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Approach Manoeuvre During Emergency Ship-to-Ship Transfer Operation with Oil Spill

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ABSTRACT: One of the major activities during Ship to Ship (STS) transfer operation at sea is to safe approach the Ship to be Lightered (SBL) which moves on a constant heading with slow speed or drifting. In the paper described the manoeuvring problem for approaching during emergency STS transfer operation with oil spill. The approach manoeuvre is considered as a sequence of navigation manoeuvres in specific navigational environment with environmental and operational constraints as well as ship dynamic performance. Additional constraints results from STS transfer operation guide and navigation practise.

1 INTRODUCTION

1.1 *Problem description*

During the last century, the share of maritime trade in the total value of world trade is constantly increasing. Nowadays more than 90% of trade is estimated to be transported by sea (EMSA 2015). This statistics portrays also that the world oil tanker account for about 30% of global seaborne trade. Through the use of new technology of shipbuilding, modern navigation and control systems, shipping in the world's become more secure. Despite this, the total number of ships involved in accidents is still large. The accidents often result from collision, loss control, grounding and structural damage, fires or explosion. Only from 2011 to 2014 about 4620 cargo ships involved in accidents, of which oil tankers represent about 9% (415 units). In the last decade the total volume of oil lost to the environment was approximately 33 000 tonnes. As a result of tankers incidents increases also the need to carry out the cargo transfer between damaged ship and another one in order to safe cargo (crude oil, petroleum products, liquefied gas) and to mitigate emission to the environment, called in naval terminology the STS (Ship-to-ship) transfer operation. STS transfer operation generally involve transshipment between two ships, the large called SBL (Ship to be Lightered) and small one called SS (Service Ship) positioned alongside each other, either while stationary or underway in order to commence cargo transfer (OCIMF/ICS 2005, OCIMF 2009). Usually this operation is carried out for huge oil tankers in open sea, when ship does not berth in port or jetty, especially due to draught restrictions or the port berthing charges. The motivation for performing these operations is a lack of deep water ports and economic aspects. These types of marine operations are expected to increase significantly in frequency, and expand into new geographical areas in the coming years.

Before mooring and cargo transfer start, the Service Ship has to approach the Ship to be Lightered, which moves on a constant heading with slow speed or drifts about zero. For this purpose basically a collision avoidance manoeuvre has to be carried out in order to obtain the required safety distance between two ships and to take side by side position. The manoeuvring operations are individually different depending on variation in the environment condition, manoeuvring performance of the individual ship (Pedersen et al. 2008, Husjord &Pedersen 2009 , Husjord 2016). During emergency STS transfer operation can appear additional important aspects like ship and cargo condition (transhipment from undamaged side), time limits (to ensure fast transhipment) as well as water area constraints (close to port area), avoidance moving oil spill or other rescue units.

Our objective is to define Approach Manoeuvre during emergency STS transfer operation as a problem of safe trajectory planning for approaching taking into account weather condition (wind direction), traffic density and stop and speed control performance of the vessels involved. Trajectory of approaching determined on available information allows to take proper manoeuvring decision by ship operator using rudders and propellers and to mitigate oil spill to the environment.

1.2 *The principle of a standard Approach Manoeuvre during STS transfer operation*

The STS transfer operation requires proper coordination, equipment in according to STS operation plan and administration approval. The purpose of the STS transfer operation plan is to provide a step by step description of STS procedure according to guidelines or recommendations from Iranian Classification Society (ICS), Oil Companies International Marine Forum (OCIMF) and the International Maritime Organization (IMO). This plan should deal with the following stages of operation:

- Pre-Approach Planning;
- Approach Manoeuvre;
- Mooring;
- Cargo Transfer;
- Unmooring;
- Departure Manoeuvre.

