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The geometry and dynamics of Danish anchor seine ropes on the seabed.

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Abstract

We present a two-dimensional kinematic description of the geometry and dynamics of the ropes of demersal seines during deployment, towing and hauling, using piriform curves. Piriforms (which means pear-shaped) are relatively simple analytical curves, which we parameterise, using basic positional and operational data from typical Danish anchor seine hauls. We then demonstrate how we can estimate the area fished, and the speed, direction and angle of attack of any part of the seine net rope, at any time during the fishing process. This sort of information is fundamental to a better understanding of the capture process of demersal seines, their whole gear selectivity and their environmental impact.

Keywords:

demersal seining; Scottish seining; fly-dragging; piriform curves; whole gear selectivity; benthic impact.

Introduction

Demersal seining is a fishing technique that is practised in many regions of the world to capture both demersal roundfish and flatfish species. In the original method, namely Danish anchor seining, the ropes and the net are set out from an anchored dhan (marker buoy), along an approximate triangular path. The deployment usually finishes some distance along the return leg to the dhan, after which the gear is towed the remaining distance to the anchor. The gear is then hauled by the winches while the vessel is held stationary by the anchor. During the deployment phase the ropes encircle fish, which are herded into the path of the net during the towing and hauling phases (Thomson, 1981; Galbraith *et al.*, 2004).

During the nineteenth and twentieth centuries, Danish anchor seining was taken up and adapted in many other fisheries worldwide (Walsh and Winger, 2011). There are demersal seine fisheries in many European countries eg Denmark (Noack *et al.*, 2017), the Netherlands (van Hal, R. and Machiels, 2017), Ireland (McHugh *et al.*, 2019), Scotland (Galbraith *et al.*, 2004), Norway (Cojocaru, 2019) and Iceland (Solmundsson *et al.*, 2005). There are also important demersal seine fisheries in Australia (Hunt *et al.*, 2014), Indonesia (Wijayanto *et al.*, 2020), Japan (Suzuki and Takagi, 2008), Russia (Lowry *et al.*, 2018), Korea (Jeong and Lee, 2019), the Philippines (SEAFDEC, 2007) and Canada (Walsh and Winger, 2011). The demersal seining practised in most of these countries, is a modified technique called either Scottish seining, Danish seining, fly-dragging or fly-shooting. In this technique, when the vessel returns to the dhan, the vessel moves forward while the gear is hauled, thus fishing a larger area.

While demersal seining has suffered a decline in popularity in many countries during the last few decades, it has, more recently, attracted renewed interest (Kinds *et al.*, 2016; Gobillon and Wolff, 2020). It is considered to be more fuel efficient, to have better quality catches and to have a more benign environmental impact on the seabed than other mobile gears (Suuronen *et al.* 2012). In some jurisdictions, even though there have been very few studies in support of these opinions, they have been given exclusive access to be used on sensitive sites (Noack *et al.*, 2019).

In comparison to trawls, there is little information regarding the efficiency, operational performance, and environmental impact of demersal seines (Walsh and Winger, 2011; Eigaard *et al.*, 2016; Noack *et al.* 2019). There have been a number of studies of their catching performance and selectivity (Reeves *et al.*, 1992; Isaksen and Løkkeborg, 1993; Herrmann *et al.*, 2016a, 2016b; Noack *et al.*, 2017; Ingólfsson *et al.*, 2019) but very few concerning the fish herding process by the ropes and net, the resultant whole gear selectivity and their physical interaction with the seabed. Noack *et al.* (2019) used GPS loggers and video cameras to measure the position and dynamics of a Danish anchor seine. From the video footage, they noted that the majority of fish enter the seine net towards the end of the fishing operation and that, during their trials, interactions of the ropes and the seabed appeared to be relatively minor.

