MODELING AND CONTROL OF UNDERWAY REPLENISHMENT OPERATIONS IN CALM WATER

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Abstract: Ship-to-ship operations, such as underway replenishment (UNREP), lightering, etc., entail potentially hazardous situations due to the possibility of collisions between two ships operating in close proximity. In order to ensure safe joint operations with collision avoidance, knowledge of the hydrodynamic interaction loads between the two vessels is highly advantageous. This paper thus considers the hydrodynamic interaction effects between two advancing ships and their maneuvering behaviors in calm water during typical replenishment operations. For this purpose, a unified seakeeping and maneuvering model of two interacting ships based on a two-time scales and modular concept relevant for calm water is employed. The maneuvering module is based on generalized slender-body theory, while calm-water interaction forces and moments between the two ships are estimated using Newman-Tuck theory. Automatic steering and speed control algorithms for both ships are also employed to achieve high-precision and collision-free UNREP maneuvers, which is illustrated through a numerical simulation involving the well-known ‘ESSO OSAKA’ and 'MARINER’ models from the ship literature.

Keywords: Underway replenishment, Calm water, Maneuvering, Hydrodynamic interaction effects, Two–time scale model, Automatic motion control

1. INTRODUCTION

Underway replenishment (UNREP) operations involve cargo transfer between two or more cooperating ships in transit (Miller and Combs, 1999), and represent very important capabilities that enable navies to accomplish global missions. In this context, the task of the so-called guide ship is to maintain steady course and speed while the so-called approach ship moves up alongside the guide to receive, e.g., fuel, munitions, food, and personnel, see Fig. 1. When the two ships start to operate in close proximity, their maneuvering behavior becomes affected by the hydrodynamic interaction loads between them. These loads may cause strong and sudden attraction or repulsion effects between the ships, and the magnitude and duration of the effects depend on the size of the vessels, their lateral and longitudinal separation distance, speeds, wetted hull shapes, water depth, and transverse distance from a channel bank. The interconnection among these variables may initiate a deviation in the desired course of one or both of the ships, creating a possible collision situation which may be further worsened if the involved ships experience significant environmental loads due to waves, wind, and current.

The present study investigates UNREP maneuvers involving two advancing ships in calm water. Hydrodynamic interaction loads are theoretically predicted by Newman-Tuck (1974) theory, which is one among several slender-body theories (such as, e.g., Abkowitz et al. (1970), Dand (1974), Yeung (1978), and Kijima and Yasukawa (1984)) capable of predicting the interaction effects between two bodies in infinite fluid at moderate Froude numbers $F_r < 0.2$. These theories are based on potential flow, which means that the viscous effects are not accounted for and that calm-water conditions are assumed.

A unified seakeeping and maneuvering modular model was applied to two ships with forward speed in calm water by Skejic and Faltinsen (2007, 2008) and Skejic (2008). However, to achieve successful simulations of an UNREP maneuver, a unified seakeeping and maneuvering model must also include motion control modules on both ships that are capable of satisfying requirements imposed by the approach and guide ship in a way that mimics, as much as possible, realistic situations in accordance with the international and US Navy regulations (Naval Warfare Publication, 2004).

Using these modules, a numerical simulation of an UNREP maneuver in calm water is presented and discussed later in the text, accounting for the main maneuvering and motion control variables of ship speeds, longitudinal and lateral separation distances, rudder inclination angles, and hydrodynamic interaction effects. These data are shown in
order to exemplify the critical stages of an UNREP maneuver, i.e., stages which are potentially dangerous for both ships from a navigational safety point of view.

Recent work concerning UNREP-like formation control issues can be found in (Skjetne, 2005), (Hille, 2006), (Kyrkjebo, 2007), and (Borhaug, 2008). Unfortunately, these authors do not consider the hydrodynamic interaction effects occurring between the formation members. However, previous work more in the vein of this paper can be found in (Dimnick, 1978) and (Brown, 1983).

