EXPERIMENTAL INVESTIGATION OF BOUNDARY LAYER TRIPPING ON OSCILLATING-FOIL TURBINES

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ABSTRACT
A foil that oscillates in pitch and heave can, under proper kinematics, be used to extract energy from a flow. Existing numerical and experimental research campaigns have spanned laminar, transitional, and turbulent regimes in attempts to quantify the unsteady coupled fluid-structure interaction. Laminar numerical studies indicated a coherent leading edge vortex to be the dominant energetic source in the flow. However, this mechanism can be suppressed at higher Reynolds numbers ($O(10^5 - 10^6)$). In transitional regimes ($Re O(10^4)$) which are encountered in many model-scale experiments, the flow is less predictable. We performed an experimental study to develop an approach for mitigation of the uncertainties associated with the transitional flow regime by applying surface roughness to promote a controlled bypass to turbulence. The experiments were conducted in a recirculating water channel with an oscillating NACA 0015 hydrofoil in the range of Reynolds numbers of $20,000 \leq Re \leq 40,000$. We employed a combination of direct force measurements and particle image velocimetry (PIV) to quantify the hydrodynamic performance of the foil and provide quantitative insight into the structure of its near-wake. The experiments involved a smooth foil and a foil with a strip of roughness applied at the position of its maximum thickness. Under oscillating conditions, both the smooth and roughened foils exhibited flow structures and performance that approximated known baseline conditions corresponding to $Re = 500,000$ for smooth foils.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>AR</td>
<td>Aspect ratio ($AR = s/c$)</td>
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<tr>
<td>c</td>
<td>Chord length [m]</td>
<td></td>
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<tr>
<td>d</td>
<td>Total swept displacement [m]</td>
<td></td>
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<tr>
<td>$C_L$</td>
<td>Lift coefficient ($C_L = 2L/\rho U_\infty^2 cs)$</td>
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<tr>
<td>$f$</td>
<td>Frequency [Hz]</td>
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<tr>
<td>$f^*$</td>
<td>Reduced frequency ($f^* = fc/U_\infty$)</td>
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<tr>
<td>$H_0$</td>
<td>Heave amplitude [m]</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>Lift [N]</td>
<td></td>
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<tr>
<td>$P_{\bar{}}$</td>
<td>Cycle-averaged power extracted [W]</td>
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<tr>
<td>$P_a$</td>
<td>Total available power ($P_a = \frac{1}{2}\rho U_\infty^3 sd$) [W]</td>
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<tr>
<td>$Re$</td>
<td>Reynolds number ($Re = U_\infty c / \nu$)</td>
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</tr>
<tr>
<td>$s$</td>
<td>Span length [m]</td>
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<tr>
<td>$t$</td>
<td>Time [s]</td>
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<tr>
<td>$T$</td>
<td>Period [s]</td>
<td></td>
</tr>
<tr>
<td>$U_\infty$</td>
<td>Freestream velocity [m/s]</td>
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</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of attack [°]</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency ($\eta = P/P_a$)</td>
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</tr>
<tr>
<td>$\theta_0$</td>
<td>Pitch amplitude [°]</td>
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<tr>
<td>$\omega^*$</td>
<td>Non-dimensional vorticity ($\omega^* = \omega c/U_\infty$)</td>
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INTRODUCTION
A wing that oscillates with proper kinematics in heave and pitch provides a viable, efficient, and subjectively elegant method to extract energy from a fluid flow. Such systems, dubbed oscillating-foil turbines, have received growing research interest in the last decade [1].

Numerical research campaigns on the subject have largely been divided into purely laminar studies ($Re O(10^3)$), and studies at higher Reynolds numbers ($Re O(10^5 - 10^6)$) which more accurately represent a practical operating regime [2]. Non-
negligible increases in system performance were observed at the higher Re cases as a result of more robust turbulent boundary layers strongly influencing flow separation dynamics. Numerical works have largely avoided the intricacies of intermediate flow regimes that are dominated by transitional effects. In contrast, experimental campaigns have typically existed in the transitional range of Reynolds numbers due to physical constraints of the flow facilities. It has not yet been thoroughly assessed how these experimental systems represent the desired higher Reynolds number flows.

