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## CURRENT INDUCED DRAG FORCES ON CULTIVATED SUGAR KELP

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## ABSTRACT

*To obtain more knowledge of current induced drag forces on sugar kelp, towing tests with ropes containing cultivated sugar kelp was conducted. As freshwater may damage the kelp and cause changes in its mechanical response, tests were performed in a test facility containing seawater. A special purpose test rig was constructed for towing of ropes at different constant velocities through the water, thus simulating water current. The ropes were mounted horizontally and perpendicular to the towing direction. Several ropes, all 3 meters long, with either a medium level or high level of growth, were tested individually. The ropes with sugar kelp were collected from a seaweed farm prior to the experiments and tested with the kelp still attached to the ropes on which they were grown. The total drag forces on the ropes were measured along with the towing velocity. Based on the results from the experiments relations between drag forces, measured size, weight of the kelp and current velocity were found. The results also show signs of reconfiguration of the plants, i.e. adaption to the current flow to reduce the experienced loads. As a result, a power function with an exponent smaller than 2 can be used for modelling of the drag forces. The drag force seems to go towards a value proportional to the velocity squared for higher velocities, indicating that the plants might no longer be able to reduce the forces through reconfiguration. Results from this study expand the knowledge of drag forces on ropes with cultivated sugar kelp and may be implemented into a suitable numerical code for estimation of hydrodynamic loads on seaweed farms.*

Keywords: Saccharina latissima, sugar kelp, aquaculture, seaweed farms, drag forces, reconfiguration

## NOMENCLATURE

| | | |
|---|---|---|
| u | [$ms^{-1}$] | Towing velocity |
| f | [$Nm^{-1}$] | Force per meter of rope |
| F | [N] | Force |
| w | [$Nm^{-1}$] | Wet weight of biomass per meter of rope |
| $L_{stipe}$ | [m] | Average length of stipes |
| $L_{blade}$ | [m] | Average length of blades |
| $B_{blade}$ | [m] | Average width of blades |
| L | [m] | Sum average length of blade and stipe |
| $A_p$ | [$m^2$] | Area proportional to estimated sum average blade area for each rope |
| $\sigma_{L,Stipe}$ | [m] | Sample standard deviation of stipe length |
| $\sigma_{L,Blade}$ | [m] | Sample standard deviation of blade length |
| $\sigma_{B,Blade}$ | [m] | Sample standard deviation of blade width |
| n1 – n4 | [-] | Index of rope 1 – 4 |
| a | Dependent on b | Constant in fitted power function |
| b | [-] | Constant in fitted power function |
| $\psi$ | [-] | Vogel exponent |
| $\nu$ | [$m^2s^{-1}$] | Kinematic viscosity (set to $10^{-6}$) |
| $\rho$ | [$kgm^{-3}$] | Density of water during the tests (Measured to 1022.1) |
| $R^2$ | [-] | Coefficient of determination |

## INTRODUCTION

Industrial production of seaweeds is a growing industry in Norway and is expected to continue to grow from a value added

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of 0.8 billion NOK in 2014 to an estimated value added of 27 billion NOK by 2050 [1]. Seaweeds or products from seaweed, are used as bioenergy, fertilizers, feed ingredients, food or food ingredients as well as in pharmaceuticals [2]. With a projected world population of 9.8 billion by 2050 [3], sustainable food production is likely to become one of the major challenges in the future. Seaweed is traditionally used as food in Asian countries such as China, Japan and South Korea [2]. Even so, it is one of the largest unexploited resources and seaweeds are some of the fastest growing plants in the world, in addition to occupying the lowest tropic level [4].

To meet the projected need for biomass production in Norway, seaweed farms may need to be situated in exposed areas farther from the coast due to area conflicts such as fisheries, aquaculture, seaways and nature conservation in coastal areas. Studies have also indicated that due to more stable water temperatures, higher nutrient concentrations and better light conditions, the largest potential for industrial production of seaweeds and macroalgae, such as sugar kelp (*Saccharina latissima*), may be offshore [5, 6]. Combined structures, such as the use of offshore wind farms as a platform for seaweed farming, are looking promising [7]. The development of aforementioned offshore combined food-energy systems requires research, development of technologies, marine spatial planning as well as transparent and adaptive management processes [7]. Bak et al. [8] aimed to develop a cultivation method economically profitable in the Atlantic Ocean, for macroalgae, and demonstrated that large-scale kelp cultivation is possible in the Faroe Islands.

Going offshore to more exposed locations introduce challenges, as wind, wave and current loads tend to be higher. As a response to a fluid in motion, the flexible macroalgae will reconfigure, reducing the experienced drag force [9-11]. Reconfiguration leads to self-shading and streamlining. Self-shading occurs on both blade and patch level, i.e. a blade reconfiguring its geometry thereby shading itself, or by one blade shading another. The reduction in force due to reconfiguration can be expressed by introducing the Vogel exponent, $\psi$, in the relationship between force and velocity; $F \propto u^{2+\psi}$. For flow past a blunt, submerged body that does not reconfigure, the Vogel exponent is equal to zero. The Vogel exponent has been reported to be anything from -0.30 to -1.11 for brown algae [12]. Due to the flexibility of macroalgae, wave actions are often assumed to be of lesser importance. The assumption being that macroalgae have the capacity of reducing the effect of brief loads through an increased response time [13]. However, studies comparing transient effects with static expectations, has on the contrary shown increased loads [13] as well as dislodgement of plants at considerably lower velocities [14].