Each stage consists of different procedures to follow and check-lists to complete. A standard way to carry out an STS transfer operation is when the SBL maintain a constant heading at minimum controllable speed (5 knots or less) or drift with wind and currents but SS approach the first one and berths normally with its port side to the starboard side of the constant heading ship (Fig.1). The standard Approach Manoeuvre is divided into two phases. The initial phase is basically a collision avoidance manoeuvre from current position p_0 to final position p_k in order to obtain the required safety distance between Service Ship and Ship to be Lightered. The safety distance is called the Distance at Closest Point of Approach (DCPA) and it is appropriate to the conditions. During this phase SS must approach the first one on a parallel course and adjust its velocity to equal SBL. The second phase which is operation of a ships alongside takes place after the required safety distance has been verified. On closer approach, the manoeuvring ship should then position itself relative to the constant heading ship. Contact is made by the manoeuvring ship, reducing the distance until the fenders touch. Subsequently both ships are on parallel courses with similar velocity and their manifold in line to minimize force of berthing simultaneously on all fenders.

In the open waters the standard Approach Manoeuvre begins at distance of 0.5 Nm from the destination point and finish at DCPA approximately 50-100 m off. The mooring lines start about 20-30 m away from each ship. Normally the manoeuver will be made with the wind and sea ahead, however local conditions and knowledge may indicate an alternative side. Usually transhipment is completed after 10-24 h depending on cargo quality and weather condition.

Throughout any berthing operation the visibility should be good enough for safe manoeuvring, taking into account safe navigation and collision avoidance requirements. This standard Approach Manoeuvre (Fig.1) is of assistance when ships are under power, considering normal STS transfer operation. The procedures may vary from this guidance according to circumstances (emergency with oil spill, inshore operation, limited geographical scope of operation), dynamical and kinematical ship properties, weather condition and traffic density. In each unique situation Approach Manoeuvre almost base on knowledge, experience and assessment of navigational situation from navigators.

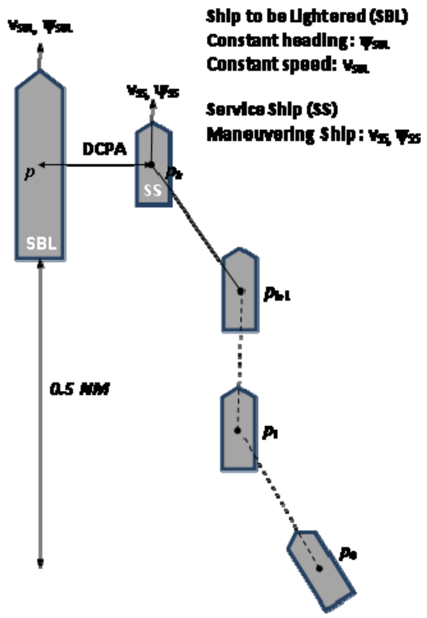

Figure 1. The principle of a standard Approach Manoeuvre in STS lightering operations (OCIMF/ICS 2005, OCIMF 2009)

The most common incident to occur during STS operations is a collision between the two ships while manoeuvring alongside each other or sailing (Ventikos & Stavrou 2013). Collision between two ships typically occur for reasons which include: incorrect approach angle between the manoeuvring ships; approaching at excessive speed; failure of one or both ships to appreciate meteorological conditions. To mitigate the risk of incidents, guidelines will be needed for the navigator of Service Ship, which include information about reference trajectory for approaching in meaning of reference way points p_i: position (x_i, y_i)/or (heading ψ_i) and velocity v_i to take a proper steering decision by ship operator at each stage of ship manoeuvring.

2 OPERATION ASPECTS DURING EMERGENCY STS APPROACH MANOEUVRING

2.1 *Accident scenario with oil tanker & STS operation to mitigate oil spill.*

The following example accident scenario with oil tanker is considered in this paper for trajectory planning. Product tanker after collision with general cargo ship lost its ability to manoeuvre and start drifting NE due to NW'ly wind. Immediate actions were carried out to reduce oil spill overboard, arranged transfer cargo from damaged tank to other compatible tanks and increased heel to port using ballast tanks to keep all cracks on bulkhead above the sea water level. Prepare floating cotton barrier to reduce oil spot in the vicinity of ship, started oil spill pump and collected oily water to slops tanks. At the same time all parties (administration, owner, charterer, insurer, SAR) were informed accordingly. Small tanker with very good manoeuvring characteristic was designated to emergency STS operation.

