P_{\text{in}}}{1/2\rho U^3 2sr} \tag{5}$$

$$C_{P\text{out}} = \frac{P_{\text{out}}}{1/2\rho U^3 2sr} \tag{6}$$

The efficiency of the device is defined as the power generated from the foil's heave minus the hydrodynamic power required to pitch the foil, divided by the available energy in the area of the flow swept by the foil's trailing edge:

$$\eta_{\text{T.E.}} = \frac{P_{\text{out}} - P_{\text{in}}}{1/2\rho U^3 2s h_{\text{T.E.}}} \tag{7}$$

Experimental apparatus

An illustration of the experimental model OFEC is shown in figure 2. The device consists of a vertically aligned aluminium NACA0012 foil of leading edge span $s = 0.34$m and chord $c = 0.1$m. The foil edges are within 5mm of the water tunnel ceiling and floor in order to reduce wing tip vortices. The device is tested in a water tunnel at the School of Civil Engineering Fluids Laboratory. The device is located in a rectangular section of width 0.6m and height 0.39m.

The pitch $\alpha(t)$ of the foil is controlled via a pitching mechanism by a stepper motor mounted beneath the water tunnel. The angular heave $\theta(t)$ of the foil is realised through 2 swing arms of length $r = 0.3$m hinged to the top and bottom of the foil. The lower swing arm is unrestricted and free to rotate, the upper swing arm is rigidly connected to the output shaft. The rotation of the output shaft is resisted by a viscous damper (dashpot) used to model the resistance of the power take off of an energy converter. The position of the foil's pitch $\alpha(t)$ is tracked in software, the position of the foil's heave $\theta(t)$ is measured by an encoder on the output shaft. The torque applied to drive the pitch of the foil is measured by a torque transducer on the stepper motor shaft. An identical torque transducer measures the torque applied by hydrodynamic forces acting on the foil to the output shaft.

The objective of the present study was to experimentally determine the influence of the pitch amplitude α_0 and reduced frequency k on the power generation and efficiency of an elastically supported OFEC. A set of tests were conducted at a fixed

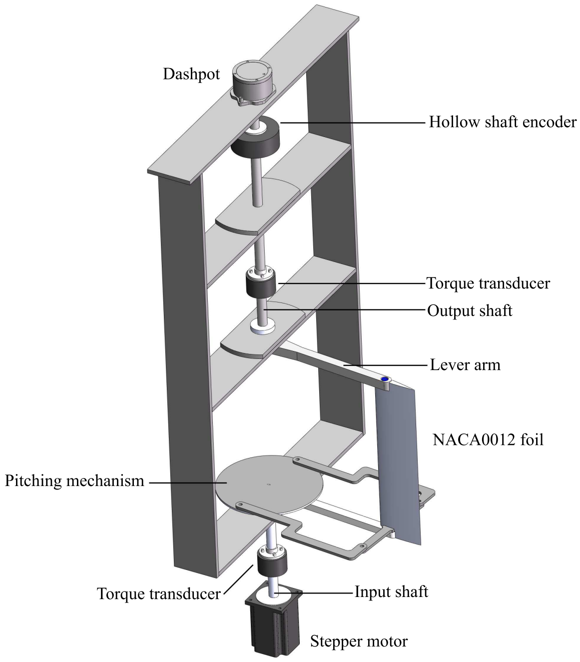


Figure 2: Experimental model OFEC

flow speed of $U = 0.5\text{ms}^{-1}$, this results in an $Re = 45,000$ with respect to the foil's chord. The dimensionless damping rate was fixed at $C' = 29.5$. The reduced frequency k was varied from 0.025 to 0.2 in 0.025 increments. At each reduced frequency the pitch amplitude α_0 was increased from 4° to 30° in 2° increments and 30° to 62° in 4° increments. In total 184 unique tests were conducted to map the parametric space $[k,\alpha_0]$.

Results

Test data

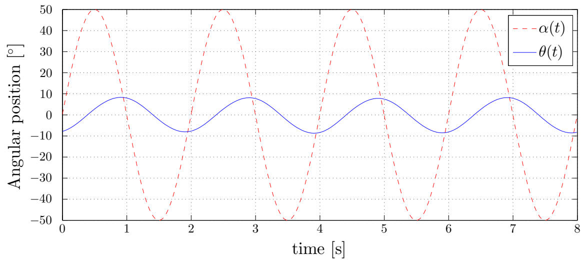
An example of experimental data is presented in figure 3. For the case presented the foil's heave $\theta(t)$ approximates a sine wave with an amplitude of $\theta_0 = 8°$ at a phase angle of $\phi = 74°$ to the foil's pitch. While the heave amplitude of the foil is 6.25 times lower the pitch amplitude, the torque on the output shaft is approximately 10 times greater than the total input torque required to pitch the foil and drive the pitching mechanism. In the case presented $P_{\text{out}} > P_{\text{in}_{\text{total}}}(t)$ and energy is extracted from the flow.