The morphology of the blade is affected by the habitat. Previous studies have found that sugar kelp grown in less exposed habitats have relatively wide blades with ruffled margins, compared to specimens grown under offshore or exposed conditions [15]. The morphology will influence plant-flow interaction and drag, with blades grown under sheltered conditions experiencing higher drag forces than exposed-grown blades under similar current velocities [15]. The holdfast attachment might also be more be resilient in kelp grown under more exposed conditions or that have experienced a series of storms [14, 16]. Patch density is also an important parameter to consider due to plant-plant interactions [11]. When looking to go offshore, a lower density may be required as it has been seen that singly grown plants withstand stronger forces from current and waves, if only slightly [15]. When grown singly, the plants has a chance to anchor their holdfast to the rope, and do not aggregate on top of the holdfast of neighboring plants [15]. However, this might be balanced by the shielding neighboring plants provide from the environment [15].

With the emerging interest in seaweed farming, there is a growing need to look at the plant-flow interactions on patch scale as well as mooring systems. Sulaiman [17] performed towing tests using previously dried clumps of seaweed, that were assumed to be restored to nearly nominal properties after being soaked in water over a period of time. Two lines were towed together, both transversely and diagonally to the towing direction, and it was found that the front line in transverse direction clearly produced more drag while the second towing lines have lower values compared to the first lines, likely due to shielding. Numerical models can be used to determine the feasibility of moving to exposed sites and can form the basis for comparing different mooring systems. Sulaiman et al. [18] looked at this using Bureau Veritas 7 software and looked at mooring systems based on current drag calculations only. However, additional drag due to waves should also be considered.

The current study focuses on the effect of the average drag force on patch scale caused by currents. To obtain more knowledge of current induced drag forces on sugar kelp, towing tests with ropes containing cultivated sugar kelp have been conducted. The study was performed in seawater, as freshwater may cause changes to the mechanical response of sugar kelp, as stiffness and ability to recover from deformation has been found to decrease with exposure to freshwater [19]. This is a challenge when testing macroalgae, as most facilities do not allow for neither the use of biological material, nor water with a salinity level close to seawater.

Finding relations between drag forces on ropes grown with sugar kelp and measurable kelp parameters is the main focus of this study. This will be an important contribution to methods for estimating the environmental forces affecting a kelp sea farm and be important for design and dimensioning.

# 1 Materials and Methods

## 1.1 Experimental setup

The tests performed in this study were limited to kelp ropes being tested separately and oriented perpendicular to the experienced water current, i.e. the orientation that is expected to produce the highest drag forces [17]. The two main orientations of kelp ropes in Norwegian seaweed farms are horizontal and vertical. In this study the kelp ropes were mounted horizontally in a test rig and towed through a stationary body of salt water with constant velocities ranging from 0 $ms^{-1}$ to 0.85 $ms^{-1}$. All ropes were tested with a submergence of 1.1 m.

### 1.1.1 Test facilities

The "Subsea Test Centre" on Dora in Trondheim, Norway provided a testing facility with salt water. The facility consists of a dock with dimensions 130 x 20 x 14 meters. The dock uses water from the Trondheim fjord, and is situated at the mouth of the river Nidelven. Timing of the opening of the sluices with the tide provide water inside the dock with a salinity level close to that of sea water (29.5 $g{\cdot}kg^{-1}$), meeting the demands for the environment. Temperature and water density were recorded to 13.3 °C and 1022.1 $kgm^{-3}$, respectively.

In addition to providing an environment that will not cause significant changes to the mechanical properties of the kelp, the dock enabled testing in a stationary body of water. The superstructure of the dock also sheltered most of the test area from wind. It can therefore be assumed that the effect of wind was negligible.

The facility did not have a towing carriage or other installments normally used in facilities tailored for model testing of marine structures and a test rig had to be built. As the body of water was stationary, the water current was simulated by towing the test rig with the kelp ropes attached. The test rig consisted of a raft and a frame for attaching the kelp ropes. Towing was achieved by building a rope-pulley-system with an electric motor attached.

**FIGURE 1:** TEST RIG. RAFT CONSISTING OF TWO KAYAKS AND A TIMBER FRAME. FRAME RESTING ON BRACKETS (PIVOT POINTS). PICTURE SHOWING RAFT AT REST. TOWING DIRECTION TOWARDS THE LEFT.

### 1.1.2 Test rig – raft and frame

The raft was a catamaran design with kayaks as hulls. The deck of the catamaran consisted of wood beams with a plywood deck (**FIGURE 1**), providing a work deck and area to place the needed equipment. The frame mounted on the raft was designed in such a way that kelp ropes could be connected and disconnected without the need to hoist the frame or raft out of the water. **FIGURE 2** and **FIGURE 3** show a schematic front and side view of the test rig arrangement.

The frame was A-shaped, made from steel pipes (with a diameter of 60.3 mm), and rested in steel cradles – one cradle over each hull. The frame pivoted around the contact points in the cradles. The longitudinal position of the frame was directly above the seating position in the kayaks, as this was thought to be close to the center of buoyancy for the hulls. Positioning the heavy frame – weighing slightly less than 100 kg – above the buoyancy center would minimize stationary pitch due to the weight of the frame and equipment. The kelp ropes were connected to a rope-pulley arrangement on the frame, and pretensioned to approximately 115 N.