For considered accident with oil tanker two variants of Approach Manoeuvres are proposed based on good navigation practice and STS transfer operation guide (OCIMF/ICS 2005, OCIMF 2009, Wilczynski 2014). They depend on different circumstances like wind direction, oil spill area and ship actuator equipment (manoeuvring performance). The examples are shown in Figures 2-3.

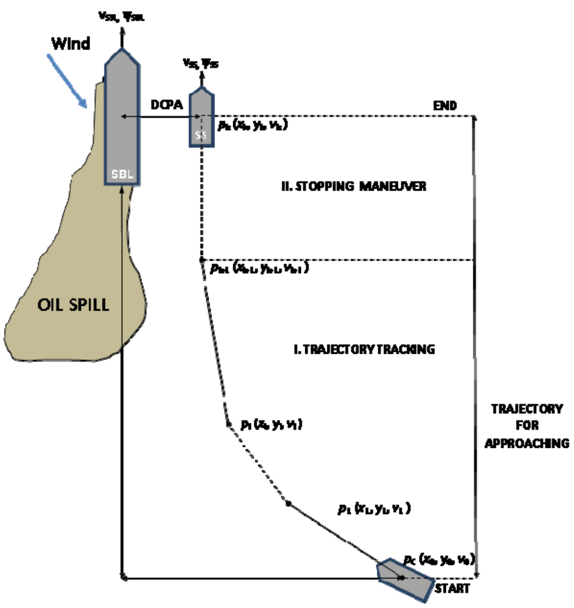

Figure 2. The example trajectory for approaching in STS transfer operations with 2 control modes (I,II) - variant A

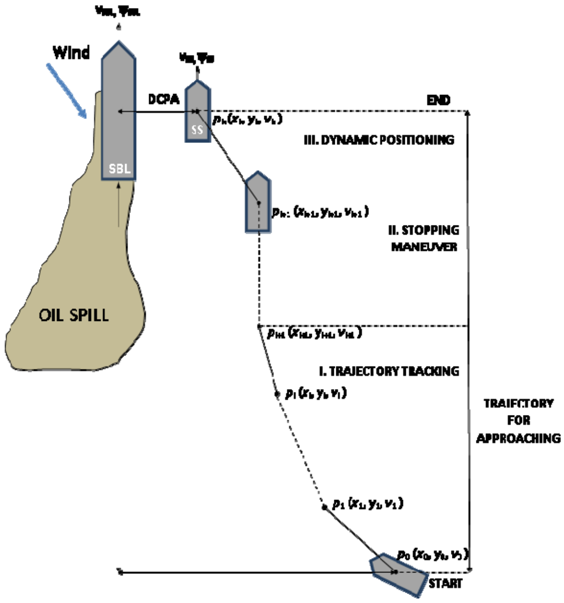

Figure 3. The example trajectory for approaching in STS transfer operations with 3 control modes (I,II,III) - variant B

Both manoeuvres are from leeward and to the starboard side of the constant heading ship. They differ only in possibility to run Dynamic Positioning control mode (variant B) or without possibility of running it (variant A).

2.2 *Control modes during emergency STS procedure*

The possibility of using different control modes during STS procedure depends (among other) on ship current velocity and actuator equipment. The Service Ships dedicated for conducting STS transfer operation are mostly equipped with aft main propeller usually in conjunction with rudder and bow tunnel thruster. Main propeller produce the necessary surge force needed for transit and rudder produce yaw moment which can be used for steering control. The tunnel thruster produces a sway force and is only effective at low speed . This set of three actuators can realize Trajectory Tracking operation of Approaching and then Berthing. Azimuth thrusters can produce two force components surge and sway in the horizontal plane. They are attractive in Dynamic Positioning since they can produce forces in different directions (Fossen, T. 2011).