2. MATHEMATICAL MODELING

Modeling UNREP maneuvers is achieved by a unified model formulated on two time scales, i.e., a slowly and rapidly varying time scale, respectively related to maneuvering and seakeeping analyses.

The Cartesian right-handed maneuvering body-fixed coordinate systems $O_{C_{1}}X_{C_{1}}Y_{C_{1}}Z_{C_{1}}$, shown in Fig. 2 with positive $z_{C_{1}}$ axis pointing upwards, are used both for the seakeeping and maneuvering problem. Here, index $i \in \{A, B\}$ represents the approach ship A and the guide ship B, respectively. A transformation between the coordinate frames that define the seakeeping and maneuvering problem is described by Skejic (2008).

The centre of gravity (CG) of each ship is in the origin $O_{C_{1}}$ of the coordinate system $O_{C_{1}}X_{C_{1}}Y_{C_{1}}Z_{C_{1}}$, which is located in the lateral symmetry plane of each body. $OX_{E}Y_{E}Z_{E}$ is an Earth-fixed coordinate system with positive $Z_{E}$ axis pointing upwards. $X_{i}$ and $Y_{i}$ are hydrodynamic forces defined positively in the positive $x_{C_{1}}$ and $y_{C_{1}}$ directions, respectively. $K_{i}$ denotes the roll (heel) moment about the $x_{C_{1}}$ axis, while $N_{i}$ is the yaw moment about the $z_{C_{1}}$ axis, defined positively as shown in Fig. 2. Furthermore, $u_{i}$ and $v_{i}$ are $x_{C_{1}}$ and $y_{C_{1}}$ components of the total ship speed $U_{i} = \sqrt{u_{i}^{2} + v_{i}^{2}}$. The roll angular speed is represented by $p_{i}$, while the yaw angular speed is denoted by $r_{i}$. Also, $\phi_{i}$, $\psi_{i}$, $\delta_{i}$ and $\beta_{i} = \text{atan}(-v_{i}/u_{i})$ are respectively the roll (heel), yaw (heading), rudder, and drift angles from the maneuvering analysis. The longitudinal and lateral distances between the CGs of the ships ($O_{C_{1}}A$ and $O_{C_{1}}B$) are $s$ and $e$, respectively, defined in respect to the coordinate system of the guide ship B. The ship lengths between perpendiculars are $L_{i}$ for $i \in \{A, B\}$.

The slowly-varying system (1) consists of the ITTC (1975) nomenclature and used by the maneuvering module represents a modified version of the generalized surge-sway-yaw slender-body theory by Söding (1982), derived from the 6 DOF nonlinear maneuvering equations given by Imlay (1961). One modification relative to Söding (1982) is that coupling with roll is accounted for. A moderate Froude number, i.e., $Fn \ll 0.2$ is implicitly assumed so that steady wave generation is small.

The maneuvering model is based on a modular concept, which means that the forces and moments in (1) due to rudder (subscript R), resistance $R$ and propulsion $T$, and nonlinear viscous cross-flow (subscript CF) form the separate modules. Further details about each module are given by Skejic and Fältinsen (2008) and Skejic (2008).

The ship mass, moments and products of inertia within (1) are respectively defined as $M_{i} = I_{ai} = I_{ai} + M^{2}_{e_{i}}$, $I_{ai} = I_{ai}$, $I_{ai} = I_{ai}$, and $I_{ai} = I_{ai}$, where the symbol ‘$\approx$’ denotes values with respect to the centre of gravity $O_{C}$ of the maneuvering body-fixed coordinate systems, while $i \in \{A, B\}$.

\[
M \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & -Mr & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} + \begin{bmatrix} X_{a} \\ Y_{a} \\ N_{a} \end{bmatrix}
\]

\[
X_{a} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} 0 & -R_{a} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} + \begin{bmatrix} Y_{a} \\ N_{a} \end{bmatrix} + \begin{bmatrix} \dot{\phi} \\ \dot{\psi} \end{bmatrix}
\]