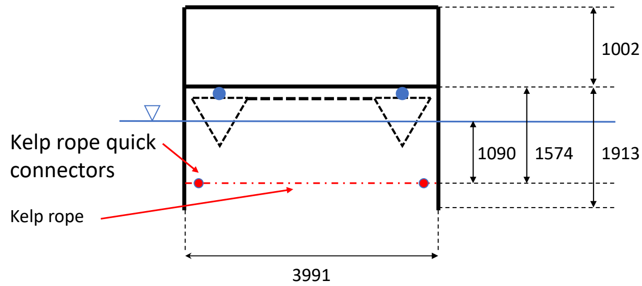


**FIGURE 2:** SCHEMATIC FRONT VIEW OF TEST RIG. SOLID BLACK LINES REPRESENT THE FRAME, DASHED LINES REPRESENT THE RAFT WHILE THE DASH-DOTTED LINE REPRESENTS THE KELP ROPE. ALL MEASUREMENTS ARE CENTER TO CENTER (FRAME PIPES) AND GIVEN IN MILLIMETERS.

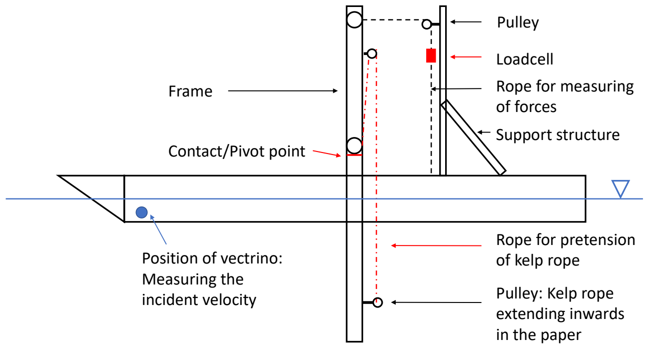


**FIGURE 3:** SCHEMATIC SIDE VIEW OF TEST RIG. THE VECTRINO IS POSITIONED IN THE MIDDLE BETWEEN THE TWO KAYAKS. TOWING DIRECTION TOWARDS THE LEFT.

Load cells, one on each side of the frame measured the forces. The load cells were connected to ropes coming from the top of the frame. These ropes were oriented horizontally from the frame, and then went over pulleys to be oriented vertically before being connected to the load cells. This minimized the effect of the weight of the loads cells on the results. A moment balance about the pivot point would then provide the means to derive the drag forces affecting the kelp rope. Dry tests on land, however, revealed a percentagewise discrepancy between applied and derived forces using a moment balance. The discrepancy was probably due to friction between the frame and frame rests and friction in the pulleys leading to the load cells, as well as due to the vertical center of mass of the frame assembly being slightly higher than the pivot point. The frame was also allowed to rotate slightly between loaded and unloaded position, such that zero measurements between each run could be conducted with a completely unloaded frame.

Dry tests were then extended to find a correlation coefficient between the exerted force on the rope and the measured force on the frame. A surrogate rope replacing the kelp rope was pulled with a load cell and this force was compared to the measured forces at the top of the frame. The force applied on the surrogate rope was a point load applied in the 'drag force direction' directly in the center between the kelp attachment points seen in **FIGURE 2**. The forces exerted during the dry test ranged from 25 N to 250 N and gave a linear relation with $R^2 = 0.9993$ for the entire range. The measured forces during testing of the ropes ranged from 5 N for the lowest velocity tested to obtain frame drag, to approximately 250 N for the highest recorded load during kelp rope testing.

#### 1.1.3 Towing mechanism

To achieve constant towing velocities, simulating a water current, a towing mechanism was designed. A bridle was connected to the fore and aft of the raft. The bridle at the fore was connected to a rope going to a pulley close to water level at one end of the dock. The rope was directed through a cathead attached to an electric motor, and then redirected by pulleys to the far end of the dock. Finally, the rope was directed down close to the water surface through pulleys and further to the bridle at the aft of the raft. The rope was pretensioned to avoid slip.

The setup enabled towing of the raft with a variety of constant velocities through the length of the dock. After reaching the end of the dock, the raft was repositioned to the far end by reversing the motor.

### 1.2 Force measurements

Force measurements were conducted with U9C load cells from HBM with a capacity of 1 kN. Zero measurements were run before each run, meaning that the rig was stationary for a certain amount of time to allow for measuring of load cell output when unloaded to account for load cell creep. In addition, this allowed the raft and water to settle.

### 1.3 Velocity measurement

The towing velocity, or simulated current velocity, were measured by a Vectrino 3D Field Probe (doppler) from Nortek, measuring velocity in 3 dimensions. The resulting value of these measurements were used in the analysis of the data. The Vectrino was attached at the front of the raft, directly between the two hulls. The probe and half of the conical extension of the housing were submerged, situating the measurement volume approximately 30 cm below the surface.

### 1.4 Data acquisition and post-processing

A conventional towing tank has a carriage with a power supply. Using a specially built test rig caused a challenge regarding how to log the data and provide power to the equipment. This were solved by using a 12 V car battery in conjunction with a sine converter to get frequency and voltage that could supply the computer, amplifier and sensors with electric power.

