A simplified model for bottom trawl fishing gears

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Computational modeling is a valuable complementary tool to assess behavior of bottom trawl fishing gears. A simplified model of the gear that mainly affects to the net is proposed. The model is constrained to steady towing conditions, flat seabed and gear symmetry. Simulations proportionate a number of relevant outcomes like distribution of tensions at the warp, balance of forces at the otterboards or spread under different haul conditions such as depth or towing speed. In this paper we mainly focus on the description and implementation of the model. Nevertheless, some preliminary comparison with experimental data is also shown.

1 INTRODUCTION

Bottom trawl fishing gears are complex systems in which the different constitutive components (net, sweeps, otterboards and warps) are intimately coupled. Information on gear response has been traditionally inferred from empirical experience, in situ data acquisition (Henriques 1992; Sala 2006) and scaled prototypes in flume tank experiments (Fiorentini et al. 2004). In addition to empirical studies, a number of theoretical models of increasing complexity have also emerged in parallel with the development of computational capabilities. However, attempts to model simultaneously all the components of fishing gears are rare (Bessonou et al. and Marichal 1998). To date, most modeling efforts have been addressed towards the study of net geometries (Bessonou and Marichal 1998; O’Neill 1999; Wan et al. 2002; Priour 2003; Suzuki et al. 2003; Shimizu et al. 2004) and net drag evaluations (Reid 1977; Galbraith 1983; Ferro et al. 1996; Hu et al. 2001), normally for the case of pelagic trawls.

In this paper we develop a simplified model for bottom trawl fishing gears which requires the total net drag and the net opening at the wing ends as input parameters. The model predicts the configuration of the gear solving for the equilibrium equations of the otterboards and the system of ordinary differential equations (ODE’s) of the warp. Simulations proportionate also the distribution of tensions, otterboards spread and attack angle as well as the balance of forces at the otterboards under different haul conditions like fishing depth or towing velocity.

The manuscript is arranged as follows. Firstly in §2 we discuss the assumptions and limitations of the model. In §3 we derive the governing equations for each component of the gear. In §4 we describe the numerical implementation of the model.

2 MODEL HYPOTHESIS

The behavior of a real gear during a haul is likely to be affected by multiple time-dependent and often unpredictable factors such as, for instance, seabed irregularities, waves or water currents. In order to simplify the problem we constrain to an ideal scenario in which the following hypothesis apply: steady state (i.e. constant towing velocity and negligible effect of waves and currents on the gear), flat seabed and gear symmetry with respect to the vertical plane.

Some additional simplifications for the components of the gear are also contemplated. Rather than the full net geometry we consider only the horizontal net opening and we assume a known total net drag. The sweeps are assumed to behave as a rigid bar. Finally, we consider that the otterboards do neither pitch nor heel.
3 MODEL GOVERNING EQUATIONS

The gear is towed with speed \( \mathbf{u} \) with components: net, sweeps, otterboards and warps. Taking into account the model hypothesis described in section 2 it is only necessary to derive the governing equations of the otterboard and the warp.

3.1 Otterboard equations

In this section we derive the governing equations for the otterboards imposing equilibrium of forces and moments. The function of the otterboards is to spread the gear horizontally and, simultaneously, to keep it in contact with the seabed. In general, an otterboard has six degrees of freedom which must be balanced under the steady towing assumption. In order to derive the equilibrium equations let us consider an orthonormal frame of reference \( \mathbf{x}_0 = \langle x_0, y_0, z_0 \rangle \) attached to the otterboard and having the origin located at the center of pressure. This local basis is defined so that \( x_0 \) points backwards (opposite direction of towing), \( y_0 \) points outwards, and \( z_0 \) points downwards. The system \( \mathbf{x}_0 \) and the cartesian frame of reference \( \mathbf{x} \) are related by \( \mathbf{x} = \mathcal{D} \cdot \mathbf{x}_0 \) (or \( \mathbf{x}_0 = \mathcal{D}^{-1} \cdot \mathbf{x} = \mathcal{D}^T \cdot \mathbf{x} \)) where, in general, \( \mathcal{D} \) results from composing a rotation of heel angle \( \varphi \) along the \( x_0 \) axis, a rotation of pitch angle \( \theta \) along the \( y_0 \) axis, and a rotation of yaw angle \( \Psi \) (angle of attack) along the \( z_0 \) axis. However, since we constrain to the case where the otterboard does neither heel \((\varphi = 0)\) nor pitch \((\theta = 0)\) the transformation matrix reduces to a single rotation:

\[
\mathcal{D} = \begin{pmatrix}
\cos \Psi & -\sin \Psi & 0 \\
\sin \Psi & \cos \Psi & 0 \\
0 & 0 & 1
\end{pmatrix}
\] (1)

where \( \Psi \) is the angle of attack.