The current paper encompasses an experimental campaign designed to evaluate the validity of oscillating-foil turbines tested in transitional Reynolds numbers ($20,000 \leq Re \leq 50,000$). The effects of surface roughness promoting a bypass to turbulence are considered as an attempt to eliminate the uncertainties associated with natural transition and increase similitude with turbulent regimes. The applicability of a common blockage correction method is also assessed, in a further attempt to replicate open-water conditions. System performance is quantified by a combination of direct force measurements and particle image velocimetry (PIV) techniques. The thoroughly validated numerical study by Kinsey and Dumas performed at $Re = 500,000$ is used as a benchmark for comparison [3].

**EXPERIMENTAL SYSTEM AND TECHNIQUES**

Experiments were performed in a recirculating water channel with a cross section of 45 cm x 45 cm. A NACA 0015 foil, machined from aluminum, with a chord length of 50 mm and a span of 375 mm was positioned vertically in the middle of the test section, as shown in Fig. 1. The hydrofoil was supported on a two-degree-of-freedom motion control and positioning system. The pitch and the heave of the foil were controlled independently by servo motors to create sinusoidal motion profiles, with heave leading pitch by a 90° phase shift. The pitching axis was located at 1/3 of the chord length from the leading edge of the foil. Oscillations were performed in a reduced frequency range of $0.06 \leq f^* \leq 0.18$. These aforementioned kinematics represent the most common values found in both surveyed literature and studies cited within this paper, and have been selected here to allow the current study to be a general reference. Endplates were implemented to minimize finite aspect ratio effects on the foil, and were sized such that the edges of the endplates extended approximately 1/2 chord lengths from the edge of the foil, as was done by Kim et al. [4].

Distributed roughness elements with a nominal height of 0.425mm were applied in a 3-mm-wide strip along the entire span of the foil at the location of the maximum thickness on both foil sides. The methods of Braslow and Knox were used to quantify the roughness height required to promote transition under steady flow conditions [5]. However, this method does not address the unsteady motion of a flapping-foil, and the validity of its application was not known a priori; especially in the circumstances of an oscillating-foil that operates well above static stall angles throughout the bulk of a kinematic cycle. Unsteady forces acting on the foil were measured by a load cell, which was positioned between the foil and the motion system, as shown in Fig. 1. Measurements of lift and drag forces were averaged over 20 cycles of foil oscillation to produce a statistically converged representation of a mean cycle. A suite of calibration experiments was performed for each kinematic condition to isolate the desired hydrodynamic forces required to assess turbine performance. Inertial forces were quantified by running the experimental motion profile in still air and assuming negligible fluid resistance. The measured forces were subsequently subtracted from those measured in the submerged cases. Hydrodynamic forces on the submerged mounting equipment were quantified by running the experiments with the foil removed. Thus, only hydrodynamic forces exerted on the foil itself remained, allowing proper comparison with published numerical studies that did not consider the mass of the foil.

The flow was seeded with tracer particles with a mean diameter of 10 μm that were illuminated by a pulsed Nd:YLF dual diode-pumped laser. Phase-averaged images were calculated by averaging 150 instantaneous velocity fields corresponding to the same phase of the foil’s oscillation. Only one side of the foil was illuminated by the laser sheet.

The foil’s endplates were removed during PIV image recordings to allow unobstructed image capture. An assumption was made that the flow structures at the midspan of the foil were not affected by removal of the endplates. This was indeed observed to be the case in the study performed by Kinsey and Dumas on the subject of finite aspect ratio effects on oscillating-foil turbines [6].

Performance metrics of the oscillating-foil turbine follow the definitions provided in the nomenclature. It is noted that here efficiency is defined as $\eta = \frac{P}{P_a}$, where $P_a$ is the hydrokinetic energy flux of the freestream flow throughout the maximum extent of the flow window swept by the oscillating foil.
RESULTS

The hydrofoil was initially tested at static angles of attack to observe the influence of the roughness elements on flow transition. These experiments were numerically reproduced in the software xfoil [7], with free and forced transition to turbulence implemented to replicate the smooth and the rough foils, respectively. Free transition (if any occurred) was computed via the envelope $e^n$ transition criterion with a nominal value of $n = 9$.