Hydrodynamic interaction sway forces and yaw moments estimated by Newman-Tuck (1974) theory are accounted for by the vector $\text{[INT]}$, and given as follows:

- for $i = A$: $\text{[INT]}_{i} = [0 \ Y_{ab} \ 0 \ N_{ab}]^{T}$,
- for $i = B$: $\text{[INT]}_{i} = [0 \ Y_{ba} \ 0 \ N_{ba}]^{T}$,

where $Y_{ab}$ stands for the interaction sway force on ship A (approach ship) due to the presence of ship B (guide ship), while $N_{ab}$ stands for the interaction yaw moment on ship A due to the presence of ship B, and vice versa. The positive direction of the interaction loads is defined with the arrows as indicated in Fig. 2.
Let us now focus on the parameters within (1) which are of importance for the UNREP operation analysis. The $C_{TN}$ – nondimensional coefficient is associated with the resistance term $-C_{TN}v_C r$ and is an empirical coefficient that modifies the predictions of potential flow theory at moderate speeds. The $C_{TN}$ coefficient in (1) has been selected as 1.0 in the later numerical example of an UNREP maneuver since both ships are moving mainly on a straight course in a joint parallel configuration.

Simulation wise, the maneuvering system (1) is solved with a time integration algorithm based on the 4th-order explicit Runge-Kutta method with constant time steps.

The seakeeping module based on the STF strip theory of Salvesen-Tuck-Faltinsen (1970) generalized to 6 DOF is used to calculate zero encounter-frequency added mass values which are needed to estimate parts of the maneuvering derivatives, see (1).

The vessel positions in the Earth-fixed coordinate system OXEYEZE (see Fig. 2) can in general be obtained by transformation of the slowly time-varying velocities $(u, v, w, p, q, r)_i$, defined with respect to the maneuvering ship-fixed coordinate systems $O_{CA}X_{CA}Y_{CA}Z_{CA}$, into the velocities $(\dot{X}_e, \dot{Y}_e, \dot{Z}_e, \dot{\phi}_e, \dot{\theta}_e, \dot{\psi}_e)$, which are defined with respect to the Earth-fixed coordinate system OXEYEZE. The transformation is carried out by using the finite Euler angles matrices and can be expressed as

$$[\dot{X}_e, \dot{Y}_e, \dot{Z}_e, \dot{\phi}_e, \dot{\theta}_e, \dot{\psi}_e] = J_{enh} [u, v, w, p, q, r]$$

$$J_{enh} = R_{3x3} 0_{3x3} S_{3x3}$$

where

$$R_{3x3} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$S_{3x3} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix},$$

and $0_{3x3}$ is the 3x3 zero matrix for $i \in [A, B]$. 

3. MOTION CONTROL SYSTEM

UNREP operations are currently performed manually, demanding the very best of helmsmanship. In particular, the hydrodynamic interaction effects appearing when the cooperating ships close in on each other make it difficult to achieve desired inter-vessel spacing by manual course and speed control. However, the required UNREP maneuvers might be automated by developing a purposeful motion control system. Potential benefits include enhanced maneuver precision and increased crew safety. This section considers the development of such a control system, which is used for the simulation reported later.

