

Time Domain Modeling of ROV Umbilical using Beam Equations

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Abstract: This paper presents a finite element model for representing the cable dynamics of a typical ROV (Remotely Operated Vehicle) umbilical. The goal is to produce a model able to capture the most important dynamic effects of the umbilical affecting the ROV by solving the Euler-Bernoulli beam equations using finite element method. The model is general and is applicable to a wide variety of deep-sea ROV systems. The presented model is demonstrated by numerical examples for umbilical and ROV systems, both for steady state and dynamic response. The model is further validated by comparison with published results.

Keywords: Remotely Operated Vehicle, Umbilical cable, FEM, Beam equations, Simulation

NOMENCLATURE

$\eta \in \mathbb{R}^{6 \times 1}$	Position/orientation relative to Earth.
$\nu \in \mathbb{R}^{6 \times 1}$	Velocity vector (u,v,w,p,q,r).
$\nu_d \in \mathbb{R}^{3 \times 1}$	Desired velocity.
$\nu_r \in \mathbb{R}^{3 \times 1}$	Actual Velocity.
$\tau \in \mathbb{R}^{6 \times 1}$	Thruster forces and moments.
$C \in \mathbb{R}^{6 \times 6}$	Rigid body Coriolis and cent. matrix.
$C_A \in \mathbb{R}^{6 \times 6}$	Added mass Coriolis and cent. matrix.
$C_a \in \mathbb{R}$	Analytic added mass coefficient.
$C_d \in \mathbb{R}$	Normal drag coefficient.
$C_t \in \mathbb{R}$	Tangential drag coefficient.
$D \in \mathbb{R}$	Umbilical diameter.
DOF	Degree of Freedom.
$EI \in \mathbb{R}$	Bending stiffness.
$F_D^{n/t} \in \mathbb{R}$	Drag force(normal/tangential).
$g(\eta) \in \mathbb{R}^{6 \times 6}$	Restoring matrix of ROV.
$K(\nu) \in \mathbb{R}^{6 \times 6}$	Damping matrix.
$K_L \in \mathbb{R}^{6 \times 6}$	Linear damping matrix.
$K_Q \in \mathbb{R}^{6 \times 6}$	Quadratic damping matrix.
$L, B, H \in \mathbb{R}$	Length, Breadth & Height of ROV.
$l \in \mathbb{R}$	Length of element in umbilical.
$M_A \in \mathbb{R}^{6 \times 6}$	Added mass matrix.
$M \in \mathbb{R}^{6 \times 6}$	Rigid body mass matrix.
$V_r \in \mathbb{R}$	Relative velocity.

UUVs can typically be divided into two categories, Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs). As the name suggests AUVs have the ability to operate autonomously i.e. without external inputs (only to a certain degree) while ROVs typically relies extensively on user inputs, most often transmitted through an umbilical cable. For UUVs the hydrodynamic properties are of paramount importance. The hydrodynamic properties greatly affect the performance and maneuverability of the vehicles and knowledge of these properties are therefore important in design and operation (Eidsvik and Schjølberg, 2016).

AUVs typically do not have an umbilical cable, this combined with a much simpler geometry greatly simplifies the problem of identifying the vehicle properties. As ROVs have an umbilical cable and a more complex geometry the problem of identifying vehicle properties become much more complex. Most ROV models neglect the effects from the cable, simply due to the difficulty in estimating these effects (Fang et al., 2007)(Buckham et al., 2003). Different methods for estimating the cable effects have been suggested in literature. Fang et al. (2007) suggested a method based on calculating the tension force in an inextensible cable by assuming a certain cable configuration. The tension force in the cable is then found by using the Runge-Kutta method. A weakness in this method is that the cable can not resist bending moment or compression force. Buckham et al. (2003) used a lumped mass coupled finite element model to simulate the effects of a towed cable and verified the results experimentally with good results. This model does not take into account bending forces, but provides a good model for an ROV towing an umbilical cable. Feng and Allen (2004) presented a numerical scheme to evaluate the effects of the umbilical cable with zero tension attached to an underwater flight vehicle. Here a cable drum was introduced at the surface to continuously deploy cable into the water as the tension in the inelastic cable increased. This model provides a good method for estimating cable dynamics for flight vehicles advancing in still water. The