The measured and the calculated values of the lift coefficient, $C_L$, as a function of the angle of attack, $\alpha$, are provided in Fig. 2 for tests at $Re = 20,000$. Data was sampled at $0.5^\circ$ resolution. A poor agreement between experimental and numerical results was apparent for smooth foil cases. The transition to turbulence at this Reynolds number is highly sensitive to external disturbances, including turbulence intensity [8]. It is thus non-trivial to make baseline comparisons between experiments and computations, where a variety of responses can be expected.

At low angles of attack, negative values of the lift coefficient were observed both experimentally and numerically in the case of the smooth foil. This result may be attributed to the existence of a laminar separation bubble (LSB), which is discussed by Tank [9], and was confirmed by dye visualizations in the present study. The LSB was also apparent in the xfoil results, indicated by separation and reattachment points along the foil’s surface.

The coherence between experimental and numerical results was increased in the case of the rough hydrofoil. The development of an LSB was suppressed in both the experiments and the numerical simulations, and the two approaches yielded good general agreement. A slight reduction in lift between the experimental (3D) and the numerical (2D) values was attributed to tip losses. The roughness elements did not influence the stall angle at this Reynolds number.

Figure 3 shows lift polars plots for the range $20,000 \leq Re \leq 50,000$ for only the rough foils. At $Re \leq 35,000$, a distinct delay in static stall angle was observed for the rough foils; this stall delay did not occur for the smooth foils. Also of note, the LSB size and position on the smooth foil was sensitive to the Reynolds number. A transition to turbulence via the surface roughness was indicated by these results. Lift coefficients at these moderate Reynolds numbers were consistently lower than that predicted by thin airfoil theory.

The results of the oscillating foil, tested with motion amplitudes of $\theta_0 = 75^\circ$ and $H_0/c=1$, is presented Fig. 4. Efficiency, $\eta$, is provided as a function of the reduced frequency, $f^*$, for several tested Reynolds numbers. Within the range covered during the experiments, a negligible dependence on Reynolds number was observed. The case of the rough foil at $Re = 35,000$, which previously showed a significant delay in static stall angle indicating a more robust turbulent boundary layer, surprisingly displayed no noticeable difference from the lower Reynolds number cases. These lower Reynolds number tests did still show signs of forced boundary layer transition via the elimination of the laminar separation bubble, but were not accompanied by stall delay. All cases performed similarly when oscillating; a consequence of the oscillating-foils operating at angles of attack well above static stall limits for the bulk of a cycle.

The presence of surface roughness resulted in an increase in absolute efficiency of up to a 2.5%, compared to the case of the smooth foil, with larger differences occurring at higher oscillation frequencies. Instantaneous force measurements revealed that smooth and rough foils had highly similar force profiles throughout most of an oscillation cycle, with an exception occurring at the limits of the heave cycle when the foil reversed direction. Under the current kinematics, energy must be put into the system at the limits of the heave cycle to reverse the foil’s direction. Less power was required to reverse the rough foil’s motion.

It was hypothesized that the lack of influence of roughness elements throughout the rest of the cycle, which experiences
higher angles of attack, was a result of flow separating upstream of the roughness location. Additional tests were therefore performed with roughness elements placed undoubtedly upstream of the separation point; one set of tests with a thin strip of roughness at the leading edge, and additional tests with a large strip extending from the leading edge to the point of maximum thickness. Indiscernible differences occurred as a result, both in terms of the force measurements and the flow structures.