To control the movement of the Service Ship during STS Approach Manoeuvre a few general control modes are possible, in order to achieve the final Distance from SBL, parallel course and equal speed (Fig. 2). They consist of:

1. Trajectory Tracking (moderate or high-speed manoeuvring)
2. Stopping Manoeuvre (stop ship)
3. Dynamic Positioning (low-speed manoeuvring)

The control modes mention above are classified according to control objectives during STS Approach by using different types of available actuators include propulsion system, thrusters and rudders.

Trajectory Tracking (Tomera 2016): The first control objective is to minimize a tracking error between a desired trajectory given by a desired time-varying position and velocity reference signals.

During STS operation tracking control can be used for course-changing manoeuvres and speed-changing control separately or simultaneously. The task is mostly realized at the first phase of Approach Manoeuvre to assume moderate or high ship speed (more than 2m/s). At this speed rudder for course control and main propeller for speed control (ROT and ruder angle control) are only effective.

Stopping Manoeuvre (ABS, 2006): The second control objective is related with a reduction of current ship velocity along trajectory segments between way points. The stopping ability of the vessel is judged using emergency stop manoeuvre or normal stop menouvre. The emergency stopping test must be performed starting from the test speed. After the steady state is achieved, the "full astern" command is given from the engine control mode on the bridge. The test is considered to be completed when the ship speed is about zero.

During stop manoeuvre the operator should stop its engine and only course keeping by using rudders amidships. The test is considered to be completed when the ship speed is dead on the water .

Dynamic Positioning (Fossen, 2011, Witkowska 2013). The third control objective consist in manoeuvring the ship at low speed (less than 2 m/s). The only course and position control are associated with this mode. At these speed ship steering is carried out by using mostly azimuth thrusters, bow thrusters, stern thrusters, water jets. The efficiency of rudders at low velocity significantly decreases. Dynamic Positioning mode can be activated at last phase of approaching (after speed reduction) to realize various kind of ship movement like longitudinal, transverse, rotation around its axis or side manoeuvre at certain angle.

After Approach Manoeuvre by using I, II or/and III control modes, the ships should manoeuvres alongside at the required safety distance (DCPA). That means both SS and SBL keep their constant heading $\psi_{SS} \approx \psi_{SBL}$ and constant speed $v_{SS} \approx v_{SBL}$ or drifting about 0. In this condition the Berthing operation by using tunnel thruster and Mooring procedure by using lines can start.

2.3 *Stopping and speed control characteristics*

Comprehensive details of the ship stopping and speed control characteristics are included in the manoeuvring booklet. This booklet is required to be on board and available for navigators. Most of the manoeuvring information in the booklet can be estimated but some should be obtained from trials. They contain (among other relevant data) characteristics of main engine, stopping test results (emergency and normal) and deceleration performance. The characteristics of main engine contain possible engine order (Full Sea Ahead, Full Ahead, Half Ahead, Slow Ahead, Dead Slow Ahead, Dead Slow Astern, Slow Astern, Half Astern, Full Astern), propeller revolution, speed, power, pitch ratio.

Stopping ability is measured by the track reach, head reach, side reach, time required to speed reduction and final course (Fig. 4).

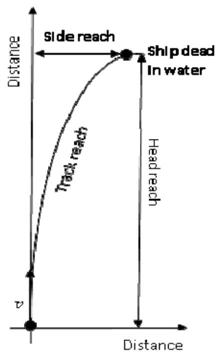

Figure 4. Definition used in stopping test.

It covers the following modes of stopping manoeuvers: from Full Sea Ahead to Full Astern; from Full Ahead to Full Astern; from Half Ahead to Full Astern; from Slow Ahead to Full Astern; from Full Sea Ahead to stop engine; from Full Ahead to stop engine; from Half Ahead to stop engine; from Slow Ahead to stop engine.

Deceleration performance concern track reach, head reach and time required. It covers the following modes: from Full Sea Speed to Full Ahead; from Full Ahead to Half Ahead; from Half Ahead to Slow Ahead; from Slow Ahead to Dead Slow Ahead. When the vessel travels along a straight line with the original course (autopilot is on) the track reach and time reach values are taken as the longest travelling distance and the maximum time to decelerate ship velocity.