1. INTRODUCTION

UNMANNED UNDERWATER VEHICLES (UUVs) are today applied in a wide range of deep water industries. New areas of applicability and increasingly advanced mission requirements forces the design of UUVs and their control systems to be under constant development. The development of underwater vehicles clearly goes in the direction of autonomy (Christ and Wernli, 2014). Reasons for this is among others that a higher degree of autonomy can reduce operation time, dependence on weather conditions and dependence on human factors (Schjølberg and Utne, 2015).

simulation results were verified against model results and showed that the numerical scheme is effective and provides means for developing a feed-forward controller to compensate for cable effects. The models suggested in previous mentioned work typically has limitations with regards to operating conditions and maneuverability. Especially bending stiffness is often neglected. Bending stiffness is of importance when the ROV cable has low tension, which might often be the case during ROV operations. Obtaining a general model applicable to a wide range of operating conditions is therefore challenging.

The main objective of this paper is to prove that, by solving the modified Euler-Bernoulli beam equations using the finite element method the dynamics of a typical umbilical cable, and hence the effect of the cable on the ROV can be modeled. The contributions of this paper is two folded:

- To present a universal finite element model for simulating the coupled ROV-umbilical system using Euler-Bernoulli beam equations and implement in Matlab.
- To verify the results by applying the model in a case study.

The structure of this article is as follows. Sections 2 and 3 describes the cable and ROV models respectively. The simulator properties used are presented in Section 4 Section 5 holds the results and the conclusions are given in Section 6.

2. UMBILICAL MODELING

2.1 Reference frames

For the ROV-umbilical system two reference coordinate systems are defined. One coordinate system is fixed relative to earth(g) and one which is fixed with respect to the umbilical(l). These are for future reference denoted as global and local coordinate systems respectively. Following the discretization of the finite element approach a total number of $N+1$ local coordinate systems will be used, N denotes the number of elements the umbilical is divided into. In other words each node will have a local coordinate system.

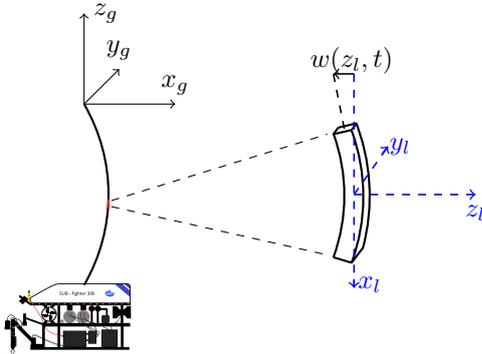


Fig. 1. Reference frames for ROV-Umbilical model.

2.2 Governing equations

The umbilical is developed in 3 dimensional space, hence 3 governing equations are used. The longitudinal equation

of motion for a beam with uniform cross-section can be described as (Weaver Jr. et al., 1974):

$$S + \frac{\partial S}{\partial x} dx - S - \rho A dx \frac{\partial^2 u}{\partial t^2} = 0 \quad (1)$$

where S denotes the internal axial stress resultant on the cross-section at a point x on the beam, u denotes the deflection, ρ denotes the mass density and A is the area of the cross-section. Using Hookes law the equation can be presented as (Weaver Jr. et al., 1974):

$$EA \frac{\partial^2 u}{\partial x^2} = \rho A \frac{\partial^2 u}{\partial t^2} \quad (2)$$

The transverse equation of motion in y -direction is obtained from Euler-Bernoulli beam theory:

$$\frac{\partial^2}{\partial x^2} (EI_y \frac{\partial^2 v}{\partial x^2}) + A\rho \frac{\partial^2 v}{\partial t^2} = F_y(x) \quad (3)$$

where $F_y(x)$ represents the external load and I_y is the second moment of inertia with regards to the y -axis. Similarly the equation in z -direction becomes:

$$\frac{\partial^2}{\partial x^2} (EI_z \frac{\partial^2 w}{\partial x^2}) + A\rho \frac{\partial^2 w}{\partial t^2} = F_z(x) \quad (4)$$