Data were obtained as time series, sampled at 25 and 100 Hz, for the velocity and force measurements, respectively. The values presented in this paper are average values for velocities and forces for each test run over a time interval with constant velocity. While the test runs lasted about 60 s, average values were calculated mainly for intervals ranging between 20 and 40 s, with a few intervals as short as 10 s due to limited duration with constant velocity. Frequency analysis, removing time-varying values from the interval, were used for control of the average value.

### 1.5 Sugar kelp

The sugar kelp was procured from a seaweed farm close to Frøya, Norway (harvested on the 11th of May 2018). The blades of the kelp were relatively wide with ruffled margins (**FIGURE 6**), indicating that the site is relatively sheltered [15].

The kelp was tested still attached to the ropes on which they had been grown. In order to minimize 3D effects on the flow around the ropes they were kept as long as practically possible (approximately 3 m in length).

A total of 4 different ropes were tested, including 2 ropes with medium growth (n3, n4) and 2 ropes with a high level of growth (n1, n2). The towing tests were performed from the 28th of May to 30th of May 2018.

#### 1.5.1 Kelp parameters

In order to assess drag forces due to kelp growth, the length, width, weight and number of specimens were measured for each rope before the towing experiments. The ropes were cut, stripped of excess kelp (limiting the length of rope containing kelp to approximately 3 m) and eyelets for quick connection to the frame were attached to the ends of the prepared ropes.

The growth of the kelp was assessed by measuring the length and width of the blades and length of the stipe (**TABLE 1** and **TABLE 2**). For each rope tested, measurements were done on 20 random plants selected by throwing a pencil on top of the rope when placed on the ground and measuring the plant at which the point was resting. The length of the stipe was measured from the connection on the rope to the root of the blade, while the length of the blade was measured from the root to the tip. The width was measured at the widest part of the blade. For each rope the number of plants per meter of rope were estimated by counting the number of plants larger than 10 cm in length over a minimum of 3 clusters of kelp growth. The kelp was grown (or attached) to the rope in evenly spaced cluster (5 to 6 clusters per meter), as a consequence of the seeding process. Therefore, approximately half of the rope was cover with kelp. One cluster towards each end of the rope and one in the middle of the rope were selected for counting of number of specimens. If the growth seemed uneven over the rope by visual observation or by counted number of specimens, additional measurements were conducted.

The weight of the kelp was assessed by weighing the ropes. The procedure involved soaking each kelp rope with seawater, lifting it by the ends of the rope for excess water to run off and weighing it using a tarpaulin and a hand-held weight. The weight of the ropes, eyelets on the ends of the rope and the tarpaulin were later measured and subtracted from the measured results in order to obtain the wet biomass of the kelp. The weighing was performed after length measurements and prior to testing. The ropes were mounted to the test rig directly after measuring and subsequently tested. They were submerged in the dock when not subjected to measurements or testing.

Visual inspection of the ropes revealed that while the growth on rope n3 and n4 was even, this was not the case for rope n1 and n2 (**FIGURE 4** and **FIGURE 5**). For rope n3 and n4, the plants were distributed evenly along the rope and there was not a large variation of lengths. The lengths and densities of specimens along rope n1 and n2 however, varied. This was especially true for rope n1. Another observation was, that because the kelp grows in clusters, there is an uneven distribution of kelp volume along the rope.

Making the simplification that blade area for one plant divided by the length and width of the blade is similar for all plants, the parameter $A_p$ was introduced and have been used in the evaluation of the results. It is, based on the assumption, proportional to the total projected surface area of the kelp on the ropes (not taking the ruffles on the blades into account), and can be expressed as

$$A_p = B_{Blade} L_{Blade} \cdot plants/meter, \qquad (1)$$

for each rope.

The ropes, on which the kelp was attached, was a three strand, twisted rope, with a maximum diameter of 7 mm.

**TABLE 1:** WEIGHT OF BIOMASS PER METER, PLANTS PER METER AND AVERAGE LENGTH AND WIDTH MEASURED FOR A MINIMUM OF 20 RANDOMLY SELECTED PLANTS FOR EACH ROPE.

| Rope | Weight | Plants/meter | $L_{blade}$ | $L_{stipe}$ | $B_{blade}$ |
|---|---|---|---|---|---|
| [-] | [kgm$^{-1}$] | [m$^{-1}$] | [m] | [m] | [m] |
| n1 | 3.97 | 51 | 0.890 | 0.056 | 0.229 |
| n2 | 4.98 | 71 | 0.774 | 0.115 | 0.271 |
| n3 | 2.78 | 205 | 0.597 | 0.058 | 0.117 |
| n4 | 3.03 | 182 | 0.686 | 0.061 | 0.120 |

**TABLE 2:** STANDARD DEVIATIONS OF BLADE LENGTH, BLADE WIDTH AND STIPE LENGTH OVER A MINIMUM OF 20 RANDOM MEASUREMENTS FOR EACH ROPE.

| Rope | Standard deviations | | |
|---|---|---|---|
| | $\sigma_{L,Blade}$ | $\sigma_{B,Blade}$ | $\sigma_{L,Stipe}$ |
| [-] | [m] | [m] | [m] |
| n1 | 0.489 | 0.105 | 0.023 |
| n2 | 0.372 | 0.150 | 0.095 |
| n3 | 0.180 | 0.039 | 0.020 |
| n4 | 0.182 | 0.033 | 0.017 |

**FIGURE 4:** PICTURE OF ROPE n2. EYELET ATTACHMENT CAN BE SEEN IN THE LOWER RIGHT PART OF THE PICTURE. THE FOLDING RULER IN THE PICTURE IS ONE METER IN LENGTH.