We consider a trawl door with mass \( M_o \), length \( L_o \) and height \( H_o \) towed at speed \( \mathbf{u} \).

3.1.1 Balance of forces

Forces acting on otterboards include weight, buoyancy, ground contact forces, hydrodynamic forces and tensions exerted by the warp and the backstrop at the attachment points. On a Cartesian frame of reference \( \mathbf{x} \) oriented along the tow direction these forces write as follows:

1. Mass forces due to weight and buoyancy \((\mathbf{F}_M)\). Act along the vertical direction:

\[
(\mathbf{F}_M)_z = \begin{pmatrix}
0 \\
0 \\
M_o g - \rho_o V_o g
\end{pmatrix}
\] (2)

where \( V_o \) is the otterboard volume, \( \rho_o \) is the sea water density and \( g \) stands for the acceleration.

2. Ground contact forces \((\mathbf{F}_G)\). We limite the model to otterboard that touch the seabed slightly.

Therefore, the interaction with the seabed results on a vertical component (the normal or ground reaction force which prevents the otterboard to penetrate the seabed) and on a friction force that acts on the opposite direction of tow and which, as a first approach, can be assumed to be proportional to the normal force:

\[
(\mathbf{F}_G)_z = \begin{pmatrix}
\mu N \\
0 \\
-N
\end{pmatrix}
\] (3)

where \( \mu \) is the friction coefficient and \( N (\geq 0) \) is the normal force. Note that the minus sign has been introduced for coherence with the orientation of the \( z \)-axis.

3. Hydrodynamic forces \((\mathbf{F}_H)\). Relative movement among water and otterboards generates spreading (lift) and drag forces on the otterboards. It is well established that these forces depend on the towing speed squared, angle of attack, and otterboard design. In general, hydrodynamic forces are evaluated experimentally in terms of the drag and lift coefficients:

\[
(\mathbf{F}_H)_z = \frac{1}{2} \rho_a S_o |\mathbf{u}|^2 \begin{pmatrix}
C_D(\Psi) \\
C_L(\Psi) \\
0
\end{pmatrix}
\] (4)

where \( S_o \) is the otterboard projected surface, and \( C_D \) and \( C_L \) are the drag and lift coefficients respectively. According to our sign criteria \( \Psi < 0 \) for the port door (see Figure 1). The projection of the hydrodynamic forces onto the vertical direction vanishes because we have assumed a zero heel angle. Note also that the spreading and drag coefficients depend on the angle of attack of the otterboard. An efficient design aims to maximize the ratio \( C_L/C_D \) while keeping the otterboard stable.

4. Warp tension at the otterboard attachment \((\mathbf{T}_w)\). From Figure 1 it follows that:

\[
(\mathbf{T}_w)_z = -T_w \begin{pmatrix}
\cos \Psi_w \cos \theta_w \\
\sin \Psi_w \cos \theta_w \\
\sin \theta_w
\end{pmatrix}
\] (5)

where \( T_w, \Psi_w \) and \( \theta_w \) stand, respectively, for tension, yaw and pitch angles of the warp at the otterboard bracket. For the port otterboard and according to our sign criteria \( \Psi_w > 0 \) and \( \theta_w > 0 \).