Experimental measurements were compared to the unsteady Reynolds-averaged Navier-Stokes (URANS) computational results available in published literature. Namely, a study at Re = 1100 by Kinsey and Dumas [10] representing purely laminar flow, and a study performed at Re = 500,000 by Kinsey and Dumas [3] representing a more practical operating regime with turbulent flow. The later used the one-equation Spalart-Allmaras turbulence model with a modified strain/vorticity-based production term. The results borrowed from both studies were performed with the same NACA 0015 foil shape and kinematics as the current study, although they were 2D in nature.

Corrections were applied to the force measurements to facilitate comparison with published results of 2D unconfined simulations. A correction for 3D tip losses was drawn from the study of Kinsey and Dumas [6], who explicitly studied 3D effects on oscillating-foil turbine systems. The nearest equivalent case tested by Kinsey and Dumas was a NACA 0015 foil with AR = 7 (current, AR = 7.5) and similar endplates, which had an efficiency equal to 86% of its 2D counterpart. This factor was used to scale current experimental results from 3D measurements to a 2D equivalent. Blockage corrections were applied following the works of Gauthier et al. [11], who showed that the established BW blockage correction [12] is appropriate for oscillating-foil turbines. The current tests have blockage ratios in the range 22 to 24%, well within the proposed limits of the correction model. The blockage correction scales with the measured drag coefficient of the turbine, and therefore was computed specifically for each test case.

Figure 5 compares the results of experimental tests of the rough foil at Re = 30,000 with the numerical works of Kinsey and Dumas [3], [10]. The effect of 3D corrections and blockage corrections are shown independently for each data point to assess their relative influence. Applying corrections to the raw experimental data points (circular, in Fig. 5) yielded good agreement between experimental and Re = 500,000 numerical efficiency results. In particular, for $f^* \leq 0.10$, applying only 3D corrections allows experimental data to agree closely with the high Reynolds number 2D simulations. For $f^* \geq 0.14$, applying both 3D corrections and blockage corrections was necessary for good agreement between experimental and numerical data. The data point $f^* = 0.12$ was transitional between the previous two ranges.

This trend is generally in line with the range of applicability of the blockage corrections outlined by Gauthier et al. [11] (originally derived for rotary turbines), where it was observed that such a correction was only applicable for oscillating-foil cases with $f^* > 0.10$. Gauthier’s suggested correction limits were empirically based on the existence of and the strength of leading edge vortices (LEVs). The authors proposed that the channel confinement increases measured performance by increasing available dynamic pressure, while the confinement also decreases performance by increasing perceived angles of attack and hastening flow separation. Conflicting confinement effects approximately cancel each other for cases with significant LEVs.

The development of the LEV is closely related to reduced frequency [10]. Reducing the oscillation frequency leads to higher maximum effective angles of attack, therefore increasing the severity of the stall event that generates the LEV. At higher...
frequencies, yielding lower effective angles of attack, the LEV can be lessened in strength or suppressed completely. Using reduced frequency as a delimiter for the validity of blockage corrections is thus simply an indirect measure of the influence of LEVs on system performance.

PIV images reveal flow separation dynamics that are consistent with the above statements. Figure 6 shows patterns of the phase-averaged vorticity at Re = 30,000 for smooth and rough foils at \( f^* = 0.08 \) and \( f^* = 0.14 \). Figure 6 also provides a kinematic diagram for phasing reference, showing the foil’s motion through the freestream (not to scale). Development of dynamic stall is shown sequentially at phases \( t/T = 2/8, 3/8, \) and \( 4/8 \), corresponding to the kinematic diagram included in the figure. At the lower reduced frequency, a LEV on the scale of the foil’s chord length had developed by phase \( t/T = 2/8 \). The LEV subsequently convected past the foil’s trailing edge and deep stall occurred before the foil reversed direction. In fact, a strong trailing edge vortex (TEV) was able to develop by phase \( t/T = 3/8 \). Limited differences existed between flow structures of smooth and rough foils throughout the majority of the heave motion, except the foil reaches the extent of its heaving motion (\( t/T = 0/8 \) and \( 4/8 \)). At these limits, where power input was required to reverse the foil motion, the roughness elements hastened the reattachment of flow to the foil by bypassing slow transitional effects occurring at the low angles of attack. These observations were consistent with the instantaneous force profiles of the foil’s motion, where the only considerable differences occurred near where the foil reversed heave directions.