**FIGURE 5:** PICTURE OF ROPE n3. THE FOLDING RULER IN THE PICTURE IS ONE METER IN LENGTH.

**FIGURE 6:** DETAILED VIEW OF ONE PLANT FROM ROPE n4. THE FOLDING RULER IN THE PICTURE IS ONE METER IN LENGTH.

 

## 1.6 Frame drag and presenting of kelp rope drag

The frame had two pipes piercing the water surface (**FIGURE 2**) and has a relatively large cross-sectional diameter. Since the pipes pierce the water surface there will be resistance due to waves generated, in addition to drag forces on the pipes. It was assumed that the kelp ropes would not influence the total resistance on the frame significantly due to the distance between the main part of the rope and the frame, and the orientation of the ropes being perpendicular to the submerged parts of the frame. The horizontal distance between the frame and the kelp-grown part of the ropes is approximately 0.45 m on either side of the frame.

To determine the resistance of the frame itself, the raft and rig were towed at a series of velocities. A quadratic regression was fitted to the force measurements for velocities up to 0.65 $ms^{-1}$. One single measurement above this velocity (1.03 $ms^{-1}$) was omitted due to visibly large vibrations during the run and maximum velocity for testing of the kelp ropes not exceeding 0.85 $ms^{-1}$. To keep the drag forces close to the frame drag experienced during the towing tests of the kelp, the tests were run with the vertical ropes and pulleys (used to fix and pre-tension the kelp ropes) attached to the frame. For a velocity of 0.65 $ms^{-1}$, the regression curve estimates 31.5 N at the top of the frame.

To obtain the drag forces on the kelp ropes, the measured forces on the frame was first subtracted from the raw data. It was assumed that rope drag and frame resistance were independent and that the contribution to the measured forces at the top of the frame was equal whether a kelp rope was present or not. The correlation coefficient derived earlier was then used on the resulting raw data to obtain the drag forces on the kelp ropes. The results are presented as drag force per meter.

# 2 Results and discussion

## 2.1 Drag forces on the kelp ropes

There are several parameters and effects that may affect the magnitude of drag forces on the ropes. The drag force is expected to come from shear stress as well as pressure difference [11]. How large these effects are compared to each other is challenging to address based on these experiments alone. It is reasonable to assume that friction drag, i.e. integrated shear stress over the plants, have a noticeable effect on the drag forces experienced by the ropes due to the large surface area. The stipes grow directly on the rope, nearly perpendicular to the rope axis around the whole diameter of the rope. This means that the kelp may present a projected area and volume larger than the mass alone would suggest when seen in the current direction. The stipe is expected to bend or reconfigure to the flow, thereby changing this projected area and volume. This is due to the stipe having a relatively low bending stiffness, which may affect the loads exerted on the kelp. These observations indicate the possibility for pressure drag along with viscous drag. The plants may also arrange themselves or flutter in such a way that flow separation occurs. The diameter of the rope and the density and distribution of the kelp on the rope, determined by the seeding process, may also affect the drag forces. The rope may contribute with a force similar to that of a circular cylinder, however the rope and kelp grown on it will interact hydrodynamically.

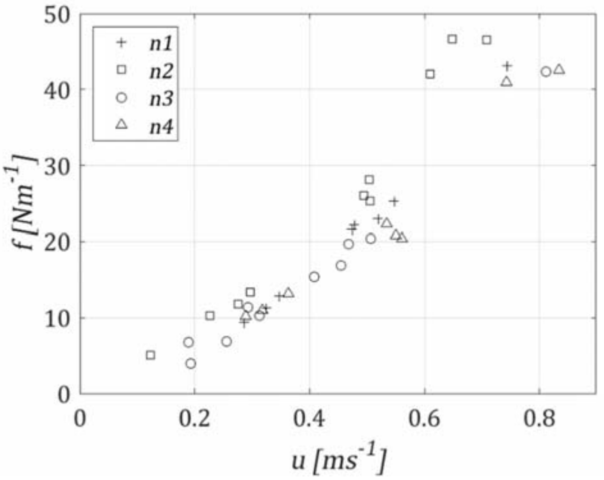


**FIGURE 7:** AVERAGE DRAG FORCE PER METER FOR ALL KELP ROPES AS A FUNCTION OF TOWING VELOCITY.

When evaluating the measured drag forces on the ropes individually, the focus was on the relation between the average force affecting the rope as a function of the average velocity. Force per meter rope as a function of towing velocity is shown in **FIGURE 7**. Each point represents the average measured velocity and drag force during one run obtained when the velocity was constant or very close to constant and transient effects no longer were present. It should be noted that the forces were oscillating around a mean value with overlapping frequencies due to contributions from the frame (observed in the results for frame drag) and – although not confirmed – possible oscillations of the kelp and kelp rope.

As a trend, the average drag force per meter rope increases with increasing average velocity. There are however some discrepancies. Such a discrepancy can be seen for rope n4 at velocities close to 0.55 $ms^{-1}$. The average drag force per meter can be seen to seemingly decrease, rather than increase, with increased velocity. A small variability was observed for the frame drag measurements for the highest velocities, which may partly explain the observation. As we have no visual observation of the kelp during towing, it is unclear how the kelp rearrange itself during runs, and how this affects the drag force. A previous study on the use of surrogates for model experiments observed a lack of repeatability at higher velocities, above 0.50 $ms^{-1}$, causing a large standard deviation [20]. At these higher velocities, the models were observed to change arrangement relative to each other during runs. For kelp, as the models used in [20] were of a stiffer material, this phenomenon might emerge at lower velocities, i.e. n3 at approximately 0.2 $ms^{-1}$.

