A Method to Fabricate Kelp Models with Complex Morphology to Study the Effect on Drag and Blade Motion

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A Method to Fabricate Kelp Models with Complex Morphology to study the Effect on Drag and Blade Motion

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Running Head: Fabrication of and Drag on Corrugated Blades
Acknowledgements

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Abstract

Macrocystis blades develop longitudinal corrugations in regions with strong current and wave action. This study examined the effect of corrugations on blade motion and blade drag by constructing flexible blades with different corrugation amplitude and a control blade with no corrugation. The models were designed to be dynamically and geometrically similar to natural blades. Acrylic molds were etched using a laser cutter and filled with a silicone-based polymer to create flexible model blades with sinusoidal corrugations. The corrugated and flat model blades were tested in a water channel using drag force measurements and video analysis. The corrugated blades experienced a drag reduction of up to 60% compared to the flat blade. Additionally, the corrugated models exhibited smaller motion, as quantified by the maximum vertical displacement. The reduction in drag may explain why corrugations are observed in exposed regions of high current and wave action, where a reduction in drag provides important protection against breakage.
Introduction

Kelp blades alter their morphology to adapt to changes in their environment, such as variations in nutrient availability and hydrodynamic conditions, with the morphological changes either enhancing nutrient availability or reducing hydrodynamic drag (Koehl et al. 2008). This process is known as phenotype plasticity. For example, in exposed regions with strong current and wave action *Macrocystis* blades are thicker and have longitudinal corrugations (Figure 1), compared to sheltered regions, where the blades are thinner and exhibit little or no corrugations (Hurd and Pilditch 2011, summarized here in Table 1).

The longitudinal corrugations appear in regions of high velocity which are less likely to be nutrient limited (e.g. Gerard 1982 a, b), so the purpose of the corrugations is unlikely to be associated with nutrient flux. Rominger and Nepf (2014) hypothesized that the corrugations develop to reduce hydrodynamic drag. Previous studies of corrugation in metal sheets have shown that corrugation enhances rigidity (Briassoulis 1986). Rominger and Nepf (2014) showed that in some flow conditions, increasing blade rigidity significantly reduces drag by limiting the blade motion that occurs in response to flow oscillations (e.g. turbulence or waves). The degree of blade motion, in response to flow, can be characterized by the following non-dimensional force ratio of blade rigidity (resistance to bending) to fluid drag (Michelin et al. 2008):

\[ \eta = \frac{EI}{\rho_f b U_\infty^2 l^3}, \]

where \( E \) is the Young’s modulus, \( I \) is the area moment of inertia, \( \rho_f \) is the density of the fluid, \( U_\infty \) is the streamwise velocity, and \( b, h \) and \( l \) are the width, thickness and length of the blade, respectively.

Rominger and Nepf (2014) created six flat blade models with a range of \( \eta \) between \( 10^{-6} \)
and 10 by varying the material (high and low density polyethylene, and aluminum) and the model blade thickness \( h \). They found that below \( \eta = 10^{-4} \), both the mean and instantaneous drag forces on the model blade increased rapidly with decreasing non-dimensional rigidity \( \eta \). The instantaneous peaks in drag, which can tear or dislodge blades, were associated with inertial forces created by the large-amplitude flapping motions of the blade. Rominger and Nepf (2014) also showed that the range of \( \eta \) values over which blade drag is most sensitive to blade rigidity \( (\eta < 10^{-4}) \) corresponds to the range of \( \eta \) values exhibited in real kelp blades in coastal environments. Therefore, for real blades in the field, changes in morphology that increase blade rigidity are expected to reduce drag.

In this study, we test the drag-reducing effect of corrugations, as hypothesized in Rominger and Nepf (2014). A method was developed to fabricate a set of dynamically- and geometrically-scaled model blades with different degrees of realistic corrugation using etched acrylic molds. We measured the drag on each model blade when exposed to the same flow conditions and used video analysis to observe the effects of corrugation on the motion of the blade.