For slender marine structures it is often desirable to apply a certain amount of top-tension(pre-tension) to reduce the amplitude of the horizontal motion. In the case of low bending-stiffness these amplitudes may become large. For a ROV-umbilical the bending stiffness will be low and a certain amount of top-tension can be applied to reduce deflections. It can be shown that if an applied top-tension (T) is assumed to be constant throughout the entire length of the umbilical, Eq. (3) becomes (Sparks, 2007):

$$\frac{\partial^2}{\partial x^2} (EI_y \frac{\partial^2 v}{\partial x^2}) + \frac{\partial}{\partial x} (T \frac{\partial v}{\partial x}) + A\rho \frac{\partial^2 v}{\partial t^2} = F_y(x) \quad (5)$$

Likewise Eq. (4) is extended similarly. As the umbilical is completely submerged in water an additional inertia term must be included to account for the hydrodynamic mass(added mass), Eq. (5) then becomes:

$$\frac{\partial^2}{\partial x^2} (EI_y \frac{\partial^2 v}{\partial x^2}) + \frac{\partial}{\partial x} (T \frac{\partial v}{\partial x}) + (1+C_a)A\rho \frac{\partial^2 v}{\partial t^2} = F_y(x) \quad (6)$$

where C_a is the added mass coefficient of a two-dimensional circular disk ($C_a = 1$). Eq. (4) is extended similarly.

2.3 Boundary Conditions

The initial configuration of the cable, as well as 10 boundary conditions are needed. These are :

- $u(0) = v(0) = w(0) = 0$
- $u(L) = u_{rov} \quad - v(L) = v_{rov} \quad - w(L) = w_{rov}$

The torsional degree of freedom (i.e. rotation around the local x -axis) is neglected for the umbilical. This is done because the torsional rigidity is very small due to the large length-to-width ratio and of little interest in the umbilical modeling(hence total DOFs for each beam element is reduced from 12 to 10). For the ROV on the other hand all 6 degrees of freedom are of interest. The ROV is therefore modeled using all 6 degrees of freedom. The velocity and position of the ROV is denoted according to SNAME notation(Fossen, 2011).

The mentioned boundary conditions translates to keeping the surface ship in a fixed position. The top node is assumed to have a moment-free connection (simply supported) to the vessel. The other end of the umbilical is connected to the ROV. The umbilical is assumed to be connected to the ROV in the center of gravity which is also assumed to be the center of rotation. The end node will therefore have the same position as the ROV. The node connected to the ROV is also assumed to be moment-free. Since the boundary nodes are moment-free i.e. no bending moment, the degrees of freedom at the boundaries are reduced from 10 to 6.

2.4 External Loads

For a neutrally buoyant ROV-umbilical submerged in water the external loads can be divided into three main contributions:

- Ship loads
- ROV loads
- Environmental loads

It follows intuitively that the ship loads are connected to the boundary conditions at the top-end of the umbilical while the ROV loads are connected to the bottom-end. The ship-loads are assumed to be zero following the boundary conditions enforced in the previous subsection.

The ROV loads consists of 3 main contributions (Fossen, 2011):

- Mass and added mass due to ROV acceleration
- Hydrodynamic damping due to the ROV velocity relative to the incident current
- Thruster forces

Coriolis, centripetal and hydrostatic restoring forces and moments are assumed zero in the coupled DOFs, as only translational DOFs are coupled