5. Backstrop tension at the otterboard attachment \((\mathbf{T}_b)\). Consider an otterboard rigged with a twin backstrop attachment in which the lengths of both chains are equal and have a pitch angle \( \theta_b \). From Figure 1:

\[
(\mathbf{T}_b)_z = (T^o_b + T^b_b)_z
\] (6)
and

\[
\begin{cases}
T_b^u = T_b^u \begin{pmatrix}
\cos \Psi_b \cos \theta_b \\
\sin \Psi_b \cos \theta_b \\
\sin \theta_b
\end{pmatrix} \\
T_b^l = T_b^l \begin{pmatrix}
\cos \Psi_b \cos \theta_b \\
\sin \Psi_b \cos \theta_b \\
-\sin \theta_b
\end{pmatrix}
\end{cases}
\tag{7}
\]

In order to close the balance of forces it is necessary to add an additional constrain for \( T_b^u \) and \( T_b^l \) at the backstrop attachment point:

\[
\begin{align*}
(T_b^u + T_b^l) \cos \theta_b &= T_b \cos \epsilon \\
(T_b^u - T_b^l) \sin \theta_b &= T_b \sin \epsilon
\end{align*}
\tag{8}
\]

with \( \epsilon \) defined as in Fig. 1.

The balance of forces at the otterboard is obtained by combining equations (2) to (8) and imposing equilibrium. It yields, for each spatial component:

\[
\begin{align*}
\mu N + F_{Hx}(\Psi) + T_b \cos \epsilon \cos \Psi_b = T_w \cos \Psi_w \cos \theta_w \\
F_{Hy}(\Psi) &= T_w \sin \Psi_w \cos \theta_w - T_b \cos \epsilon \sin \Psi_b \\
M + T_b \sin \theta_b = \rho_0 V g + N + T_b \sin \theta_b + T_w \sin \theta_w
\end{align*}
\tag{9}
\]

The above set of equations is written in a way that highlights the effect of each contribution. Terms in the LHS act in the positive directions whereas terms in the RHS act in the negatives. In the \( x \)-direction, friction, hydrodynamic drag and tensions at both backstrop attachments oppose to movement and are balanced just by the component of the warp tension along the tow direction (\( x < 0 \) direction). In the \( y \)-direction hydrodynamic lift tends to spread the otterboards (\( y > 0 \) direction) whereas warp and backstrop attachment components do the opposite (note that \( \Psi_w > 0 \) and \( \Psi_b < 0 \) so that both terms have a positive sign). Finally, in the vertical \( z \)-direction, the otterboard weight and the upper backstrop attachment rig pull downwards (\( z > 0 \) direction) whereas buoyancy, ground reaction, warp tension and lower backstrop attachment rig pull the otterboard upwards.

3.1.2 Balance of moments

In addition to the balance of forces, the equilibrium hypothesis requires also a zero net balance of pairs. The balance of moments for the \( x \) and \( z \)-directions is calculated with respect to the origin of reference of the system \( \hat{\mathbf{x}}_b \) (i.e. the center of pressure). It follows that the pair exerted by the hydrodynamic forces is zero because, by definition, the resultant force acts at the center of pressure. On the other hand, weight and buoyancy forces do not either produce any moment under the hypothesis zero heel. In consequence, we limit to the pairs exerted by the warp and backstrop attachments:

(1) Warp moment \( (M_w) \). Let \( (r_w)_\mathbf{x}_b = (x_w, y_w, z_w)^T \) be the position vector of the warp bracket in the \( \hat{\mathbf{x}}_b \) frame of reference. It follows from (1) that:

\[
(r_w)_x = \mathbf{D} \cdot (r_w)_{\mathbf{x}_b}
\tag{10}
\]

so that the moment exerted by the warp yields \( M_w = \mathbf{D} \cdot (r_w)_{\mathbf{x}_b} \times T_w \) with \( T_w \) given by (5).

(2) Backstrop moment \( (M_b) \). Let \( (r_b^n)_{\mathbf{x}_b} = (x_b^n, y_b^n, z_b^n)^T \) and \( (r_b^l)_{\mathbf{x}_b} = (x_b^l, y_b^l, z_b^l)^T \) be the position vectors of the upper and lower backstrop attachments in the \( \hat{\mathbf{x}}_b \) frame of reference. Then:

\[
(r_b^n)_x = \mathbf{D} \cdot (r_b^n)_{\mathbf{x}_b}
\tag{11}
\]

and analogously for the lower component \( (r_b^l)_x \). The moment exerted by the two backstrop attachments yields:

\[
M_b = r_b^n \times T_b^n + r_b^l \times T_b^l
\tag{12}
\]

with \( T_b^n \) and \( T_b^l \) given by (7). Finally, imposing equilibrium one gets the \( x \) and \( z \) components:

\[
\begin{align*}
(M_w)_x + (M_b)_x &= 0 \\
(M_w)_z + (M_b)_z &= 0
\end{align*}
\tag{13}
\]