Methods

Fabrication

We designed and fabricated three model kelp blades: one flat blade and two blades with sinusoidal corrugations running parallel to the streamwise length of the blade, with different amplitudes. The model blades were made from a silicone-based polymer and cast using laser-cut acrylic molds (more details provided below). The three models had the same length \( l \), width \( b \), and sheet thickness \( h \), and were fabricated from the same material, so that they had the same value of \( E \). The design parameters were chosen using three constructs: First, working under the...
hypothesis that kelp blades develop corrugated morphologies in regions where changes in blade rigidity have the greatest effect on drag force, each blade was designed to be within the critical range $\eta < 10^{-4}$. This, according Rominger and Nepf (2014), is the range over which variations in rigidity have the most significant effect on drag. Second, the ratio of blade thickness to corrugation wavelength and amplitude should mimic what has been observed in actual kelp blades (Figure 1 and Table 1). Third, the model parameters were limited by the resolution and total size of the fabrication tools. Specifically, the molds were fabricated using a laser cutter with a bed size of 46 cm x 81 cm and an x-y resolution of 0.1 mm.

The flat blade can be approximated as a rectangular beam, for which the area moment of inertia about the horizontal axis perpendicular to blade length (y-axis in Figure 2) is

$$I = \frac{bh^3}{12}$$  \hspace{1cm} (2)

For the corrugated models, the area moment of inertia can be approximated as

$$I = \frac{ba^2h}{2} \left(1 + \frac{\pi^2a^2}{2\lambda^2}\right)$$  \hspace{1cm} (3)

where $a$ is the amplitude of the corrugation, and $\lambda$ is the wavelength of corrugation, as shown in Figure 2b (Lau, 1981). The blades were made from a silicone-based elastomer, vinylpolysiloxane (VPS), which is available in a range of elastic moduli. Specifically, we used a VPS (Zhermack Elite Double 8) with a Young’s modulus of $E = 0.23 \pm 0.01$ MPa. This material is prepared by mixing equal parts base and catalyst in liquid form, after which polymerization occurs in approximately 20 minutes. To reach a non-dimensional force ratio ($\eta$) in the scaled-down model blade that was comparable to real kelp blades, the elastic modulus ($E$) was intentionally chosen to be less than that of real blades ($E = 5$ MPA, Table 1). The VPS has a density of $1024 \pm 20$ kg/m$^3$, so that the models were somewhat buoyant, which is consistent with real blades ($\rho = 1040$ kg/m$^3$, Hale 2001).
The flat model was designed to have a value of $\eta \approx 10^{-5}$ in a current of $U_\infty = 20$ cm/s (see eqn. 1). In order to meet that target, we set length $l = 30.0 \pm 0.1$ cm, width $b = 3.0 \pm 0.1$ cm, and thickness $h = 0.75 \pm 0.01$ mm, with the uncertainty representing the measurement uncertainty of the completed blade. These dimensions were held constant for all three blades. For geometric similarity, the corrugated model blades were constructed to have similar ratios of thickness to amplitude and wavelength of corrugation ($h:a:\lambda$) as real blades from exposed sites. We combined measurements from Hurd and Pilditch (2011, shown in Table 1) and measurements from the *Macrocystis* blades shown in Figure 1 ($h = 0.45$ mm, $a = 1.13$ mm, $\lambda = 5.0$ mm), which yielded $2.5 < a/h < 3$ and $6 < \lambda/h < 11$. The first corrugated model was designed with amplitude $a = 2.7h$ (2.0 \pm 0.05 mm), which is in the middle of the range observed in the field. A second corrugated model was chosen with corrugation amplitude $a = 2h$ (1.5 \pm 0.05 mm) to produce a dimensionless rigidity halfway between the flat and fully corrugated models. The wavelength was set at $\lambda = 8h$ (= 6.0 \pm 0.05 mm) for both corrugated blades, which is also in the middle of the observed range.