To be able to describe quantitatively the performance and environmental impact of demersal seines, it is necessary to understand the geometry and dynamics of the seine gear, and in particular of the ropes. The ropes of demersal seines are the components of the gear that are in most contact with the seabed. They can be many kilometres long, yet little is known about how they operate when fishing. Suzuki and Takagi (2008) and Lee *et al.* (2019) develop a lumped mass model, Priour and Billard (2019) a finite element model and Madsen *et al.* (2016) a cable-element model of Scottish

seine rope dynamics, which simulate the physical behaviour of seine ropes during the fishing process, the latter of which has been used to compare the efficiency of different types of initial deployment patterns (Madsen *et al.* 2017). Here we develop a two-dimensional kinematic model of the geometry and dynamics of demersal seine ropes. In particular, we use basic positional and operational data for a Danish anchor seine (Noack *et al.*, 2019) to show how a relatively simple analytical curve (a piriform) can characterise the rope geometry and dynamics. Although, we focus on the Danish anchor seine, as it is the only relevant data set we can find, our analysis will also apply to other demersal seine techniques. We then demonstrate how our model can estimate the area fished, and the speed, direction and angle of attack of any part of the seine net rope, at any time during the fishing process. This sort of information is fundamental to a better understanding of the capture process of demersal seines, their whole gear selectivity and their environmental impact (O'Neill and Ivanović, 2016; Noack *et al.*, 2017; O'Neill *et al.*, 2018; Ingólfsson *et al.*, 2019).

Material and methods

Piriform curve

Piriform means pear-shaped and is a particular example of a broad class of tear dropped-shaped curves. It is a quartic curve and in cartesian coordinates can be expressed as

$$a^4 y^2 = b^2 x^3 (2a - x)$$

where a is half the distance from the tip to the base of the tear drop and b is the perpendicular distance to the curve from this mid-point (Figure 1) (Weisstein, 2020). Here we use the data of Noack *et al.* (2019) to show that this type of curve can be used to describe the geometry of the Danish seine following deployment and during towing and hauling. There are many other tear dropped shaped analytic curves which we could have used, but we choose the piriform because of the ease with which parameters a and b can be interpreted and estimated using basic operational and positional data. In addition, it can be shown that the maximum perpendicular distance from the mid-line is $\frac{3\sqrt{3}}{4}b$, that it occurs three quarters of the way along the mid-line, and that the area enclosed by a piriform is πab .

Piriforms can also be expressed parametrically as

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a(1 - \cos \theta) \\ b \sin \theta (1 - \cos \theta) \end{pmatrix}$$

where θ is in the range $(0, 2\pi)$. The form it takes when we rotate it an angle λ about the origin is

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos \lambda & -\sin \lambda \\ \sin \lambda & \cos \lambda \end{pmatrix} \begin{pmatrix} a(1 - \cos \theta) \\ b \sin \theta (1 - \cos \theta) \end{pmatrix}$$

which, when we allow λ , a and b to vary with time, becomes

$$\begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} \cos \lambda(t) & -\sin \lambda(t) \\ \sin \lambda(t) & \cos \lambda(t) \end{pmatrix} \begin{pmatrix} a(t)(1 - \cos \theta) \\ b(t) \sin \theta (1 - \cos \theta) \end{pmatrix}$$

Here, to use piriforms to describe the performance of a Danish seine, we define three distinct phases of the fishing operation: the deployment phase (from t_o to t_d); the towing phase (from t_d to t_t); and the hauling phase (from t_t to t_h); where t_o is the start time of fishing process, t_d is when the seine net and the seine ropes are laid out, t_t is when the vessel is back at the dhan and t_h is the time the seine net is hauled back on the vessel. These phases differ slightly from those of Noack *et al.* (2019) who define deployment (or setting), herding and catching phases. Their focus was on fish behaviour and capture, and while our deployment phases are the same, their herding phase encompasses all our towing phase and the first part of our hauling phase, and their catching phase is the latter part of our hauling phase.

Noack *et al.* (2019) used GPS loggers to record the course of a Danish seiner and the movement and position of the seine gear. The seine gear had 360 meshes (120 mm mesh size) around the fishing circle, a 44 m ground rope and two 15-coil sets of 220 m long, 26 mm diameter leaded seine rope. They obtained GPS data for six hauls ranging in duration from 2:44 to 3:47 hours (Table 1) and we use these positional gear and vessel data to find appropriate values for $\lambda(t)$, $a(t)$ and $b(t)$ during each of the phases.