3 TRAJECTORY PLANNING FOR APPROACHING

The Service Ship trajectory $\boldsymbol{P}$ for approaching is defined as a set of turning points $\boldsymbol{P}=\{p_0, p_1, ..., p_k\}$ on ship route from current position (initial point) p_0 to the destination (final point) p_k. The way points $p_i(x_i, y_i, v_i), i \in \{0,1,\ldots,k\}$ of desired trajectory have position x_i, y_i determined to avoid obstacles on considered area with respect to a top ship speed $v_i, i \in \{0,1,\ldots,k\}$ on each way points. The way points divide trajectory into a set $S=\{s_1, s_2, \ldots, s_k\}$ of trajectory segments with a lengths $D=\{d_1, d_2, \ldots, d_k\}$. The s_i compose of the path position sequences between way points on straight line. The way points components are respectively reference ship position and speed on each turning point.

Planning of the safe trajectory during STS assumed that each of trajectory segment $s_i, i=\{1,\ldots,k\}$, between way $p_i, i=\{0,\ldots,k\}$ points does not cross in the area of the environment with the static and dynamic obstacles. The choice of top speed elements v_i, $i \in \{0,1,\ldots,k\}$ at each way points of desired trajectory depend on set $v_i \in V$, $V=\{0, v_{FA}, v_{HA}, v_{SA}, v_{DSA}\}$, where the following engine orders are considered: Full Ahead (v_{FA}), Half Ahead (v_{HA}), Slow Ahead (v_{SA}), Dead Slow Ahead (v_{DSA}).

The designed trajectory satisfies deceleration condition if the ship is able on each trajectory segment

s_{i+1} to decelerate ship velocity from. It means that for a given starting reference speed v_i at p_i it is possible to approach by ship the ending one $v_{i+1} < v_i$ at p_{i+1} with segment length d_{i+1}. The feasibility of trajectory is checked based on stop and speed control constraints collected in manoeuvring booklet. When the vessel travels in a straight line along the original course the segment length value can't be less than track reach needed for speed deceleration or stop ship:

$$d_{i+1} \geq track\,reach_{i+1} \quad (1)$$

where $track\,reach_{i+1}$ is the travelling distance need to decelerate ship velocity from v_i to v_{i+1}.

The planning of the last way points $p_i, i = \{k-2, k-1, k\}$, $k \geq 2$ depend additionally on ship manoeuvrability constraints during STS, results by using variants A or B of Approach Manoeuvre.

3.1 *Way points planning - variant A*

The initial way point p_0 consist of a current position (x_0, y_0) and velocity v_0 of Service Ship when it start Approach Manoeuvre (Fig. 5). The destination point $p_k(x_k, y_k, v_k)$ has a parallel position $(l_{ss} \parallel l_{SBL})$ in a safety distance (DCPA) from position of Ship to be Lightered and the some velocity $v_k = v$, to allow starting manoeuvring alongside. When emergency STS trajectory is planning the SBL maintain its current position (x, y) constant and speed about zero, $v \approx 0$. In this case the initial p_0 and destination p_k points are approximately constant and chosen by the operator or calculated by the simple geometric relationship:

$$p_k |_{(x_k, y_k)} \in l_{SS},\ l_{SS} \parallel l_{SBL}, \quad (2)$$

$$v_k \approx 0,\ DCPA = p |_{(x,y)}\, p_k |_{(x_k, y_k)}\ 2, \quad (3)$$

where

$p |_{(x,y)} = (x, y), p_k |_{(x_k, y_k)} = (x_k, y_k)$,

l_{SS} – straight line covers SS diametrical line,

l_{SBL} – straight line covers SBL diametrical line.