The reported uncertainty corresponds to measurements of the final blade, which contributes to the uncertainty in $\eta$. For the flat blade, $\eta = 7.8 \pm 0.3 \times 10^{-6}$, calculated using eqs. 1 and 2. For the corrugated blades, $\eta = 2.4 \pm 0.2 \times 10^{-4}$ and $\eta = 5.0 \pm 0.4 \times 10^{-4}$, for $a = 1.5$ mm and 2 mm, respectively, calculated from eqs. 1 and 3.

The templates for laser cutting the blade molds were designed in Matlab. Each mold consisted of two acrylic plates out of which a sinusoidal topography was etched. Given the x-y resolution of the laser cutter (0.1 mm) and the wavelength $\lambda = 6.0$ mm, the corrugations for the models were created as discrete curves with 60 steps per wavelength. Visual inspection of the *Macrocystis* blade (Figure 1) indicates that the blade thickness is uniform when measured perpendicular to the local blade surface (red line in Figure 3), and this characteristic was
preserved in the model blade. The surface arcs of the mold were constructed such that the perfect sinusoid was at the center of the blade (dashed black curve in Figure 3). The upper and lower surfaces of the blade are one-half the thickness \( (h) \) above or below the sinusoidal curve, measured in the direction perpendicular to the center curve (e.g. red line in Figure 3) at each discrete point.

The surface curves (blue lines in Figure 3) were converted to values ranging from 0 to 255, and the discrete vectors were extended to create 2D matrices, which were finally converted to grayscale images. The grayscale images were used as templates for the laser cutter. The power and speed of the laser were set to etch a depth of twice the amplitude for black pixels. The laser then adjusted to a fraction of that power corresponding to the grayscale value (between 0 and 255) for non-black pixels. Photographs of an example of the resulting template and acrylic plates are shown in figure 4.

The acrylic molds were cut leaving 1.5 cm of flat space along three sides of the blade area. This space was used to lay out metal spacers of the desired blade thickness \( (h = 0.75 \text{ mm}) \). The bottom mold was filled with the VPS mixture (Figure 5a), after which the top surface was screwed into place (Figure 5b) and held down with weights while the silicone-based polymer cured (requiring 20 minutes minimum). Once cured, the excess polymer was cut away from the edges of the model blade. Separate acrylic molds were created and used for the two different corrugated models, and uncut plates of acrylic were used for the flat model. Figure 6 shows all of the completed blades.

**Flume Testing**

The three blades were tested in a water channel with a width of 38 cm and a water depth of 18 cm above a false bottom. The blades were held in a horizontal position by a clamp at mid-
depth. The current speed was 20 cm/s. Following Rominger and Nepf (2014), a vortex street was
created by a 1-cm thick bar of height $D = 2.5$ cm that spanned the flume at mid-depth, which was
aligned with the clamp and blade. While mimicking the interaction of the blades with individual
turbulent eddies, the vortex street provided a single scale (bar height $D$) and a frequency (1.2 Hz)
that enabled simpler visualization and interpretation of the blade motion. The periodic eddies
created by the bar had a wavelength of $4D$. The upstream edge of the blade was placed $4D$
downstream from the bar.

Beneath the false bottom, the clamp was attached to a load cell (Futek LSB210) that
measured the streamwise forces on the clamp and blade. Mean drag was calculated as an average
over a 5 minute long record collected at 2,000 Hz. Additionally, we measured the force on the
clamp without a blade and subtracted this value to isolate the force on the blade alone. The load
cell was calibrated by measuring known weights incremented from 0 to 0.006 N, and the
measurements were recorded using Labview software. Videos were taken of each blade in the
channel (using a Sony DFW-X710 camera). The videos were used to measure the average
maximum vertical displacement of the blade tip per cycle of vortex shedding. The displacement
measurements were calculated from ten arbitrary one-cycle sequences for each blade. From each
of ten cycles, we recorded the maximum vertical displacement of the blade’s tip (in either the
upward or downward direction from the centerline) and then calculated the average over the ten
cycles. The vertical displacement was measured in Matlab by counting the number of pixels in
the image between the centerline and the tip position and then converting to centimeters using