Fitting the piriform curves

Deployment phase

During the deployment phase, the ropes and net are set out from an anchored dhan in a rough teardrop shape. The deployment usually finishes at a point along the return leg when the entire length of seine rope is laid out.

We assume that once the ropes have settled on the seabed after deployment, they have the geometry of a partial piriform and do not move again until the towing phase begins. Hence, we only consider the geometry of the ropes once they have been fully deployed.

From the ships track data, we estimate, for each haul, (i) the distance from the anchor to the point where the rope crosses the axis of symmetry of deployment and (ii) the distance from the end point of deployment back to the anchor (Table 1). We fit piriform curves to each haul by setting $a(t_d)$ to be half the first of these values, and we find $b(t_d)$ by ensuring the fitted curve satisfies the second condition (Figure 2), where the end point of deployment has an arc length of 6644 m (two times the rope length plus the ground rope) along the piriform.

Towing phase

During the towing phase, we assume that the seine ropes move from the deployment piriform configuration to a more slender piriform shape, when the vessel returns to the anchor. At this point we can estimate, (i) the distance between the net and the vessel and (ii) the path along which the net is subsequently hauled (Table 1) and thus, can estimate $a(t_i)$ and $\lambda(t_i)$ respectively (Table 2). We find $b(t_i)$ by ensuring that, after towing, the total arc length of the piriform is 6644 m.

In order to model the path of the seine rope during the towing phase we need to describe $a(t)$, $b(t)$ and $\lambda(t)$ as t goes from $t_d \rightarrow t_i$. The rope is towed at a constant speed and the average towing time over the six hauls is 29:50 min (1790 s) (Table 1). The net moves along a curved path from its deployment position, which is on average 3356 m from the anchor point, to a position after towing, which is on average 3110 m from the anchor point (Figure 3, Table 1). For each haul, this decrease is well described by a quadratic hence, we assume that $a(t_d) \rightarrow a(t_i)$ in a similar way (Figure 4). We have no information on how $b(t_d) \rightarrow b(t_i)$ or on how $\lambda(t_d) \rightarrow \lambda(t_i)$, so we assume they vary linearly.

Hauling phase

During the hauling phase, we describe the rope geometry by piriforms of decreasing length and width, that are symmetric about the line that the net is hauled. The ropes are hauled with increasing speed and when we scale the time with the corresponding hauling duration, the distance measurements between the net and the vessel are very consistent and again well described by a quadratic curve (Figure 5). Hence we assume $a(t) \rightarrow 0$ in the same way and we ensure symmetry by setting $\lambda(t) = \lambda(t_i)$ during this phase. We have no information on how $b(t_i) \rightarrow b(t_h)$, but assume it decreases linearly to zero.

Model predictions

To demonstrate the ability of the piriform model to characterise the geometry and dynamics of the seine ropes, we use the average parameter values and times of the six Noack *et al.* (2019) hauls (Table 2).

Figure 6 shows the modelled position of the seine ropes at equal time intervals from the deployment configuration through the towing phase, while Figure 7 shows the position of the ropes during the hauling phase. These plots are combined in Figure 8 to show how the configuration of the rope varies during the whole course of a haul. In particular they highlight the variable speed of different parts of the ropes during a haul, for at a given point, a greater distance between the curves indicates a faster speed of the rope at that point.

Equation 1 describes the piriform curves as functions of t and θ . A more useful parameterisation, however, is one in terms of t and s , where s is the arc length along the piriform curve from the net. We can define s during the towing phase to be

$$s(\theta, t) = 3322 - \int_0^\theta \sqrt{dx^2 + dy^2}, \quad t \in (t_d, t_t)$$

and during the hauling phase to be

$$s(\theta, t) = \int_0^\pi \sqrt{dx^2 + dy^2} - \int_0^\theta \sqrt{dx^2 + dy^2} = \int_\theta^\pi \sqrt{dx^2 + dy^2}, \quad t \in (t_t, t_h).$$

We evaluate these numerically, and use them to produce smooth functions of x and y in terms of s and t . This allows us to describe the path and dynamics of any point along the ropes (Figure 9).