The environmental loads consists of current loads due to tide and wind. Wave forces are neglected as they will not contribute to a mean force on the umbilical (zero mean wave drift (Faltinsen, 1990)). Current velocity is assumed to be constant in time and the vertical distribution recommended by DNV (DNV, 2010) is used:

$$V_c(z) = V_{c,tide}(z) + V_{c,wind}(z) \quad (7a)$$

$$V_{c,tide}(z) = V_{c,tide} \left(\frac{h-z}{h} \right)^{\frac{1}{7}} \quad \text{for } z \leq 0 \quad (7b)$$

$$V_{c,wind}(z) = V_{c,wind} \left(\frac{h_0-z}{h_0} \right)^{\frac{1}{7}} \quad \text{for } h_0 \leq z \leq 0 \quad (7c)$$

$$V_{c,wind}(z) = 0 \quad \text{for } z \leq h_0 \quad (7d)$$

where $V_{c,tide}$ is the tidal-induced current velocity, $V_{c,wind}(z)$ is the wind-induced current velocity, h is the water depth and h_0 is the depth of the wind generated current (set to be -50 m)

To estimate the current loads the drag equations for circular cylinders are applied (Morison et al., 1950):

$$F_D^n = \int_{-L}^0 \frac{1}{2} \rho C_D D V_r(z) |V_r(z)| dz \quad (8)$$

and

$$F_D^t = \int_{-L}^0 \frac{1}{2} \rho C_t \pi D V_r(z) |V_r(z)| dz \quad (9)$$

V_r is the velocity of the umbilical relative the the current ($V_r = V_c - V$).

2.5 Transformations

The finite element equations are solved in the local element-reference frames. However, the environmental forces i.e. current drag forces are given in the global reference frame. In addition it should emphasized that it is the global response that is of interest. Transformations between the local element-reference frames and the global reference frame is therefore required. For this purpose euler angles are applied. From Fig. 1 it can be seen that each element has an initial transformation. If the initial shape of the umbilical is assumed to be strictly vertical all elements will have a reference frame rotated ($\phi = 0, \theta = 90^\circ, \psi = 0$) relative to the global reference. This transformation will change for each time-step as the umbilical is deflected. The transformation between the local and global frames can hence be written using the principal rotation matrices found in (Fossen, 2011).

The euler angles (ϕ, θ, ψ) and element length for each DOF is calculated using Pythagorean rules. For e.g. yaw (rotation around global z-axis) the euler angle becomes:

$$\psi = \cos^{-1} \left(\frac{\Delta x}{\sqrt{(\Delta x)^2 + (\Delta y)^2}} \right) \quad (10)$$

And the element length becomes:

$$l = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} \quad (11)$$

2.6 Element Modeling

By following the finite element method the governing equations for the umbilical is divided into a finite number of elements. Using cubic shape functions for Eq. (6) and Eq. (4), linear shape functions for Eq. (2) and a lumped mass model the element matrices are obtained. These can be found in standard finite element literature such as (Narasaiah, 2008) and (Cook et al., 1989).

Lumped mass is used to greatly reduce computation time (compared to e.g. consistent mass). It has been proven in literature that lumped mass approximation is consistent with the dynamics of an actual highly flexible cable (Huang, 1994), and that lumped mass approach has accuracy equivalent to that of other more complicated methods (Buckham et al., 2004). To avoid nonzero diagonal elements rotational inertia is modeled as described in Cook et al. (1989).

3. ROV MODELING

3.1 Governing equations

The ROV is modeled in 6 degrees of freedom (Fossen, 2011):

$$(M + M_A) \dot{v} + (C(v_r) + C_A(v_r)) v_r + K(v_r) v_r + g(\eta) = \tau \quad (12)$$

It should be noticed that as the relative velocity (v_r), is used in Eq. 12, the current velocity and therefore the current forces are included using superposition. Wave-forces are, as mentioned earlier not included in the modeling of

the umbilical. The wave forces will have negligible effect on the behavior of the ROV due to the large distance between the ROV and the free surface. The parameters in Eq. (12) are estimated using the empirical method proposed by Eidsvik et. al (Eidsvik and Schjøberg, 2016). The ROV is assumed to operate in low speeds and has three plane symmetry. Hence off-diagonal terms in the mass and damping matrices are neglected.