Results
The measured drag force on the blades decreased significantly with the addition of corrugations (Figure 8). Specifically, the drag on the corrugated blades was reduced relative to the flat blade by 12% and 35%, respectively for \( a = 1.5 \text{ mm} \) and 2 mm (Figure 8a). Note that this drop in drag occurred despite an increase in surface area. The reduction in drag per surface area relative to the flat blade was larger; 40% and 62%, respectively for \( a = 1.5 \text{ mm} \) and 2 mm (Figure 8b). The reduction in drag confirms that corrugations of the scale observed in the field can raise stiffness sufficiently to reduce by about 1/3 the total drag on individual blades.

Over a similar change in dimensionless blade rigidity (\( \eta = 5 \times 10^{-6} \) to \( \eta = 5 \times 10^{-4} \), which corresponds to the change in rigidity between the flat and \( a = 2 \text{ mm} \) blades in this paper), Rominger and Nepf observed a 45% reduction in drag (2014). Because surface area was constant in their experiments, this reduction (45%) also extends to drag per surface area. Their observed reduction is between our observed drag reduction (35%) and drag per surface area reduction (62%). The agreement in the magnitude of drag reduction over a similar increase in dimensionless rigidity (\( \eta \)) suggests that the parameter of dimensionless rigidity works universally for rigidity associated with blade thickness or with blade morphology (here, corrugations).

The dependence of the blade motion on the level of corrugation was assessed qualitatively using video images. Figure 9 shows a video sequence for each of the three blades. The sequences are composed of 5 frames taken at intervals of 0.2 seconds, which represents approximately one cycle of vortex shedding. For a vortex shedding frequency of 1.2 Hz, one full period is \( \approx 0.83 \) seconds. The flat blade (lowest \( \eta \)) experienced the greatest oscillation amplitude, or vertical displacement from the centerline. The downstream tip of the blade exhibited a maximum vertical displacement of 5.4±0.3 cm from the neutral blade position, with the uncertainty representing the standard error measured over ten sequences. The blade movement
decreased with increasing corrugation amplitude. Specifically, the maximum tip excursion decreased to 3.0±0.2 cm and 1.9±0.2 cm for $a = 1.5 \text{ mm} \ (\eta = 2.4\times10^{-4})$ and $2 \text{ mm} \ (\eta = 5.0\times10^{-4})$, respectively. Rominger and Nepf (2014) also observed a reduction in vertical displacement for blades of higher nondimensional rigidity. Specifically, Rominger and Nepf observed a change in rms-vertical displacement from 2.5 cm ($\eta \approx 10^{-6}$) to 0.5 cm ($\eta \approx 4\times10^{-4}$) (2014).

Our least rigid blade (flat blade, $\eta = 7.8\times10^{-6}$) exhibited the most asymmetric oscillations, meaning that the blade preferentially remained above or below the clamp centerline. For example, the sequence in figure 9a shows asymmetric oscillations favoring the downward direction. We quantified this asymmetry as the difference between the maximum upward and maximum downward displacement of the tip within each vortex period, normalized by the overall maximum displacement, and averaged this fraction over ten cycles. An asymmetry of zero indicates equal displacement up and down (perfect symmetry) while 1 is the maximum asymmetry. Using this metric, the flat blade exhibited 67±6% asymmetry in its vertical motion, the $a = 1.5 \text{ mm}$ corrugated blade exhibited 56±7% asymmetry, and the $a = 2 \text{ mm}$ corrugated blade exhibited 42±8% asymmetry. These observations suggest that oscillation symmetry increases with blade rigidity. Rominger and Nepf (2014) also noted asymmetric blade motion for $\eta < 1\times10^{-4}$, and they showed that it was associated with enhanced vertical acceleration at the tip and an elevation in peak drag force.