Earlier experiments on tensile plants [9] show that the plants are able to reconfigure their shape as the fluid velocity increases in order to reduce the forces exerted on them. The force as a function of velocity may then be best represented as a power function with an exponent smaller than 2. It is only at higher velocities, when the plant is not able to reconfigure further, that the drag force may follow a quadratic relation. Fitting a power function to the data (**TABLE 3**) yields an exponent between 1.32 and 1.58. The Vogel exponent [9], expressed as $\psi$ in the curve fit

$$f(u) = au^{2+\psi}, \quad (2)$$

was found to be -0.42, -0.68, -0.56 and -0.62 for rope n1, n2, n3 and n4, respectively. These values are similar to what has been found for 'sheltered' species of brown seaweeds [12]. Due to the highly undulate nature of the blades, the kelp is likely from what can be considered a 'sheltered' area. From other studies it has been found that a plant grown in a sheltered area will experience greater drag force due to the morphology of the blade. It is likely that the drag forces recorded in this study is larger than that of a flatter blade grown at an 'exposed' site.

**FIGURE 8** shows a relationship between a variable, proportional to the drag coefficient, as a function of $u/\sqrt{L}$. As the flow velocity increases the drag force seems to go towards a quadratic relation, i.e. $F \propto u^2$. This might indicate that the kelp on the rope at these higher velocities is not able to further reduce the experienced drag force by reconfiguration.

**TABLE 3:** CURVE FIT FOR DRAG FORCES PER METER ON THE KELP ROPES AS A FUNCTION OF VELOCITY. $\psi$ CORRESPONDS TO THE VOGEL EXPONENT.

| Function | $au^b$ | | | $au^{2+\psi}$ |
|---|---|---|---|---|
| Rope | $a$ | $b$ | $R^2$ | $\psi$ |
| n1 | 67.70 | 1.577 | 0.9951 | -0.423 |
| n2 | 71.33 | 1.317 | 0.9599 | -0.683 |
| n3 | 56.20 | 1.444 | 0.9891 | -0.556 |
| n4 | 53.08 | 1.382 | 0.9522 | -0.618 |

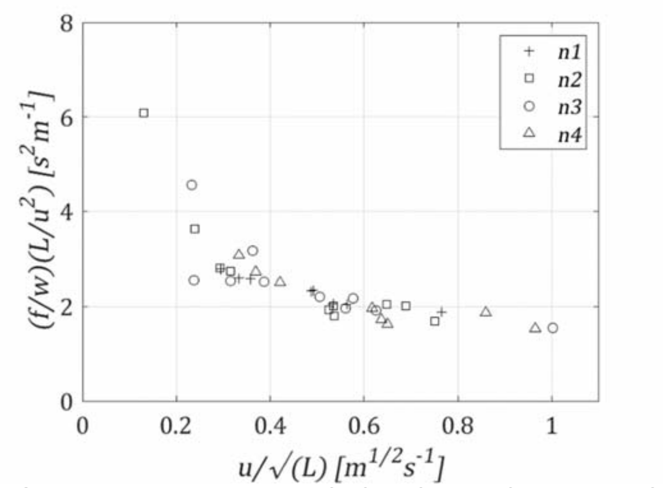


**FIGURE 8:** PARAMETER PROPORTIONAL TO THE DRAG COEFFICENT PLOTTED AS A FUNCTION OF VELOCITY AND DIMENSIONING LENGTH. L IS THE SUM AVERAGE LENGTH OF STIPE AND BLADE.

## 2.2 Parametrization of drag force

Earlier work on the subject of current induced drag forces on kelp such as sugar kelp indicate that a large portion of the drag comes from viscous forces, due to it being primarily a 'tensile plant' [11]. The plants, being long and slender with a large surface area, also supports that viscous forces must be considered. The large planform area (as seen from above) and the large total surface area of the plants also suggest that the contribution from viscous forces are significant. This led to evaluating the relation between the drag forces and the Reynolds number of the average sum length of stipe and blade (**FIGURE 9**). Reasonably good agreement can be seen for rope n2-n4, while the results for rope n1 deviates. The uneven distribution of plant lengths and growth density along n1, described in 1.5.1, may have caused the measured average length to be inaccurate or not fully represent the dimensioning length of the kelp on this rope. However, dividing the drag forces with water density and $A_p$ (described in 1.5.1), see **FIGURE 10**, shows that inclusion of the width – and thus implicitly the estimated sum area of the blades – yields a better parametrization of the drag forces.