The case of \( f^* = 0.14 \) exhibited a delayed onset of the dynamic stall due to the reduced effective angle of attack and the higher pitch rate stabilizing the boundary layer. By mid-stroke, the onset of dynamic stall had begun, but the LEV was at the initial stage of formation. The vortex continued to convect downstream, and its shedding was well timed with the reversal of the foil. Similar to the case of \( f^* = 0.08 \), the roughness elements had minimal influence except at the limits of the heave cycle.

The flow structures observed through PIV for the case \( f^* = 0.14 \) were different from the flow structures observed in the numerical simulations (not shown). The LEV in the experimental case developed earlier and was larger than its unconfined 2D numerical equivalent. This was attributed to channel confinement, where the increased effective angle of attack resulting from confinement increases the likelihood and strength of flow separation as previously discussed. Although it is evident that performance measurements in confined experimental systems can be corrected to represent open water, higher Reynolds number operation, it is unlikely that full similitude in

**FIGURE 4**: PHASE-AVERAGED OUT-OF-PLANE VORTICITY IN THE NEAR WAKE OF THE FOIL. SMOOTH AND ROUGH FOILS WERE TESTED AT \( f^* = 0.08 \) AND \( f^* = 0.14 \), UNDER THE CONDITIONS \( h_0/C = 1, \theta_0 = 75^\circ \), AND \( Re = 30,000 \).
wake structure between cases is achieved. This conclusion is particularly relevant in the cases where arrays of turbines are considered and it is desirable to accurately reproduce the wake structure imposed on downstream turbines.

CONCLUDING REMARKS
An experimental campaign was conducted to assess the feasibility of employing oscillating-foil turbine experiments at moderate Reynolds numbers to represent more practical operating conditions occurring at higher Reynolds numbers. Quasi-steady analysis suggested transition to turbulence would be highly influential to system performance. Indeed, experimental tests on foils with steady angles of attack indicated a high dependence on transition effects. Laminar separation bubbles developed in both experimental and numerical (xfoil) tests when the foil was below static stall angles. The LSB strongly modified lift polars, and resulted in general lack of coherence between experimental and numerical results. Surface roughness elements were effective in promoting transition to turbulence by eliminating the difficult-to-predict effects of the LSB and increasing static stall angle. The aforementioned trends were sensitive to small changes in Reynolds number indicating a delicate balance between the viscous and the inertial forces. This strong dependence on both the Reynolds number and the surface roughness was not apparent under oscillating conditions, where matching performance was observed for all tested Reynolds numbers. Surface roughness elements affected the flow dynamics only during brief periods, when the foil reversed heave directions producing low instantaneous angles of attack. The roughness allowed the flow to reattach more quickly. Although the effect of roughness was small, it was found to increase coherence with data from previously published higher Reynolds number flows, which was simulated numerically.

Correcting the experimental data for finite aspect ratio effects and blockage effects allowed the present experimental results to accurately represent higher Reynolds number, unconfined conditions. Corrections for the confinement were only applicable to results above a certain reduced frequency. A larger experimental dataset is required to adequately define a range of applicability of the blockage corrections.

The experimental results aligned more closely with the numerical simulations at Re = 500,000 than those at Re = 1100. This observation suggests that the dynamic stall events occurring on oscillating-foil turbines are relatively independent of the Reynolds number, provided that the boundary layer is turbulent. The degree of similitude of the wake structure in confined experimental systems to those in unconfined operation remains to be assessed. Such information is important when considering experimental campaigns on turbine arrays, where it is desirable to accurately reproduce the wake structure imposed on the downstream turbines. Variations in wake patterns will also be particularly influential on arrays of fully-passive turbine designs, the kinematics of which result from interactions between the incoming flow and tuned structural properties [13], [14].

ACKNOWLEDGMENTS
The author’s gratefully acknowledge support from the Natural Sciences and Engineering Research Council of Canada’s CGS-M funding.

REFERENCES