**Discussion**

Our measurements of drag demonstrate that corrugations of the scale observed in the field can raise stiffness sufficiently to reduce by one-third the drag on individual blades. The reduction in drag is similar to that achieved by changes in blade thickness over a comparable
range of non-dimensional rigidity. Decreasing drag protects the blade from being dislodged or
torn.

Rominger and Nepf (2014) identified the following trade-off with blade stiffness: stiffer
blades have the positive influence of decreasing drag, but the negative influence of also
decreasing flux to the blade surface, because stiffer blades exhibit less relative motion between
the water and blade surface. This trade off may explain why kelp selects corrugation, rather than
an increase in blade thickness, in order to enhance rigidity. Nutrient intake is a function of the
surface area of the blade. Developing corrugations maintains a constant surface area to volume
ratio, whereas increasing thickness decreases this ratio, which can diminish nutrient flux per
blade volume. Previous studies have also shown that in high-flow environments, the nutrient
uptake by kelp is limited by physiological controls – how fast the kelp can store or use nutrients
– not by hydrodynamic controls – how fast nutrients are delivered to the blade surface (Gerard
1982 a, b). This means that in high-flow environments, the decrease in flux to the blade surface
caused by increased stiffness may not be detrimental to blade survival, since the uptake by the
blade is not limited by hydrodynamic controls in these environments. At the same time, the
decrease in drag associated with corrugations will have the greatest benefit in high-flow
environments, where the scale of drag (which increases with current speed squared) is higher
than in low flow environments. This may explain why corrugations are observed only in high-
flow environments.

Next, we consider additional complexity that can be added to the model blade
morphology with this fabrication method. The sinusoidal models used in these experiments were
developed to mimic the longitudinal corrugations observed on *Macrocystis* blades. However, the
actual corrugations observed in nature are not perfect sinusoids, but have curved peaks and
valleys and begin and end at random locations along the length of the blade (Figure 1). In order
to create templates of more realistic corrugations, we began with an image of lines representing
the peaks of the corrugations (Figure 10a). The distribution of peak lines was based on tracings
of *Eisenia arborea* blades made by Denny and Robertson (2002) and contour edits of the image
of a *Macrocystis* blade (Figure 1). A Matlab code filled in a linear vertical gradient where each
peak line ended and a horizontal sinusoidal gradient between adjacent peaks. An example of
peak lines converted to a grayscale template is exhibited in Figure 10b.

Finally, our blade fabrication method can be used to build a canopy of kelp blades to
consider how blade stiffness (gained either through blade thickness or corrugation) influences the
interactions between multiple blades. Kelp blades do not exist in isolation in nature, and when
the blades become entangled, they are at higher risk of tearing. The new models could be used to
explore whether increased rigidity reduces entanglement between blades. Changes in blade
rigidity may also impact light availability, and thus photosynthesis within a canopy. Less rigid
blades, which move more freely, might produce more even light conditions within the canopy, as
the movement of blades keeps any individual blade from being shaded for an extended period of
time. Alternatively, the light absorption of a submerged blade is related to its projected
horizontal area (Zimmerman, 2005). More rigid blades maintain a more horizontal position in
flow (Figure 9), which may provide an advantage in light capture and photosynthesis.
References


J. Rominger and H. Nepf. 2014. Effects of blade flexural rigidity on drag force and mass


Springer, Dordrecht.
Table 1: Measurements of *Macrocystis* blade morphology from exposed and sheltered sites from Hurd and Pilditch (2011). The standard deviation of each measurement is given in parentheses.

The elastic modulus of algal material was reported by Hale (2001).