3.2 ROV-Umbilical model

The two models are connected by applying the ROV forces and moments to the last (N+1) umbilical node (boundary conditions). The shared DOFs between umbilical and ROV are surge, sway and heave. Roll and pitch are uncoupled as the boundary conditions for the umbilical are moment free (simply supported). The torsional DOF was also neglected which makes the yaw DOF independent of the umbilical. The forces and moments on the ROV node are found using superposition principle and applying Newton's third law on the last node of the umbilical (Schjøberg, 1996):

$$\begin{bmatrix} F_{ROV,x} \\ F_{ROV,y} \\ F_{ROV,z} \end{bmatrix} = (M_U + M_{ROV})\dot{v}_n + C_{ROV}(v_{r,n})v_{r,n} \quad (13)$$

$$+ (K_U(v_{r,n}) + K_{ROV}(v_{r,n}))v_{r,n} \quad (14)$$

where subscript U and ROV denotes umbilical and ROV parameters respectively and v_n denotes the velocity vector of the last node (N+1). The remaining DOFs (rotations) of the ROV (which are assumed independent of the umbilical) are run parallel to the umbilical-governed DOFs and are superimposed to create the complete 6 DOF ROV-model.

4. SIMULATION MODEL

The combined model described in the previous sections is implemented in Matlab.

4.1 ROV System (Sf-30k)

The implemented model is verified using a case study. The ROV, umbilical and environmental parameters for this case study are based on the ROV SF-30k (see Fig. 2) and the parameters can be found in appendix A. The governing equations are solved using Newmark- β time integration (Newmark, 1959) using constant average acceleration and zero artificial damping. For the simulations performed in this paper all time steps are set to be 0.001 seconds and the number of finite elements used is 30.

4.2 ROV Controller

To verify the effect of umbilical cable forces on the ROV-system a nonlinear model-based PD controller is used for ROV control. For this purpose the nonlinear controller described in (Smallwood and Whitcomb, 2004) is used. i.e. :

$$\tau(t) = (M + M_A)\dot{v}_d(t) + (C(v_d) + C_A(v_d))v_d \quad (15)$$

$$+ K(v_d)v_d + k_p\Delta x(t) + k_d\Delta v(t)$$

where k_p and k_d are proportional and derivative gains respectively, used to correct for model errors. $\Delta x(t)$ and

$\Delta v(t)$ are the state errors for position and velocity respectively.

4.3 Simulations

This subsection contains a description of the performed simulations to validate the ROV-umbilical model. Three case studies are performed:

- Simulation of ROV cable dynamics (Sec. 5.1 & 5.2).
- Simulation of effects of cable dynamics on ROV with model-based controller (Sec. 5.3).
- Comparison with published results (Sec. 5.4) in Quan et al. (2015).

The first case study is to validate the umbilical model by applying a steady current on the ROV and record the umbilical response over time while the ROV is held in a fixed position. The second case study is to simulate the response of the ROV using the nonlinear model-based controller described in the previous section with and without including the effects of the umbilical cable. The last case study is to apply the model on a tether management system as described in Quan et al. (2015) and compare the the steady state responses. A tether-management system (TMS) is normally used for deep-sea ROV operations and can be viewed as a heavy pendulum (negative buoyancy) going from the surface ship down to the ROV.

5. RESULTS

The results obtained for the case study is presented in the following.

5.1 Motion of umbilical with fixed end conditions

The steady state deflection for the umbilical with varying tidal-current velocities is simulated using fixed end-positions and parameters presented in appendix A. Fig. 3 shows the steady state deflection for different tidal current velocities. This confirms that the cable configuration is very dependent of the current (magnitude). From Fig. 4 it can be seen that the vertical force is dominating when the ROV is kept in a fixed position(vertical-umbilical).

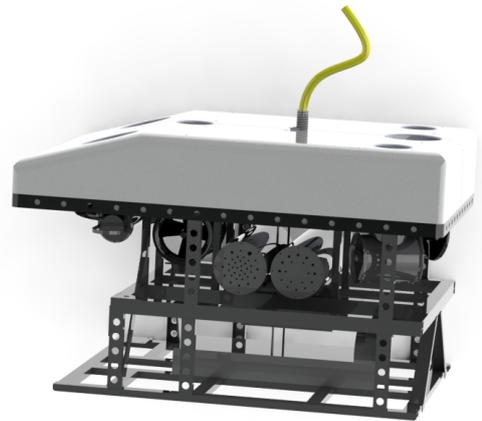


Fig. 2. ROV Sf-30k.