The previous way point p_{k-1} has position determined on straight line l_{SS} parallel to l_{SBL}.

$$p_{k-1} |_{(x_{k-1}, y_{k-1})} \in l_{SS}, \qquad l_{SS} \parallel l_{SBL}. \quad (4)$$

The reference speed v_{k-1} is modelled as minimum controllable speed v_{DSA} (Dead Slow Ahead) for safety manoeuvring in close proximity.

$$v_{k-1} = v_{DSA}, \quad (5)$$

with satisfying feasibility condition of trajectory segment s_k :

$$d_k = p_{k-1} |_{(x_{k-1}, y_{k-1})}\, p_k |_{(x_k, y_k)}\ 2 \geq track\,reach_k \quad (6)$$

where $track\,reach_k$ is the travelling distance need to decelerate ship velocity from v_{DSA} to about 0.

The way point p_{k-1} is determined on the arc L_{AB} between the end points A and B satisfying $A \epsilon l_{SS}$. The arc is a part of a circle $O(p_k, |AO|,)$ with a radius $|AO| = 0.5$ nautical miles of cells and central angle $\in < 0, 30^0 >$. We also assume that reference velocity $v_{k-2} = v_{DSA}$ is predetermine as minimum controllable.

$$p_{k-2} |_{(x_{k-2}, y_{k-2})} \epsilon L_{AB},\ \ A \epsilon l_{ss} \quad (7)$$

$$v_{k-2} = v_{DSA} \quad (8)$$

where

$$L_{AB} \epsilon\, O(p_k, |AO|,),\ \epsilon < 0, 30^0 >, |AO| = 0.5\text{NM}$$

3.2 *Way points planning - variants B*

The difference between variants A (Fig. 5) and B (Fig. 6) lie only in modelling two way points $p_i, i \in \{k-2, k-1\}$. Because of using Dynamic Positioning control mode, the maximum reference velocity v_{k-1} of approaching doesn't exceed 1 knots in the safety area of 0.3 NM [17] from destination point. The DP system at low speed allow to realize various kind of ship movement, so the point p_{k-1} is determined on the larger arc L_{CD} with a central angle $\beta \in < 0, 90^0 >$.

$$v_{k-1} \leq 1 knot, \quad (9)$$

$$p_{k-1} |_{(x_{k-1}, y_{k-1})} \epsilon L_{CD},\ \ C \epsilon l_{ss}. \quad (10)$$

where

$$L_{CD} \epsilon\, O(p_k, |CO|, \beta),\ \beta \in < 0, 90^0 >,$$

$$0.5\text{NM} \geq |CO| \geq 0.3\text{NM}.$$

The way point p_{k-2} is determined on the arc LAB between the end points A and B satisfying $A \epsilon l_{SS}$. The arc is a part of a circle $O(p_k, |AO|,)$, with a radius $|AO| = 0.5$ nautical miles of cells and central angle $\in < 0, 90^0 >$. We assume that reference velocity v_{k-2} is predetermine as minimum controllable (Dead Slow Ahead) for safety manoeuvring:

$$v_{k-2} = v_{DSA}, \quad (11)$$

$$p_{k-2} |_{(x_{k-2}, y_{k-2})} \in L_{AB},\ \ A \epsilon l_{SS} \quad (12)$$

where

$L_{AB} \epsilon O\left(p_k, |AO|,\right), \epsilon < 0,90^0 >, |AO| = 0.5\text{NM}.$