We can also calculate dx/dt and dy/dt at a given s and dy/dx at a given t and hence calculate the velocity and angle of attack of a given position of the rope (where the angle of attack is the angle between the direction of seine rope and how it is aligned on the seabed). This information can be used to provide a much more detailed, quantitative understanding of the interaction of the seine ropes and the seabed. Figure 10 plots the speed of the seine ropes at each point swept, from which it is clear (i) that the first rope deployed does not move much during the towing phase, in comparison to the considerable movement of the second rope; and (ii) that during the hauling phase, the ropes move slowly at first but then are hauled progressively faster and the central part of the gear reaches speeds similar to that experienced by the second rope during the towing phase.

The average rope speed is 0.57 ms^{-1} and these are more or less equally distributed between 0.1 and 1.0 ms^{-1} (Figure 10b). Figure 11 plots the angle of attack, and shows that during the towing phase the angle of attack of the first rope is mainly greater than 60° to the direction it is being towed, whereas that of the second rope is generally less than 30° and is towed approximately along the direction it is aligned. During the hauling phase, the angle of attack is about 90° close to the net, and decreases

towards 0° , the further the distance is from the net and the closer it is to the anchored vessel. Over the whole fishing operation, the angle of attack of the seine net ropes is less than 45° over 75% of the area swept. The component of the speed that is perpendicular to the seine rope is plotted in Figure 12. This is the speed at which a fish will perceive a seine rope to be approaching and hence is likely to influence the catching process. It averages 0.22 ms^{-1} and is generally much lower than the speed over the ground values of Figure 10. Figure 13 shows that hydrodynamic drag of the seine ropes is relatively constant along most of their length during all of the fishing operation. The hydrodynamic drag is a function of the speed, the angle of attack and the drag coefficient of the seine rope, which here we assume can be approximated by piecewise linear cylinders and has a drag coefficient of 0.63 as measured by O'Neill and Summerbell (2016).

Discussion

We have demonstrated how the geometry of seine ropes on the seabed, during deployment, towing and hauling, can be described by piriform curves. This allows us to describe the speed, direction and angle of attack of any part of the seine net rope, at any time during the fishing process (Figures 7 – 11), which will be very useful in assessing and quantifying the operational performance and environmental impact of demersal seine gears.

The model, however, is an approximation and clearly has limitations; some associated with the model assumptions and others associated with the data it uses. To model the initial deployment of the ropes on the seabed we fit a piriform to the ships track. The ships track has a more triangular shape and the piriforms do not represent it particularly well at the vertices of each haul (Figure 2). These vertices relate to two occasions when the vessel turns about 60° . The first one precedes the nets deployment, and the second is when the vessel turns back towards the anchor, a few coils after the net is deployed. This is a dynamic process and as the vessel proceeds and turns, the settling gear will be drawn inwards. This can be seen by comparing the distance along the track length (i) from the anchor to the net and (ii) from the net to the end of the second rope. In all cases these values are greater than the 3.3 km rope length, averaging 3.8 and 3.9 km respectively (Table 1). Hence, it is likely that the geometry of the deployed gear on the seabed at these points will be more rounded and better represented by a piriform, rather than by the more angular ships track.

The model predictions overestimate the movement of the first rope during the towing phase (Figure 6) in comparison to the fitted curves of the individual hauls (Figures 2 and 3). This is probably because the model assumes that the anchor point does not move during the course of the haul.

There is, however, an average difference of 153 m between where the anchor is set at deployment and the point from where the net is hauled, which is likely to be a result of how the anchor beds in when it is being deployed and whether it drags prior and during hauling (Table 1).

