

Master Thesis in Marine Technology - 2013

Guidance and control of iceberg towing operation in open water, with experimental testing

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Problem

Icebergs pose serious threats to existing and planned offshore structures, vessels, and operations in Arctic waters such as the East Coast of Canada, East and West Greenland, the Barents Sea, and the Kara Sea. A collision between an offshore installation and an iceberg could cause serious damage to the installation, and in a worst case scenario take life. Therefore, if an iceberg is evaluated as a threat, physical iceberg management must be mobilized to mitigate the threat. For open water, this is typically done by single vessel towing of the iceberg using steel hawser and synthetic floating tow lines.

Introduction

The following situation can be imagined: An offshore platform is at risk due to icebergs drifting towards it. The offshore can only be moved in emergency situations, but this is extremely expensive, both in terms of operation costs and downtime costs. A better solution is therefore to tow the iceberg in such a way that it is no longer a threat to the offshore platform. Figure 1 illustrates the concept of towing an iceberg on a collision course with an offshore installation.

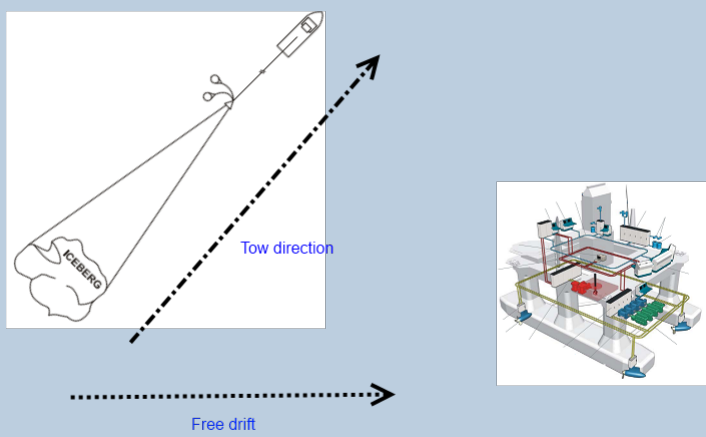


Figure 1: Iceberg drifting towards an oil installation. Courtesy of [1] and [6].

At the moment, this is done by performing a manual towing operation, using either a tug or an anchor-handling tug vessel with large bollard pull. This involves trapping the iceberg with a synthetic floating tow rope or net, that is looped around the iceberg. The ends are then connected, and attached to a hawser that again is connected to the towing vessel. The crew then performs the towing operation using manual navigation and experience from previous operations.

The aim of this thesis is to develop a model for open water iceberg towing using a single towing vessel. This includes a mathematical model of the towing vessel, the iceberg and the towline between them. It also looks into certain towline configuration choices, estimation of damping and mass, and other things that can affect the towing model. A controller is then created using maneuvering theory, as stated by [4]. This controller is responsible for making the vessel follow a certain path, and for keeping the tension in the tow line constant. The final goal is to have an application that can tow the iceberg automatically, instead of having to rely on the crew.

References

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Modeling

The main goal of the thesis is to find a *control plant model* as defined by [6, p 175]:

Control plant model is a simplified mathematical description containing only the main physical properties of the process or plant. This model may constitute a part of the controller. The control plant model is also used in analytical stability analysis based on e.g. Lyapunov stability and passivity.

[1] proposes a model that balances the momentum between the boat and the iceberg connected by a towline:

$$M_s \frac{dv_s}{dt} + M_{add,s} \frac{d(v_s - u)}{dt} = -R_s - T + P, \quad (1)$$

and

$$M_i \frac{dv_i}{dt} + M_{add,i} \frac{d(v_i - u)}{dt} = -R_i + T, \quad (2)$$

where M_s is the mass of the vessel, M_i is the mass of the iceberg, $M_{add,s}$ is the added mass of the vessel, $M_{add,i}$ is the added mass of the iceberg, v_s is the ship velocity, v_i is the iceberg velocity, u is the current velocity in surge, T is the towline force, R_s is the drag on the vessel, R_i is the drag on the iceberg, and P is the propulsion force of the vessel. The drag can be expressed as

$$\begin{aligned} R_s &= \rho_w C_{ws} S_s |v_s - u| (v_s - u) \\ R_i &= \rho_w C_{wi} S_i |v_i - u| (v_i - u), \end{aligned} \quad (3)$$

where ρ_w is the density of water, C_{ws} is the drag coefficient for the vessel, C_{wi} is the drag coefficient for the iceberg, S_s is the surface area of the vessel, and S_i is the cross-sectional surface area of the iceberg. The model is complete with the definition of the boat velocity relative to the iceberg velocity, which can be written as

$$\frac{dX}{dt} = v_s - v_i. \quad (4)$$

This is a scalar model. For the controller, a model that works in at least three degrees-of-freedom is needed. A model in the Fossen-style notation is therefore needed. For the vessel, this can be expressed as

$$\begin{aligned} \dot{\eta}_s &= R(\psi_s) \nu_s \\ \dot{b}_s &= -T_s^{-1} b_s + w \\ M_s \dot{\nu}_s + D_s(\nu_s) \nu_s &= \tau_s - R^\top(\psi_s) T + R(\psi_s)^\top b, \end{aligned} \quad (5)$$