Effective angle of attack

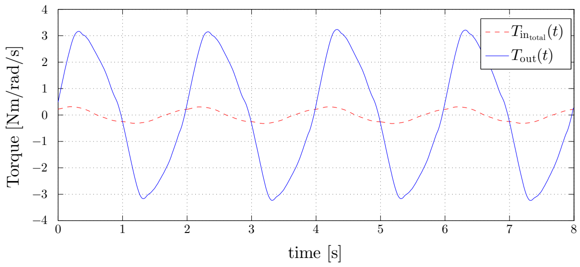
The result of the foil's pitch and heave is to change the effective angle of attack α_{eff} of the flow relative to the foil, as illustrated in figure 4. For the case presented the maximum effective angle of attack was 38.2°, 24% lower than the prescribed pitch amplitude of $\alpha_0 = 50°$. The effective angle of attack profile approximates a sine wave at a phase lag of approximately 16° to the prescribed pitch.

Heave amplitude

An important aspect of the present study is that the heave of the foil is not prescribed but is dependent on the response of the structure to hydrodynamic forcing on the foil. The heave amplitude of the foil's pivot location h_0 and the foil's trailing edge $h_{\text{T.E.}}$ is shown in figure 5. The heave amplitude of the foil is greater at lower reduced frequencies as the structure has a longer duration to move in response to hydrodynamic forcing.



(a)



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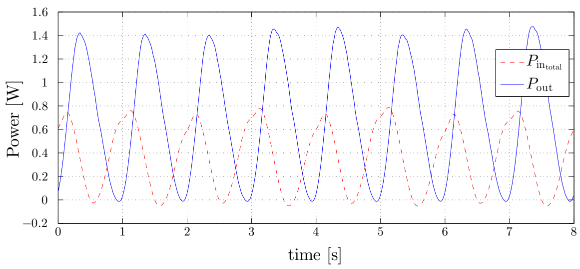


(c)

Figure 3: Test data over 4 cycles; $k = 0.1$, $\alpha_0 = 50°$, $U = 0.5$m/s and $C' = 29.5$. (a) Angular position of the foil $\alpha(t)$ and the lever arm $\theta(t)$ (b) Torque measured on input shaft $T_{in_{total}}(t)$ and output shaft $T_{out}(t)$ (c) Power to pitch input shaft $P_{in_{total}}(t)$ and power generated on output shaft $P_{out}(t)$

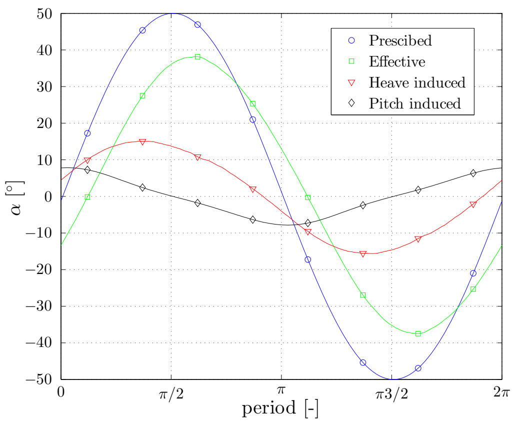
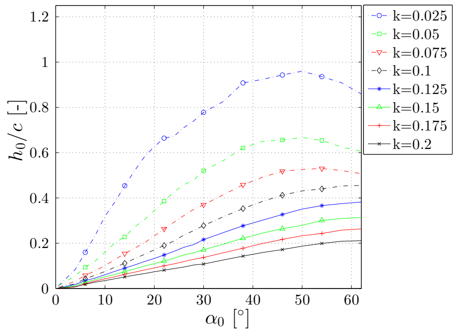


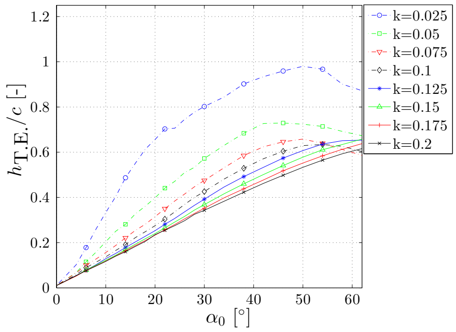
Figure 4: The prescribed angle of attack, the effective angle of attack and the induced angles of attack due to the heave and pitch of the foil. Data shown over one stroke for $\alpha_0 = 50°$, $k = 0.1$, U = 0.5m/s and C' = 29.5

Power in

The coefficient of hydrodynamic input power $C_{P\text{in}}$ is shown in figure 6a. Input power increases with both α_0 and k and is proportional to $\alpha_0{}^2 k$.



(a)



(b)

Figure 5: Dimensionless heave amplitudes over the full range of tested α_0 and k, $U = 0.5$m/s and $C' = 29.5$: (a) Heave amplitude of lever arm h_0/c, (b) Heave amplitude of foil's trailing edge $h_{T.E.}/c$

Power out

The coefficient of output power $C_{P\text{out}}$ over the tested parametric range is shown in figure 6b. The maximum recorded coefficient of output power was 0.067 and occurred at $\alpha_0 = 62°$ and $k = 0.1$ and $k = 0.15$. In the reduced frequency range $0.25 < k < 0.1$ there is a significant increase in output power with increasing k. In the range $k > 0.1$, increasing k no longer increased output power. There is a region of high output power $C_{P\text{out}} > 0.06$ at high pitch frequencies $k > 0.1$ and high pitch amplitudes $\alpha_0 > 54°$. At low pitch amplitudes $\alpha_0 < 22°$ the output power is highly similar for each reduced frequency.