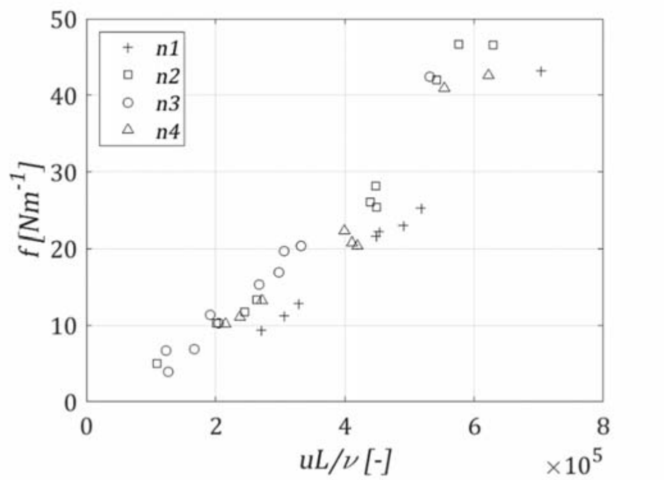


**FIGURE 9:** DRAG FORCES PER METER ROPE AS A FUNCTION OF THE REYNOLDS NUMBER. THE DIMENSIONING LENGTH IS THE AVERAGE SUM LENGTH OF STIPE AND BLADE.

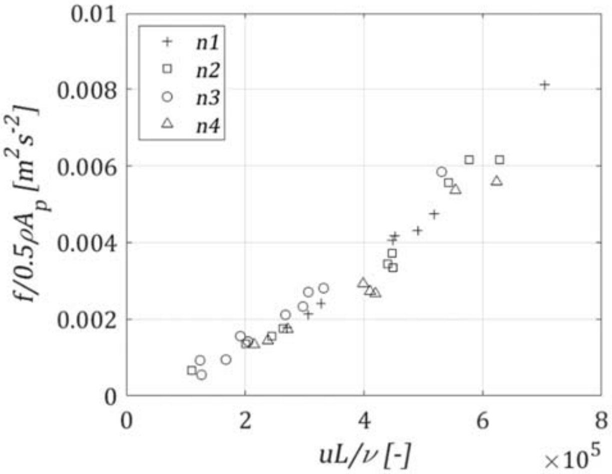


**FIGURE 10:** DRAG FORCE DIVIDED BY A PARAMETER PROPORTIONAL TO SUM BLADE AREA PLOTTED AS A FUNCTION OF THE REYNOLDS NUMBER. L IS SUM AVERAGE LENGTH OF STIPE AND BLADE.

With this study we wish to contribute to knowledge needed to develop methods for estimating environmental forces affecting seaweed farms (with sugar kelp). We therefore explored simple relationships between easily obtainable measurements for grown kelp, velocity and the measured drag force. Parameters used to estimate drag forces could be estimated based on experience and formulations for the drag forces can be implemented into suitable numerical codes, thus giving a basis for design and dimensioning.

It was found that the inclusion of the parameter weight of the biomass in Newtons, collected the data points across rope n1-n4 (**FIGURE 11**). This was done by dividing the drag forces by the weight of the biomass, creating a dimensionless parameter.

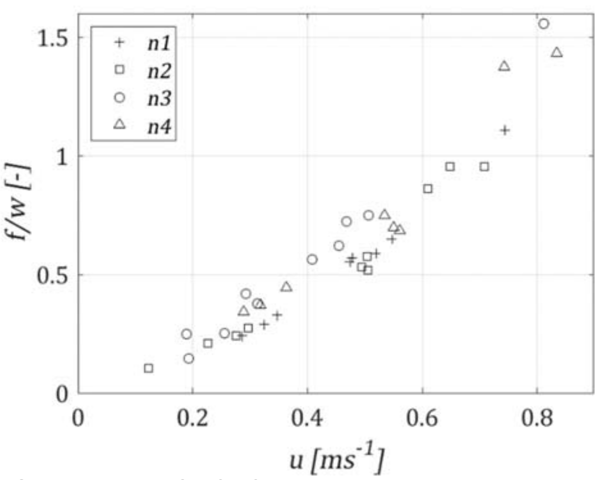


**FIGURE 11:** DRAG FORCE PER METER DIVIDED BY WEIGHT PER METER IN NEWTONS AS A FUNCTION OF TOWING VELOCITY.

However, evaluating the abovementioned dimensionless number as a function of $u/\sqrt{L}$ yielded even better results (**FIGURE 12**). This relationship is proportional to the Froude number. Interestingly, evaluating $f/w$ as a function of the Froude number yielded results comparable to evaluating $f/0.5\rho A_p$ as a function of the Reynolds number. Vettori and Nikora [21] found that the density of sugar kelp is slightly higher than sea water ($1092 \pm 91$ kgm$^{-3}$), thus indicating that the Froude number may be suitable for parametrization of the data. Still, there is a possibility that the kelp affects the surface elevation, i.e. generates waves, suggesting that the effect of submergence on the drag forces should be investigated further.

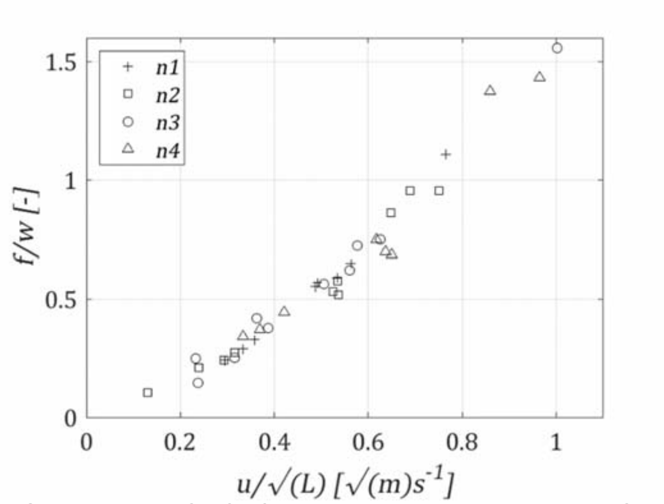


**FIGURE 12**: DRAG FORCE PER METER DIVIDED BY WEIGHT PER METER AS A FUNCTION OF TOWING VELOCITY DIVIDED BY THE SQUARE ROOT OF THE TOTAL AVERAGE LENGTH OF THE PLANTS.