Given the values of tension and yaw angle at the backstrop attachment point \( (T_b, \Psi_b) \) and the pitch angle of the warp at the warp-otterboard bracket \( (\theta_w) \), equations (9) and (13) together with the constrains (8) constitute a system of 7 non-linear equations for the 7 unknowns: otterboard angle of attack \( \Psi \), ground reaction \( N \), warp tension and yaw angle at the otterboard attachment \( (T_w, \Psi_w) \), tensions at the upper and lower chain backstrop attachments \( (T_b^n, T_b^l) \), and \( \epsilon \) angle. In fact, the non-linear system can reduce to 5 equations with unknowns: \( \Psi, T_w, \Psi_w, T_b^u, \epsilon \).

3.2 Warp equations

Consider a warp of length \( L \) and diameter \( D \) towed from a vessel at speed \( \mathbf{u} \). The warp has neither stretch nor torsion. The goal is to determine the tension \( T \) and the coordinates of each point of the warp on the Cartesian basis \( \hat{\mathbf{x}}_w = < \mathbf{x}, \mathbf{y}, \mathbf{z}> \). An orthonormal set of unit vectors \( \hat{\mathbf{x}}_w = < \mathbf{t}, \mathbf{n}, \mathbf{b}> \) is defined at each point of the warp with \( \mathbf{t} \) tangential to the warp, \( \mathbf{n} \) normal to the warp and laying in the vertical plane, and \( \mathbf{b} \) orthogonal to the formers \( \mathbf{b} = \mathbf{t} \times \mathbf{n} \). The orientation of this local basis at a certain length or parameter arc \( s \in [0, L] \) is given by the Euler angles \( \Psi(s) \) and \( \theta(s) \), that is, the system \( \hat{\mathbf{x}}_w \) and the cartesian frame of reference \( \hat{\mathbf{x}} \) are related by \( \mathbf{R} = \hat{\mathbf{x}}_w = \mathbf{R} \cdot \hat{\mathbf{x}}_w \), where:

\[
\mathbf{R} = \begin{pmatrix}
\cos \Psi \cos \theta & \sin \Psi \cos \theta & \sin \theta \\
-\cos \Psi \sin \theta & -\sin \Psi \sin \theta & \cos \theta \\
\sin \Psi & -\cos \Psi & 0
\end{pmatrix}
\tag{14}
\]
and \( \mathbf{R}^{-1} = \mathbf{R}^T \) (\( \mathbf{R} \) is an orthogonal matrix). In addition to tension, forces per unit of length acting on the warp include:

1. Mass forces due to weight and buoyancy (\( \mathbf{F}_M \)):

\[
(F_M)_x = \begin{pmatrix} F_{Mx} \\ F_{My} \\ F_{Mz} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ w \end{pmatrix}
\]

(15)

or, using (14):

\[
(F_M)_w = \begin{pmatrix} F_{Mt} \\ F_{Mn} \\ F_{Mb} \end{pmatrix} = w \begin{pmatrix} \sin \theta \\ \cos \theta \\ 0 \end{pmatrix}
\]

(16)

where \( \rho_w \) is the warp density and \( w = (\rho_w - \rho_a) \pi D^2 g/4 \).

2. Hydrodynamic forces (\( \mathbf{F}_H \)) which, in general, can be inertial and non-inertial. Under steady towing conditions the inertial forces vanish and, in consequence, one has to consider only the non-inertial forces along the tangential (\( F_{Ht} \)) and normal directions (\( F_{Hn} \) and \( F_{Hb} \)). Hydrodynamic resistance of a warp is well described by the Morison’s equation (Faltinsen 1990):

\[
(F_H)_x = \begin{pmatrix} F_{Ht} \\ F_{Hn} \\ F_{Hb} \end{pmatrix} = \frac{1}{2} \rho_u D \left( \begin{array}{c} C_t |u_x| u_t \\ C_n \sqrt{u_n^2 + u_b^2} u_n \\ C_n \sqrt{u_n^2 + u_b^2} u_b \end{array} \right)
\]