Efficiency

A contour map of efficiency is shown in figure 7. There is a well defined region of peak performance. The maximum recorded efficiency was 23.8%, based on the total excursion of the foil's trailing edge. This occurred at the second highest pitch amplitude of $\alpha_0 = 58°$ and a mid-range reduced frequency of $k = 0.1$.

Maximum efficiency occurs at the balance point between the input power required to pitch the foil and power generated from its heave. In figure 6b we see a significant increase in power output with increasing k up until $k = 0.1$. Increasing $k > 0.1$ no longer increases power output but continues to increase the input power required to pitch the foil.

The optimal reduced frequency of $k = 0.1$ is consistent with numerical research of foils undergoing a prescribed pitch and heave [4, 8, 3]. The effective angle of attack at the point of peak efficiency was $\alpha_{\text{eff}} = 46°$. This is well above the static stall angle of the foil which was experimentally determined to be 16°. This high optimal pitch amplitude is consistent with

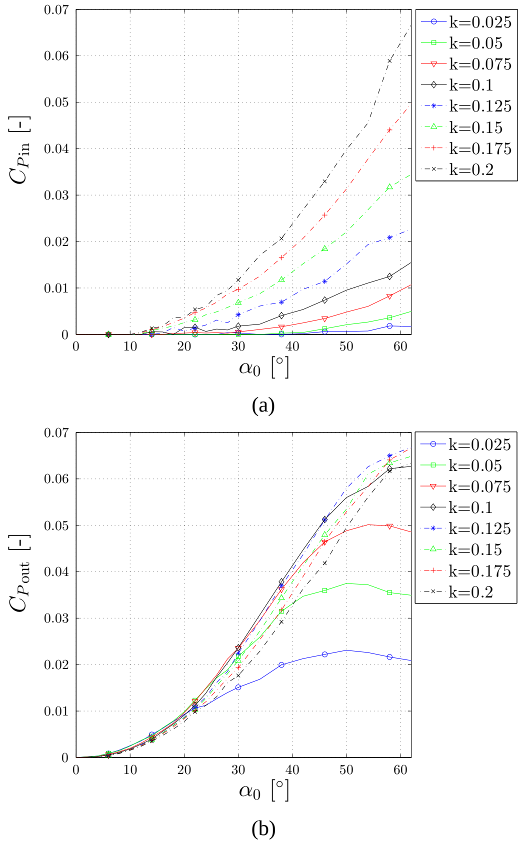


Figure 6: Coefficient of hydrodynamic input power and output power for varying pitch amplitude α_0 and reduced frequency k, $U = 0.5$m/s, $C' = 29.5$ (a) $C_{P\text{in}}$ (b) $C_{P\text{out}}$

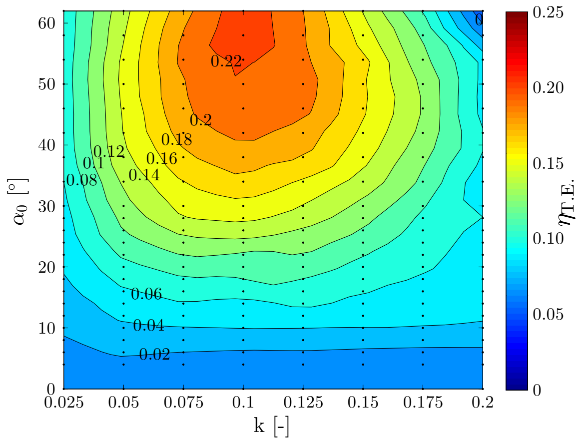


Figure 7: Contour map of efficiency $\eta_{\text{T.E.}}$ against α_0 and k, $U = 0.5$m/s and $C = 29.5$. Actual experimental tests are marked with a .

other OFEC research [4]. The potentially enhancing effects of dynamic stall, associated with the formation leading edge vortices (LEVs) augmenting and increasing the transient lift of an oscillating foil is well documented. Isogai [2] noted the formation of a LEV on the suction surface of the foil enhanced lift and power generation of their OFEC.

Conclusions

Tests of the elastically supported OFEC undergoing a prescribed pitch and free heave indicate that the device did operate successfully as an oscillating foil energy converter. A well defined peak in efficiency was observed. The highest recorded efficiency of 23.8% occurred at a pitch amplitude of $\alpha_0 = 58°$ and reduced frequency of $k = 0.1$. This is in good agreement with numerical research of OFECs undergoing a prescribed pitch and heave.

Future work

Future work is planned to investigate the influence of the dimensionless damping coefficient on the free heave of the device, power generation and efficiency.

Acknowledgements

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