### 2.3 Uncertainties

Measuring of kelp properties can be a source of error with regards to parametrization of the test results. While bias is subjected to all measurements, although it was sought to avoid this, the largest possibility for errors in the measuring of properties is considered to be rope n1, due to uneven distribution of the plants in addition to a variation in plant lengths. A larger number of samples (for measuring of length and width) would have given a more reliable estimate of kelp properties. Although time-consuming, it would have been beneficial to measure the kelp a second time after the tests had been conducted. This way it could have been quantified if a significant number of specimens had dislodged during testing. Visually, however, this was not observed. In addition, mechanical properties of the kelp may have been affected by storing the kelp in relatively stagnant water between receiving them and testing.

The perceived friction in the frame assembly may be a source for error for measured forces lower than 25 N, i.e. the lowest total measured force in the dry tests, possibly affecting results for frame drag for the lowest velocities.

Raft pitch was not measured during the tests. Difference in pitch angle between dry tests and tests in water may alter the correlation coefficient slightly through effects of change in frame angle on the force measurements and through lateral displacement of frame center of gravity. As this effect on the total force will be dependent on the sine of the change in angle (rotation) of the frame, it is thought to be a minor source for error as long as the difference in pitch angle of the raft were not too dissimilar between dry testing and the towing tests.

Additionally, the combined submerged weight of the kelp rope and vertical forces on the kelp itself, although considered small, may have affected the force readings. The rope attachment points were situated close to the frame pipes, yielding a small moment arm (~ 0.07 m) contributing to the measured forces on the frame.

The kayaks and the probe used for velocity measurements generated waves, and thus represents an uncertainty. However, due to the relatively low velocities tested creating shorter waves, and the small amplitude of waves generated, these waves are thought to not affect the measured velocities and forces significantly due to the depth of the velocity measurement volume and the depth of the kelp ropes.

## 3 Conclusion

As previously seen in studies looking at flexible objects that reconfigure, the force does not follow a relation proportional to the velocity squared. However, towards higher velocities, the drag force seems to go towards this relationship, suggesting that kelp cannot reduce the drag force further by reconfiguration at these higher velocities.

The aim was to find common parameters, for instance weight and length, that can describe the mechanisms or governing parameters for determining drag forces on ropes grown with sugar kelp. Both **FIGURE 11** and **FIGURE 12** show examples of relatively simple relations that can be implemented into a numerical code for estimation of hydrodynamic loads on seaweed farms due to current-induced drag. However, previous studies have shown that wave action is likely to also be an important contribution factor to forces acting on flexible macroalgae, such as sugar kelp. This must therefore be kept in mind if the results of these studies are implemented into methods for design and dimensioning of seaweed farms. It is also important to consider that only four ropes with kelp and only two different growth levels were used. Additionally, the kelp was all harvested from the same area. The results are therefore likely not transferable to all locations and levels of growth. Even so, the results of this study may overestimate the drag force rather than underestimate (for growth levels similar to the ones presented in this study) and might therefore still be of interest for dimensioning of seaweed farms. The reason being that 'sheltered' blades, such as those used during this study, are expected to experience a larger drag force than 'exposed' blades.

The results indicated that closeness to the water surface may have affected the results. Although the choice of submergence was based on common depths of kelp ropes in Norwegian farms with a horizontal layout of the ropes, this subject should be investigated further.

Variability or discrepancies in force measurements were observed for certain velocities. Possible causes may be variability in forces on the frame and possible rearrangement of the kelp during runs.

## 4 Further Work

The results presented in this work is for one kelp rope mounted horizontally and perpendicular to the towing direction, i.e. simulating water current perpendicular to the rope orientation. The two main orientations of kelp ropes in Norwegian sea farms are horizontal arrangement and vertical arrangement. A sea farm consists of tens or hundreds of ropes arranged in such a way that many of the ropes will be affected by the wake from upstream ropes when subjected to water current. The kelp ropes will affect the flow and the current velocity downstream will most likely be reduced. The current direction will also vary, meaning that the angle of attack (inflow angle) to the rope will vary. This, in combination with wake or shadow effect from upstream ropes creates a complicated situation. Using data from the presented or similar work, for dimensioning and design of kelp sea farms, would represent the conceived worst-case scenario in terms of loads on the farm from water current. Even so, tests investigating the wake field and effect on the forces due to varying the angle of attack would be beneficial to understanding the behavior of cultivated sugar kelp in current. It would possibly form a more realistic basis for dimensioning and would also produce valuable input for design with regards to optimizing growth, as growth is dependent on, among others, sufficient access to nutrients through the water flow [11, 22].

A limited number of kelp ropes were investigated in this study. Further studies including different levels of growth (higher and lower than tested in this study) and ropes exposed to different growth conditions are recommended to further expand knowledge. With regards to design and dimensioning one could also investigate higher velocities and the effect on drag forces due to reduced or increased submergence, which would also contribute to knowledge for evaluation of behavior in waves, which would be beneficial for design of seaweed farms deployed in more exposed areas.

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