Another important characteristic of the model is that it is two-dimensional and only models the projection of the ropes on the plane of the seabed. It does not describe their three-dimensional position as they rise from the seabed to the surface. While the implications of this will depend on the fishing depth and the length of rope deployed, in most instances it will only have a significant effect close to the vessel and hence will have minimal influence on estimates of the parameters presented in Figures 10 – 13 or on parameters such as swept area.

These concerns notwithstanding, the piriforms provide a very useful description of the geometry and dynamics of demersal seine gears on the seabed, that will provide insights into issues such as fish herding and seine gear efficiency, and in physical impact studies, will permit the estimation of the amount of sediment mobilised by a gear and the extent to which a gear penetrates the seabed (O'Neill, and Ivanović, 2016).

The swimming ability of fish plays a key role in the fish capture process (Winger *et al.*, 1999; Breen *et al.*, 2004). It influences the extent to which the ropes and sweeps of demersal mobile gears herd fish into the path of the net and hence will affect the size and species selectivity of these gears (Ryer, 2008; Noack *et al.*, 2019). The component of the speed that is perpendicular to the seine rope is important in this regard. This is the speed at which the seine rope will approach a stationary fish and the speed at which a fish will have to swim if it is to remain ahead of the rope. Figure 12 demonstrates that for over 96% of the swept area, this speed is less than 0.5 ms^{-1} , and that it is close to this value over much of the area swept by the second rope during the towing phase, suggesting that if fish herding is a concern this part of the gear should be investigated. When it comes to habitat alteration and benthic mortality, the momentum of the ropes maybe the deciding factor, and the absolute speed over the ground maybe a more important quantity. Figure 10 demonstrates that the area swept by the second rope during the towing phase may be vulnerable in this respect. For processes such as sediment mobilisation, the hydrodynamic drag of the seine ropes is important and is dependent on both their speed and angle of attack (O'Neill and Summerbell, 2016). Figure 13 shows that, throughout the fishing operation, these quantities combine in such a way that the hydrodynamic drag of the seine ropes is fairly constant indicating that the amount of sediment mobilised will be evenly distributed over the total area swept by the ropes.

Although the model presented here has only been fitted to one data set of six hauls from one Danish anchor seine vessel, we are confident that the approach can be applied to other anchor seiners. In these fisheries, there is often a high degree of uniformity of vessel power and size, of the nets and ropes used and of the deployment, towing and hauling operations (Eigaard *et al.*, 2015). Hence, the possibility of expressing $\lambda(t)$, $a(t)$ and $b(t)$ in terms of variables such as rope length, vessel power/size and fishery needs to be explored. Furthermore, we are also confident that our analysis can be extended to all demersal seiners, as it only requires that the anchor position be given a velocity profile during the hauling phase.

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Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author

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359 Figure 1. General description of a piriform curve (see text for details).

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Figure 2. Piriform curves fitted to the deployment data of the six individual hauls. We can see here that the ships track (the thinner line) has a more triangular shape and the piriforms do not represent it particularly well at the vertices of each haul (see text for details).

Figure 3. Two examples (hauls 3 and 5) of the piriform fits to the data of Noack *et al.* (2019). The smaller (solid black) piriform curves are the estimated geometries after towing. The J-shaped (dotted) curves are the actual paths that the seine net followed. The curved part of the path occurs during towing from the point when the entire seine rope is laid out to when the vessel returns to the anchor; and the straight part is the path it follows as the ropes are subsequently hauled. The blue lines are the fitted and measured deployment curves of Figure 2.

Figure 4. The distance between the net and anchor for each of the hauls of Noack *et al.* (2019) during the towing phase, where the scaled towing time = $(t - t_d)/(t_t - t_d)$ (ie time is scaled according to the corresponding towing duration). The different marker symbols refer to the different hauls. The values are very consistent and by fitting a quadratic curve through these data we can ensure that the piriforms behave in a similar way by setting $a(t) = -71.1 \frac{(t-t_d)^2}{(t_t-t_d)^2} - 1.52 \frac{(t-t_d)}{(t_t-t_d)} + 1626$.