where $\eta_s = [x_s, y_s, \psi_s]^\top$, $\nu_s = [u_s, v_s, r_s]^\top$, $b_s = [b_{s,1}, b_{s,2}, b_{s,3}]^\top$, $\tau_s = [\tau_x, \tau_y, \tau_N]^\top$, and $T = [X_{tow}, Y_{tow}, N_{tow}]^\top$. τ_x , τ_y , and τ_N are the control forces and X_{tow} , Y_{tow} and N_{tow} are the tension forces in the towline. The model for the iceberg can be written as

$$\begin{aligned} \dot{\eta}_i &= R(\psi_i) \nu_i \\ \dot{b}_i &= -T_i^{-1} b_i + w \\ M_i \dot{\nu}_i + D_i(\nu_i) \nu_i &= R^\top(\psi_i) T + R(\psi_i)^\top b, \end{aligned} \quad (6)$$

where $\eta_i = [x_i, y_i, \psi_i]^\top$, $\nu_i = [u_i, v_i, r_i]^\top$, and $b_i = [b_{i,1}, b_{i,2}, b_{i,3}]^\top$. These equations express the motion of the vessel and iceberg.

A controller can then be developed using maneuvering theory, as described by [4]. This approach balances the traditional tracking problem, and the path following problem. The theory behind the maneuvering is too large to include here. The final result is therefore shown here instead, and can be expressed as

$$\tau_s = -z_1 - K_d z_2 + D_s \nu_s + M_s \sigma_1 + M_s \alpha_1^\theta \dot{\theta} + R^\top(\psi_s) T - R^\top(\psi_s) b_s, \quad (7)$$

where

$$\sigma_1 = -K_p(\nu_s - r_s S z_1) - r_s S R^\top(\psi_s) \eta_d^\theta v_s + R^\top(\psi_s) \eta_d^\theta v_s^t, \quad (8)$$

$$\alpha_1^\theta = K_p R^\top(\psi_s) \eta_d^\theta + R^\top(\psi_s) \left[\eta_d^{\theta^2} v_s + \eta_d^\theta v_s^\theta \right], \quad (9)$$

$$\alpha_1 = -K_p z_1 + R^\top(\psi_s) \eta_d^\theta v_s, \quad (10)$$

and

$$z_1 \equiv R^\top(\psi_s)(\eta_s - \eta_d) \quad (11a)$$

$$z_2 \equiv \nu_s - \alpha_1 \quad (11b)$$

$$\omega_s \equiv v_s - \dot{\theta} \quad (11c)$$

This result is used as a controller that moves the vessel along a predestined path, η_d . The matrices K_p and K_d are used for tuning the controller to desired behavior.

Simulations and testing in a model tank

The model was first simulated in Matlab/Simulink, which gave good results. Figure 2 represents a plot of η_d , η_s , and η_i in the North-East plane. The desired path was a straight line going from (10, 10), and then North-East. The vessel and iceberg started in (0, 0), and eventually caught up with the desired path, which they then followed. The iceberg has a slight drift off due to current and tow line mechanics.

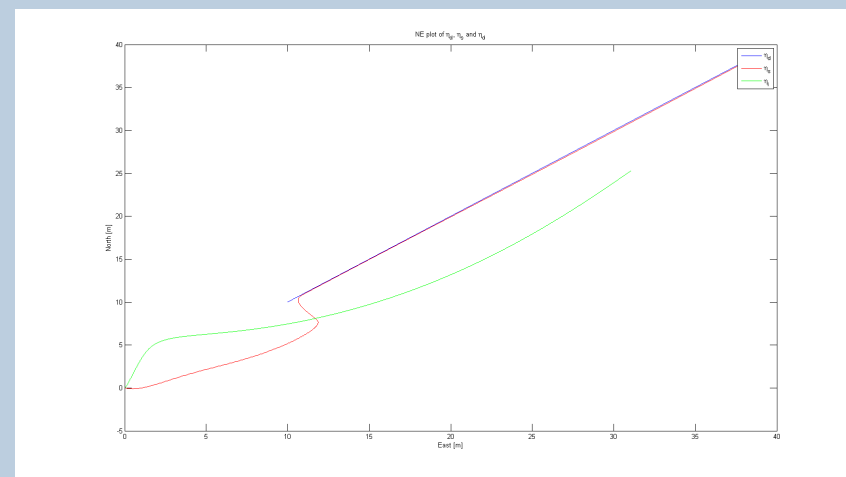


Figure 2: A plot from Simulink. The desired path, the vessel path, and the iceberg path in the North-East plane.

The system was also tested in the *MC Lab* towing tank. Due to a poor testing environment, such of lack of online tension measurements and a poor positioning system, the result was mostly in the form of qualitative data. I.e. for all practical purposes, the towing should only be in straight lines. The model vessel used can be seen in Figure 3.



Figure 3: The model vessel.

Conclusion

In this thesis a model for open water iceberg towing has been presented. A mathematical model for the vessel, iceberg and towing rope was set up. This model was based on the work of [1], which is a scalar model for surge motion. The model for the vessel and iceberg was expanded to three degrees-of-freedom using the Fossen-style of notation.

A controller was then developed using *maneuvering theory*. The controller uses the backstepping principle and its goal is to make the ship follow a certain path with the iceberg trailing behind it. Tension control was also a part of the control objective.

Finally, the system was tested in the *MC Lab*. Despite the poor testing environment, important experiences were made during the experiment. I.e. the vessel can only move in straight paths, rapid turns should be avoided at all costs, and so on.