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<th>Exposed Morphology</th>
<th>Sheltered Morphology</th>
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<td>Blade thickness, $h$ (mm)</td>
<td>0.46 (0.07)</td>
<td>0.42 (0.13)</td>
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<td>Elastic modulus, $E$ (Pa)</td>
<td>$5 \times 10^6$</td>
<td>$5 \times 10^6$</td>
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<tr>
<td>Blade length, $l$ (m)</td>
<td>0.62 (0.05)</td>
<td>0.52 (0.03)</td>
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<tr>
<td>Corrugation amplitude, $a$ (mm)</td>
<td>1.4 (0.2)</td>
<td>-</td>
</tr>
<tr>
<td>Corrugation wavelength, $\lambda$ (mm)</td>
<td>3.07 (0.15)</td>
<td>-</td>
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Figure 1: (a) A photo of a *Macrocystis* blade, showing the longitudinal corrugations running along the length of the blade. (b) A cut section of a *Macrocystis* blade, showing the regularity of the corrugation wavelength and amplitude. (Photo credit: Rominger and Nepf, 2014)
Figure 2: a) Sketch of blade attached to clamp from the side view. Flow in the channel moves in the \( x \)-direction. b) Cross section of a corrugated model blade perpendicular to flow. The area moment of inertia \( I \) is defined about the \( y \)-axis.
Figure 3: Discrete curves representing one wavelength of the blade mold cross-section, which is $5\pi\lambda = 3$ cm wide in total, for the model with corrugation amplitude $a = 1.5$ mm. A perfect sinusoid (dashed line) is aligned with the center of the blade. The top and bottom curves (blue lines) mark the templates for the acrylic molds. The red line shows the thickness of the blade measured perpendicular to the surfaces, while the green line shows the vertical displacement between the surfaces.
Figure 4: (a) The grayscale templates created in Matlab with (b) the finished acrylic molds. The holes in the corners of the molds were drilled after laser cutting to simplify the alignment process when filling the molds. The model blades were 3 cm wide ($b$) x 30 cm long ($l$), so each mold is 6 cm x 31.5 cm.
Figure 5: Casting process using the laser-cut molds. (a) The acrylic molds are set on a table. Metal spacers are placed along the outer perimeter of the left mold to set the thickness, and (b) the prepared silicone mixture is poured onto the mold. (c) The mixture is covered with the right acrylic mold and held down with weights to cure (about 20 minutes). (d) A cross-sectional view of a 4x4 cm prototype mold filled with the VPS mixture (pink).
Figure 6: Completed blades displayed here with duplicates (left to right: flat, $a = 1.5$ mm corrugated, $a = 2$ mm corrugated, flat, $a = 1.5$ mm corrugated, $a = 2$ mm corrugated). Each blade has an additional 1 to 2 mm of flat space at the end where the clamp attaches.
Figure 7: (a) Schematic of experimental setup, which is the same as Rominger and Nepf (2014).
(b) The $a = 1.5$ mm corrugated blade held horizontally in the channel by a narrow metal clamp, which is attached to the load cell beneath the false bottom.
Figure 8: (a) The measured drag force and (b) the drag force per surface area as a function of dimensionless blade rigidity. The standard error in the time-averaged drag measurements is within the size of the symbols shown. The uncertainty in the $\eta$ measurements is represented by the black lines. The uncertainty in the flat blade’s rigidity is within the size of the symbol.
Figure 9: (a) flat blade, (b) 1.5 mm amplitude corrugation, (c) 2 mm amplitude corrugation.

Each sequence represents one cycle of vortex shedding. The frequency of vortex shedding from the D = 2.5 cm bar is 1.2 Hz, which yields a period of 0.83 seconds. The 5 frames in each of the above sequences are therefore spaced 0.2 s apart ($\frac{1}{4}$ the period).
Figure 10: The image on the left shows one example of random corrugation peaks, and the image on the right is the resulting grayscale template.