The motion control system that is illustrated in Fig. 3 ensures operator-specified inter-vessel spacing by automatic course and speed control for an approach ship A attempting to rendezvous with a guide ship B. Requested lateral (transverse) distance $e$ (see Fig. 2) is given as an input to the steering module, which computes the heading control.
Fig. 3. The main components of a motion control system

In what follows, the CG of the approach ship A is
represented by its planar position \( \mathbf{p}_A \triangleq \left[ X_{e_A}, Y_{e_A} \right] \in \mathbb{R}^2 \)
and velocity \( \mathbf{v}_A \triangleq \mathbf{p}_A / \Delta \in \mathbb{R}^2 \), stated relative to the Earth-fixed coordinate system \( O_X Y_Z \) whose \( X_e \)– axis points North (see Fig. 2). Using standard notation (Fossen, 2002), the total speed of the approach ship A is then denoted
\[
U_A \triangleq |\mathbf{v}_A| = \sqrt{X_{e_A}^2 + Y_{e_A}^2} \geq 0
\] while the course angle is denoted
\[
\chi_A \triangleq \arctan2 \left( \dot{Y}_{e_A}, \dot{X}_{e_A} \right) \in \mathbb{S} \triangleq [-\pi, \pi],
\]
where \( \arctan2(\cdot, \cdot) \) is the four-quadrant version of \( \arctan(\cdot, \cdot) \in (-\pi/2, \pi/2) \). Similarly, the guide ship B is represented by the variables \( \mathbf{p}_B, \mathbf{v}_B, U_B, \) and \( \chi_B \).

3.1 Steering subsystem

The outer-loop steering module of the approach ship A utilizes the fact that the guide ship B maintains steady course and speed during the UNREP operation. Such steady course and speed of ship B imply straight-line motion, which can be parameterized by three variables, i.e., two position variables representing a point along the straight-line path and one orientation variable representing the inclination of this path relative to North, i.e., relative to the \( X_e \)– axis, see Fig. 2. Hence, these variables can be represented by \( \mathbf{p}_B \) and \( \chi_B \).

Using the lookahead-based steering law from (Breivik and Fossen, 2008), and specifying the desired inter-vessel lateral spacing as \( \varepsilon_d > 0 \), the approach ship A is able to assume a parallel course with the guide ship B by adhering to the desired course angle
\[
\chi_{da} = \chi_B + \chi_r,
\]
where \( \chi_B \) is the course angle of the guide ship B, while
\[
\chi_r = \arctan(-\hat{\epsilon} / \Delta)
\]
is a relative steering angle which employs knowledge about the cross-track distance to the parallel course which is implicitly defined by \( \varepsilon_d \). Specifically,
\[
\hat{\epsilon} \triangleq e - e_a,
\]
where \( e \) represents the cross-track distance to the guide ship path, which can be calculated by
\[
e = -(X_{e_A} - X_{e_B}) \sin \chi_A + (Y_{e_A} - Y_{e_B}) \cos \chi_A.
\]

Also, \( \Delta > 0 \) represents a tuning parameter in the steering law called the lookahead distance (Papoulias, 1991). This parameter is given in meters and usually takes values between 4 to 5 ship lengths (Healey, 2006).

Since the relationship between the course, heading, and sideslip (drift) angles for a ship is typically given by
\[
\chi = \psi - \beta,
\]
where \( \beta = \arctan(-\nu, \psi) \), the desired heading angle must be computed by
\[
\psi_{da} = \chi_{da} + \beta_A,
\]
where \( \chi_{da} \) is given by (6). The inner-loop heading controller is then just chosen as a simple PID control law
\[
\delta_A = -k_p \tilde{\psi}_A - k_d \tilde{\dot{\psi}}_A - k_i \int \tilde{\psi}_A \, dt,
\]
where \( \delta_A \) represents the rudder angle, \( \tilde{\psi}_A \triangleq \dot{\psi}_A - \psi_{da} \), while \( \psi_{da} \) is given by (11). Also, the time derivative of this angle might be approximated by
\[
\dot{\psi}_A \approx \dot{\chi}_A
\]
when assuming steady-state conditions, i.e., \( \dot{\beta}_A = 0 \). Furthermore,
\[
\dot{\chi}_{da} = \frac{X_{e_A} \sin \chi_B - Y_{e_A} \cos \chi_B}{\varepsilon_d^2 + \Delta^2}
\]
when the guide ship B moves in a straight line, i.e., \( \dot{\chi}_B = 0 \).
Finally, $k_{d,\psi_{d}} > k_{p,\psi_{d}} > k_{i,\psi_{d}} > 0$ with $k_{d,\psi_{d}} = 5k_{p,\psi_{d}}$ and $k_{p,\psi_{d}} = 10k_{i,\psi_{d}}$. Note that (12) inherently assumes the convention that a positive rudder angle gives positive yaw rate, i.e., $\delta_{d} = -\delta_{a,d}$, where $\delta_{a,d}$ is the real rudder angle.