(17)

where \( (u_t, u_n, u_b)^T \) are the components of the water speed (as seen by an observer attached to the warp), and \( C_t \) and \( C_n \) are the tangential and normal warp coefficients. It is obvious that the water speed has the opposite sense of the vessel towing speed (of the towing velocity \( u \)), that is:

\[
\begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} = |u| \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}
\]

(18)

and therefore

\[
\begin{pmatrix} u_t \\ u_n \\ u_b \end{pmatrix} = |u| \begin{pmatrix} \cos \Psi \cos \theta \\ - \cos \Psi \sin \theta \\ \sin \Psi \end{pmatrix}
\]

(19)

The governing equations for the warp result finally from imposing equilibrium of forces (Chin et al. 2000):

\[
\begin{cases}
\frac{dT}{ds} = -F_{Mt}(\theta) - F_{Ht}(\Psi, \theta) \\
\frac{d\theta}{ds} = -\frac{1}{T}(F_{Mn}(\theta) + F_{Hn}(\Psi, \theta)) \\
\frac{d\Psi}{ds} = \frac{1}{T \cos \theta}(F_{Mb}(\theta) + F_{Hb}(\Psi, \theta)) \\
\frac{d\theta}{ds} = \sin \Psi \cos \theta \\
\frac{dy}{ds} = \sin \Psi \cos \theta \\
\frac{dz}{ds} = \sin \theta
\end{cases}
\]

(20)

The above constitutes a system of ODE’s. Given the coordinates \((x, y, z)\), the Euler angles \((\theta, \Psi)\), and the tension \((T)\) of the warp at the bracket, the system is numerically integrated backwards along the parameter arc \( s \in [0, L] \) from the door \((s = 0)\) to the vessel \((s = L)\).

4. MODEL IMPLEMENTATION

Model inputs are the total net drag \((T_n)\) and the horizontal net opening (HNO) at the wing ends together with other general parameters of the gear and the haul. We present the model implementation step by step:

Step 1. Solve the equilibrium equations of the otterboards (9) and (13) given values for the yaw angle \( \Psi_b \) and tension \( T_b \) at the backstrop attachment point and for the pitch angle at the warp bracket \( \theta_w \). Note that \( \Psi_b \) is also the yaw angle of the sweep and that \( T_b \) is one half of the total net drag \( T_n/2 \) because a zero tension drop is assumed to occur along the sweeps. The outcomes are the attack angle \( \Psi \) and the tension \( T_w \) and the yaw angle \( \psi_w \) at the warp attachment point.

Step 2. Solve the warp ODE backwards in the interval \( s \in [0, L] \), with initial values: \( T(L) = T_w, \Psi(L) = \Psi_w, \theta(L) = \theta_w \). The final calculated values for \((y, z)\) are written as \( y_{ship} = y(0) \) and \( z_{ship} = z(0) \).

Step 3. The global function \( F(\Psi_b, \theta_w) = (y_{ship}, z_{ship}) \) is defined following steps 1 and 2.

Step 4. Find \((\Psi_b, \theta_w)\) such that \( z_{ship} \) equals the fishing depth \( H \) and \( y_{ship} \) equals half of the warp separation at the vessel stern, \( Y \) (i.e. ensure that the vessel lays in the vertical plane of symmetry):

\[
F(\Psi_b, \theta_w) = (Y, H)
\]

(21)

Numerical algorithms to solve steps 1 and 2 have been implemented using the open software libraries MINPACK and ODEPACK, respectively. The problem (21) is equivalent to find a zero of a system of nonlinear functions which is solved using MINPACK library, the jacobian is calculated by a forward-difference approximation. The initial condition is \( \theta_w = \arcsin(H/L) \) (straight warp) and \( \Psi_b \) varying from \(-\pi/4\) to 0 until convergence is achieved.
5 SUMMARY
We have developed a simplified model for bottom trawl fishing gears. The numerical implementation allows for an efficient and consistent coupling among gear components. A relevant feature of the model is that it skips a detailed simulation of the net and hence proportionates approximate results at negligible computational cost.

The model proportionates a detailed analysis of the otterboards including the horizontal opening, the angle of attack, the tensions at the backstrop and warp attachments, and the balance of forces and moments. In addition, the tensions and the resulting geometry of the warp are also calculated.

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REFERENCES
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Figure 1: Port otterboard with a twin backstrop adjustment. Top: Lateral view. Bottom: top view.