5.2 Motion of ROV and umbilical without ROV controller

The motion of the ROV (umbilical neglected) and ROV-umbilical (umbilical included) systems are simulated for 160 seconds without controller output (zero applied thrust) and the results are illustrated in Fig. 5. The figure shows that the coupled model (ROV + umbilical) after 160 seconds has a deflection of 18 meters while the ROV when neglecting the umbilical has moved 53 meters. In addition the ROV has traveled 10 meters vertically. Hence the cable significantly alters the ROV motion. This difference will grow over time as the tension force from the umbilical cable will continue to increase and the ROV will be pulled further towards the surface.

5.3 NL model-based controller

The nonlinear model-based controller described in Sec. 4.2 is applied to the ROV-umbilical system for the case of an incoming current with parameters given in appendix A. The controller does not take into account the presence of the umbilical. The ROV is given a sinusoidal horizontal path inline with the current. Fig. 6 shows that the ROV-umbilical is unable to follow the reference path. It is also seen that the thruster-forces greatly exceeds the maximum thrust for the ROV, which is in the range of 700 N (surge), while they are kept within the limits when cable forces

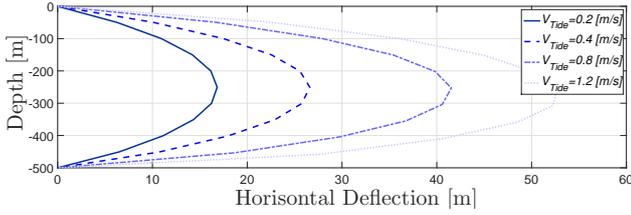


Fig. 3. Cable configuration for varying tidal current velocities.

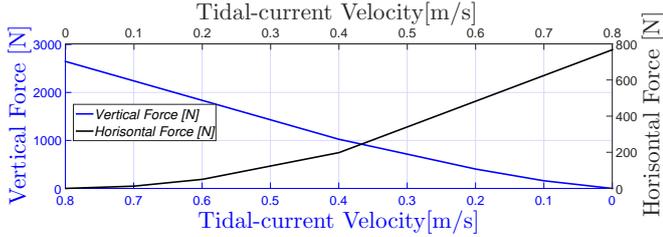


Fig. 4. Cable forces acting on the ROV for different tidal current velocities.

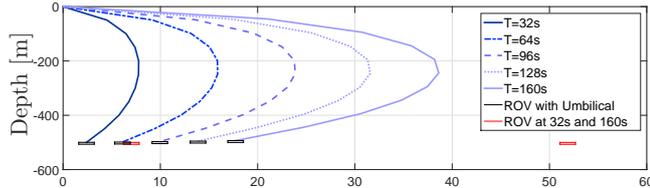


Fig. 5. Umbilical and ROV horizontal deflection every 32 second within 160 seconds with $0.4[m/s]$ tidal current velocity and zero applied thrust (black square symbolizes ROV with umbilical, red square symbolizes ROV without umbilical).

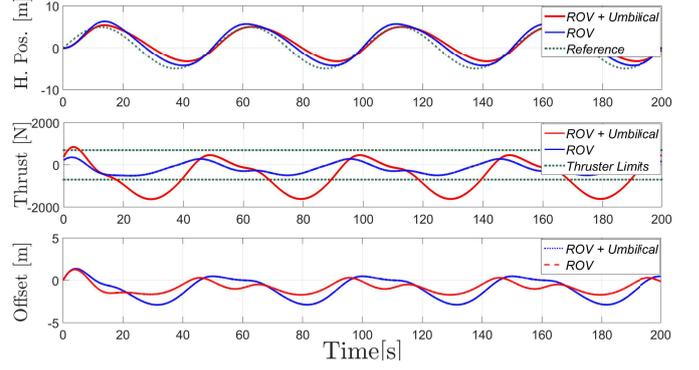


Fig. 6. Simulated results of horizontal ROV+umbilical-response using the NL model-based controller presented in Sec. 4.2. Top: horizontal ROV position. Mid: ROV thrust forces. Bottom: Horizontal offset in position relative to reference path.