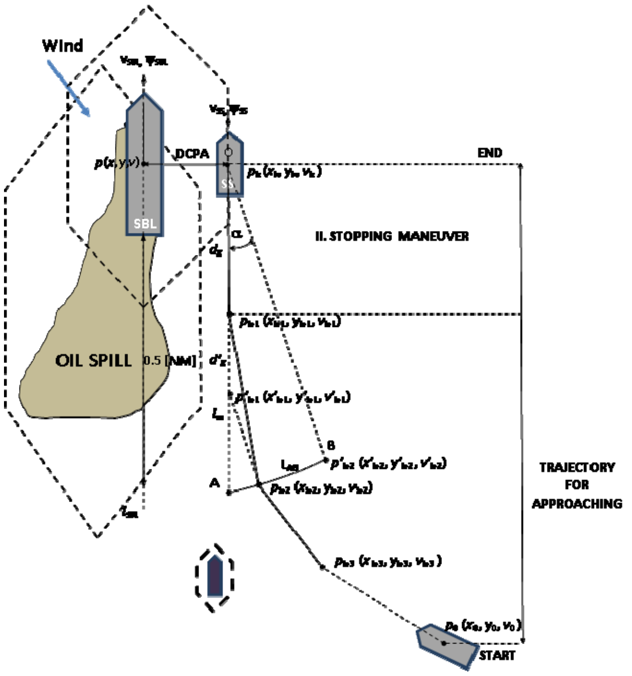

Figure 5. Modeling way points - variant A

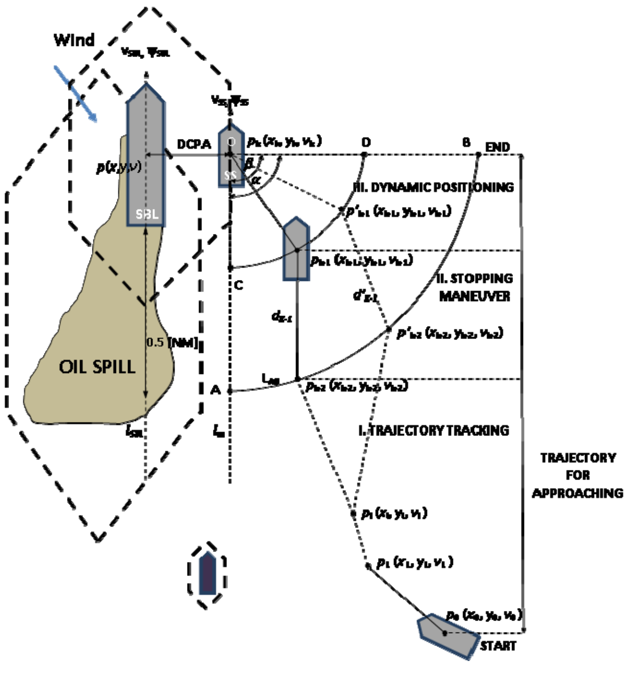

Figure 6. Modeling way points - variant B

To satisfy deceleration condition on trajectory segment s_{k-1} a distance d_{k-1} can't be less than a track reach calculated on stop and low speed characteristics:

$$d_{k-1} = p_{k-2} \left|_{(x_{k-1}, y_{k-1})} p_{k-1} \right|_{(x_k, y_k)} 2$$
$$\geq track\ reach_{k-1} \tag{13}$$

where $track\ reach_{k-1}$ is the travelling distance need to reduction v_{k-2} to $v_{k-1} \approx 1$ knot.

Additional constraints on way points depend on wind direction (side of manoeuvre if it possible from leeward) and emergency condition (side of manoeuvre approach from undamaged side)

4 CONCLUSIONS

The paper formulate the problem of Approach Manoeuvre during emergency STS transfer operation with oil spill as a problem of trajectory planning for approaching. The trajectory is considered as a sequence of way points with reference position and velocity and straight line segments between them. The way point planning process results from transfer operation guide, ship operation constraints and with respect to additional constraints depended on ship speed and stopping meneuver performance.

The presented in above way trajectory planning issue can be consider as an example of classical avoiding collisions at sea. It can be reduced as a multi-criteria, nonlinear optimization problem with navigational time, safety and economy criteria with navigational constraints:

- stationary obstacles (land, islands, shallow water, restricted area)
- dynamical obstacles (SBL ship, other ships, modeling of the prediction of the oil spill area (Łazuga et al. 2012)
- modeling of ships and obstacles by domains
- ships and obstacles domains position, course, speed.
- weather condition (wind direction)
- stopping and speed control characteristics

Several solutions can be used to solve the problem of trajectory planning for approaching defined as optimization task. One of them contain Genetic or Evolutionary Algorithm (Kuczkowski & Smierzchalski 2014), Particle Swarm Algorithm (Lazarowska 2015), Simulated Annealing (SA). The results of using Evolutionary Algorithm with taking into account speed deceleration and stopping characteristics for trajectory planning during emergency STS transfer operation is the aim of the following stage of research.

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