### 3.2 Speed subsystem

In addition to assuming a parallel course with the guide ship B (lateral alignment), the approach ship A must also synchronize its motion with the guide ship B along this course (longitudinal alignment). This synchronization can be achieved by commanding a desired total speed $U_{d,t}$ for the approach ship A as

$$U_{d,t} = U_{B} + U_{A,max} \frac{s}{\sqrt{s^2 + \Delta s^2}},$$

where $U_{B}$ is the total speed of the guide ship B, $U_{A,max}$ denotes the maximum total speed with which the approach ship A should approach the guide ship B, and where

$$s = (X_{B} - X_{A}) \cos \psi_{d} + (Y_{B} - Y_{A}) \sin \psi_{d}$$  

is the along-course distance between the approach ship and the guide ship, see Fig. 2. Also, $\Delta s > 0$ is a tuning parameter specifying the rendezvous behaviour toward the projection of the guide ship B onto the parallel course defined by $e_{d}$, ensuring that the approach ship A smoothly ramps down its total speed to $U_{B}$ as the along-course distance $s$ goes to zero.

Since the relationship between the total speed, surge speed, and sway speed of a ship is given by $U = \sqrt{u^2 + v^2}$, the desired surge speed must be computed by

$$u_{d,t} = \sqrt{U_{d,t}^2 - v_{d,t}^2},$$

where the total speed $U_{d,t}$ is given by (15). The inner-loop speed controller is then just chosen as a simple PI control law

$$n_{d} = -k_{p,a} \ddot{u}_{d} - k_{i,a} \int u_{d} dt,$$

where $n_{d}$ represents the number of propeller revolutions, $\dot{u}_{d} \triangleq u_{d} - u_{d,t}$, and $u_{d,t}$ is given by (17). Finally, $k_{p,a} > k_{i,a} > 0$ with $k_{p,a} = 10k_{i,a}$.

Note that in the following case study, the guide ship B is also controlled by a rudder controller such as given in (12) and a propeller controller such as given in (18), albeit with constant course and speed references to keep a steady course and speed.

### 4. CASE STUDY

The following case study concerns an UNREP maneuver in calm water involving the ‘ESSO OSAKA’ and ‘MARINER’ ships studied by the ITTC (1975, 2002) with main particulars according to Fig. 4. It should be noted that further details concerning the propulsion and rudder system for these ships may be found in Skejic and Faltinsen (2008).

Fig. 5 presents the UNREP maneuver in calm water between a smaller approach ship A (‘MARINER’) and a larger guide ship B (‘ESSO OSAKA’). The starting positions of the approach ship A and guide ship B are different, and the motion control module is used on both ships from the beginning of the simulation.

Ship B advances on a straight course with a constant forward speed of 10 knots, while the maximum rendezvous speed of ship A is restricted to 14 knots. The motion control system simultaneously engages speed and rudder controls on the approach ship so that she tries to establish the desired longitudinal distance $s = 0$ m between the ships, as well as a transverse clearance of $e - 0.5(B_{A} + B_{B}) = 40$ m between the facing sides of both hulls, whose value is defined in respect to the coordinate system of ship B. Here, $B_{A}$ is the beam of the approach ship A, while $B_{B}$ is the beam of the guide ship B. Hence, $e_{d} = 0.5(B_{A} + B_{B}) + 40$ m.