Figure 5. The distance between the net and anchor for each of the hauls of Noack *et al.* (2019) during the hauling phase, where the scaled hauling time = $(t - t_t)/(t_h - t_t)$ (ie time is scaled according to the corresponding hauling duration). The different marker symbols refer to the different hauls. The data are very consistent and by fitting a quadratic curve through these data we can ensure that the piriforms behave in a similar way by setting $a(t) = -1073 \frac{(t-t_t)^2}{(t_h-t_t)^2} - 422 \frac{(t-t_t)}{(t_h-t_t)} + 1555$.

Figure 6. The geometry of the seine ropes at equally spaced time intervals during the towing phase. The dotted line is the line of symmetry about which the seine gear was deployed (and identifies $\lambda(t_d)$) and the dashed line is the line of symmetry the ropes have after the towing phase (and identifies $\lambda(t_t)$).

Figure 7. The geometry of the seine ropes at equally spaced time intervals during the hauling phase.

Figure 8. The position of the seine ropes, at equally spaced time intervals during towing and hauling phase.

Figure 9. The predicted path of equally spaced points along the seine ropes, during towing and hauling. The bold line is the path taken by the net.

Figure 10. (a) The seine rope speed at each point of the area swept during towing and hauling and (b) these data summarised identifying the percentage area swept in 0.1 ms^{-1} intervals.

Figure 11. (a) The angle of attack of the seine ropes across the area swept during towing and hauling and (b) these data summarised identifying the percentage area swept in 10° intervals.

Figure 12. (a) The perpendicular component of the seine rope speed at each point of the area swept during towing and hauling and (b) these data summarised identifying the percentage area swept in 0.1 ms^{-1} intervals.

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418 Figure 13. (a) Estimates of the hydrodynamic drag (per unit frontal length) of the seine rope at each
 419 point of the area swept during towing and hauling and (b) these data summarised identifying the
 420 percentage area swept in 0.5 Nm^{-1} intervals. Note, the hydrodynamic drag of the net is not
 421 presented in this figure.

Table 1: Haul data from the trials reported in Noack <i>et al.</i> (2019). (Note, the times have been corrected to account for stops during hauling to attach and detach instrumentation)							
	haul 2	haul 3	haul 4	haul 5	haul 6	haul 7	average
distance between end of 2 nd rope and the anchor (m)	1026	1708	2111	1103	1399	1620	1494
distance between net and vessel when vessel returns to the anchor (m)	2981	3226	3101	3078	3022	3256	3111
difference in anchor positions at deployment and after hauling (m)	92	325	125	178	94	106	153
distance along vessels track from anchor to net (m)	3803	3407	3817	4142	3960	3863	3832
distance along vessels track from net to end of 2 nd rope (m)	3994	3817	4069	4184	3701	3893	3943
deployment time ($t_d - t_o$)	00:53:00	00:52:00	00:59:00	00:57:00	00:47:00	00:52:00	00:53:20
towing time ($t_t - t_d$)	00:24:00	00:27:00	00:52:00	00:24:00	00:24:00	00:28:00	00:29:50
hauling time ($t_h - t_t$)	01:27:19	01:28:08	01:43:20	01:27:13	01:36:34	01:26:14	01:31:28
total ($t_h - t_o$)	02:44:19	02:47:08	03:34:20	02:48:13	02:47:34	02:46:14	02:54:38

Table 2: Parameter values for the piriforms fitted to the haul data of Noack <i>et al.</i> (2019).							
	haul 2	haul 3	haul 4	haul 5	haul 6	haul 7	average
deployment							
$a(t_d)$ (m)	1575	1680	1655	1640	1640	1850	1673
$b(t_d)$ (m)	650	750	890	600	690	660	707
$\lambda(t_d)$ (°)	161	183	164	160	163	158	
after towing							
$a(t_t)$ (m)	1491	1613	1550	1539	1511	1628	1555
$b(t_t)$ (m)	403	184	308	327	373	145	290
$\lambda(t_t)$ (°)	168	176	174	164	168	161	