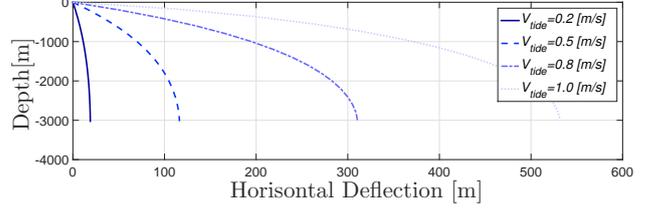


Fig. 7. Steady configuration in different depth-ocean currents at 3000 meters using inputs given in Table 1. in (Quan et al., 2015).

are omitted. Hence showing the importance of including umbilical effects in the modeling of ROVs.

5.4 Submerged Cage (Tether Management System)

The proposed umbilical model is applied to a submerged cage (TMS) and simulated with different current velocities using the cable-system parameters given in Quan et al. (2015). Fig. 7 shows the steady state configuration of the cable for different current velocities (Current profile is defined as done in the reference, which is linear decreasing over depth). The mean offset of the last node is only 8 meters and the standard deviation is only 2 meters or 0.1% of the umbilical length which proves that the two models correspond well.

6. CONCLUSION

In this paper a method to model the forces of an ROV-umbilical using Euler-Bernoulli beam equations is proposed. The model is used for simulating the most important dynamics related to an ROV-umbilical system, namely the rigid body forces and the hydrodynamic forces. The model can easily be extended to include additional effects such as surface ship motions and hydrostatic restoring (non-neutral buoyancy) and therefore presents a good platform for modeling cable dynamics.

Several case studies are performed to verify the accuracy of the method and illustrate the typical response of an ROV with umbilical. The steady state and dynamic motion of the umbilical is simulated for the case where the ROV is in a fixed position. It is shown that the dynamics

of an umbilical are highly dependent of current velocity and direction. The influence of an umbilical on an ROV drifting in steady current is simulated and found to be significant even for small offsets in position. The effect of neglecting the umbilical forces when using a model-based ROV controller is also simulated and found to be significant. When applying a NL model-based controller the thrusters become saturated when umbilical forces are included, hence proving the importance of considering umbilical forces in ROV control.

Simulations to verify the modeling are performed using cable parameters found in the literature. The simulations show a steady cable configuration. The advantage of the proposed method with regards to other methods is that it describes the coupled dynamics of the ROV and the umbilical cable giving a basis for development of robust ROV controllers.

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Appendix A. SIMULATION PARAMETERS

Table A.1. ROV Specifications

Parameter	Value
LxBxH	2.5m x 1.5m x 1.6 m
Weight in water	17913 N
Thrusters	6 thrusters of 3kW power
Quadratic damping	$K_Q = [472, 780, 1500, 163, 625, 364]^D$
Linear damping	$K_L = [76, 125, 240, 132, 171, 100]^D$
Mass	$M = [1826, 1826, 1826, 525, 794, 691]^D$
Added mass	$M_A = [629, 1540, 4113, 222, 962, 386]^D$

Coefficient matrices in Table A.1 are presented as vectors containing diagonal(non-zero) elements.

Table A.2. Umbilical Specifications

Parameter	Value
Length	500 m
Diameter	2.3 cm
Weight in Air	480 kg/km
Element rotational inertia	$0.01(\rho A l^3) kgm^2$
Normal Drag coefficient	1
Tangential Drag coefficient	0.01
Youngs Module	1.6 GPa

Table A.3. Environmental Specifications

Parameter	Value
Water density	$1025 kg/m^3$
Wind speed at 10 m elevation	$5 m/s$
Wind & Tide direction	global x-direction
Tide surface velocity	$0.4 m/s$
Ref. depth for wind generated current	$-50 m$
Water depth	$-1000 m$