A worst case scenario entails a collision between the two ships. The motion controllers thus replace the experienced helmsmen and deck crew on both ships to avoid such incidents. As time goes on, approach ship A catches up with the guide ship B at a position of approximately 6500 m with respect to $OX_{E}Y_{E}Z_{E}$, see Fig. 5. The relative longitudinal
Fig. 5. An UNREP maneuver between the ‘MARINER’ and ‘ESSO OSAKA’ ships advancing in calm water. The starting positions: Ship A (0 m, 0 m) and ship B (1200 m, – 200 m). Note that the part of the figure where 9200 m < x < 19600 m is not shown since for that range both ships are on steady course in a parallel abeam configuration.

In the last stage of the UNREP maneuver takes place from a position of about 20500 m, where the approach ship A slowly starts to increase its speed with respect to the guide ship B, which remains at steady speed and course. The possibility of collision increases again since both ships now experience repulsive interaction sway forces and yaw moments pointing in the same direction. Fortunately, the collision risk is reduced to a minimum due to the employed automatic motion control system. Finally, when the relative speed \((u_A - u_B)\) between the approach ship A and the guide ship B reaches approximately 1 knot, a rudder on the approach ship A is deflected to the port side so that she actually disengages herself from the parallel straight-line configuration with the guide ship B. This UNREP maneuver resembles quite well a real-life maneuver since it is performed according to the US Navy replenishment rules (Naval Warfare Publication, 2004).

Our discussion related to the above numerical example can be shortly summarized as follows. First of all, the UNREP maneuver in calm water showed that the hydrodynamic interaction loads between two ships estimated with Newman-Tuck (1974) theory cannot be neglected when the two ships are involved in close-proximity maneuvers. We also demonstrated the application of an automatic motion control system. The employment of such a control module has been chosen to exemplify the requirements for experienced helmsmen and deck crews needed to successfully accomplish UNREP operations in either calm water or waves, particularly avoiding any possible collision hazards during such close-proximity maneuvers.

5. CONCLUSIONS

The scenario of two advancing ships involved in close-proximity maneuvers in calm water has been simulated by using a two-time scale unified seakeeping and maneuvering
Fig. 6. Basic motion control variables and hydrodynamic interaction loads during the UNREP maneuver between the ‘MARINER’ and ‘ESSO OSAKA’ ships advancing in calm water. $B_A$ denotes the beam of the ‘MARINER’ hull on the main frame, $B_B$ denotes the beam of the ‘ESSO OSAKA’ hull on the main frame, while 1 knot = 0.5144 m/s.

model of two interacting ships by Skejic and Faltinsen (2007) and Skejic (2008). This model is based on a modular concept which in general accounts for the propulsion and resistance, rudder forces and moments, nonlinear viscous loads, calm-water hydrodynamic interaction loads, and mean second-order wave loads, which are all modelled as separate modules.
to allow for the possibility to replace or update the existing numerical procedures in a module without affecting the other modules. The calm-water hydrodynamic interaction loads between the two ships were estimated with Newman-Tuck (1974) far-field theory. Also, the latest theoretical and semi-empirical methods covering the hull, propeller, and rudder interaction effects were used, see Skejic (2008) for details.

Finally, a motion control module involving a guidance system as well as steering and speed controllers was employed for both ships in order to achieve high-precision and collision-free UNREP operations between two advancing ships of different type and size. This module was included to illustrate the critical stages of such operations. Furthermore, an UNREP maneuver was simulated in accordance with the international and US Navy regulations (Naval Warfare Publication, 2004) in order to consider realistic conditions.

Future work will concern UNREP operations in waves to further increase the realism of the simulations and the validity of the motion control system performance. Ultimately, it would be interesting to validate the theoretical two-time scale model with its motion control module for the influence of hydrodynamic interaction loads, waves, and wind for two ships involved in close-proximity maneuvers through experiments with free-running models exposed to similar wave and wind conditions.

REFERENCES


