Development of an autopilot for fast-time simulation in confined waterways

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Abstract

The execution of fast-time ship manoeuvring simulation studies requires the availability of an autopilot, which represents the control system in the simulation loop. In rather severe navigation conditions, an autopilot based on a classical control theory approach sometimes does not lead to satisfactory results. For this reason, a steering automaton was developed which is able to take account of 'predictable' disturbances, such as transient bank suction effects and steady wind forces.

The autopilot makes use of a coarse version of the mathematical manoeuvring simulation model in order to predict the ship's position for a discrete number of control actions after a short lapse of time. The control action which minimises a cost function of the ship's predicted position is considered as an optimum.

The autopilot was applied for evaluating the effect of the length of a panamax bulkcarrier on collision risk in a restricted canal with long bends and variable bank suction. The described autopilot offered the advantage to be unbiased with respect to the ship's dimensions, and appeared to react in a way comparable to the behaviour of pilots during real-time simulations.

1 Introduction

Ship manoeuvring simulation is increasingly more often considered as a reliable tool in studies concerning port and waterways accessibility, e.g. design of new navigation areas, evaluation of the access of new shipping traffics to existing ports. A ship manoeuvre can be considered as the result of interaction between three major factors:

- the ship;
- the environment (e.g. wind, channel geometry, tugs, ...);
- a control system (human or artificial).

In spite of recent developments in control systems, manoeuvres carried out in rather 'extreme' conditions are in practice always performed by experienced pilots nowadays. The performance of human controllers can be incorporated in a simulation study by means of real-time interactive simulation techniques.

On the other hand, the introduction of a human factor can be considered as a source of scatter and uncertainty. Indeed, every human controller has unique, individual 'characteristics', which are changing permanently. Moreover, real-time interactive simulation runs are time-consuming, not only because of the duration of each individual run, but also because the number of runs to be performed successively by the same pilot is limited.

For these reasons, fast-time simulation runs are often carried out for studies in which real-time runs do not lead to an adequate solution. This is particularly the case in the concept design stage of channels and waterways, where fast-time simulations result into a first evaluation of the feasibility, and may give an indication of critical conditions and possible bottlenecks. However, fast-time simulations can also be applied for investigating the influence of a particular external parameters on a specific manoeuvre, in conditions where the influence of human factors would cause too much scatter in the results.

The following paragraph will give a concise description of a typical case-study which requires the application of fast-time simulation techniques. This example will be used for determining the requirements which the steering automaton (autopilot) controlling the ship during the simulation run has to meet. An overview is given of the methodology followed for the development of such an autopilot module for the case-study mentioned before.

2 Case study

2.1 Overview

On the canal connecting the River Scheldt in Terneuzen (the Netherlands) to the Port of Ghent (Belgium), ship dimensions are subject to following limitations: $L_{oa} \leq 256$ m; $B \leq 34$ m; $T \leq 12.25$ m. The main reason for the length limitations is the presence of two long bends and three bridges fulfilling a crucial role in road connections, see figure 1. Flanders Hydraulics was requested to carry out a simulation study in order to investigate the influence of extending the admitted ship length to 265 m on the sailing ability in the canal. A detailed description of the investigation is given by Laforce et al [1], and Laforce & Vantorre [2].

Due to the limited under keel clearance, being 10% of draught, and the lateral restrictions, resulting into a blockage of 27% in the standard canal section (figure 2), interaction forces are predominant. Systematic captive motion tests with 1/64 scale models of panamax bulkcarriers with L_{oa} = 230 m, 245 m and 265 m were performed in the *Towing Tank for Manoeuvres in Shallow Water* at Flanders Hydraulics in three conditions:

- in open, shallow water;
- in the trapezoidal standard cross section of the canal;
- in a scale model of the canal, including bottom width variations and side branches.

During these tests, several parameters (forward speed, drift angle, rudder angle, propeller revolutions, lateral position) were varied.

Mathematical models were developed for the hydrodynamic forces and moments acting on the ships in open shallow water and for the stationary and transient ship-bank interaction forces; the latter required the introduction of look-up tables.

The influence of ship length was evaluated by means of fast-time simulation runs, carried out in 107 different realistic wind conditions. A statistic post-processing of results of the simulation runs led to an estimation of the effect of ship length on the swept path in the canal and, as a result, on the probability of grounding.

2.2 Autopilot requirements

For several reasons, it was impossible to base the study by means of real-time simulation runs only:

- as each run takes about one hour in real time, the execution of a sufficient number of runs for each ship length in several representative wind conditions would consume too much time;
- it was expected that the difference in behaviour between different pilots, and even the evolution of one particular pilot's reactions during successive simulation runs would cause more scatter than the effect of the ship's length.

Therefore, systematic fast-time simulation runs were required in order to investigate the influence of the parameter 'ship length'. Such an approach implies the availability of a steering automaton or autopilot which takes over the human navigator's function. This autopilot should meet some basic requirements.

Firstly, in order to guarantee a 'honest', unbiased comparison between the three ships, the 'quality' of the autopilot should be independent of the ship's inherent manoeuvring characteristics, so that none of the ships would be favourised by the control system. As a consequence, the control algorithm should be related to the ship's manoeuvring behaviour and, therefore, to the ship's mathematical manoeuvring simulation model (hydrodynamic coefficients), in an objective way.

The first requirement compensates for the impredictable aspects of human behaviour. On the other hand, it is likely that in extreme conditions a human controller such as an experienced mariner will perform in a more successful way than a classical artificial control system. In the present conditions, a controller will only lead to an acceptable performance if its behaviour anticipates the ship's reaction to 'predictable' disturbances, such as transient bank suction effects and steady wind forces. Therefore, as a second requirement, the controller should not only take corrective actions, but should also take into account future modifications of the prescribed trajectory and of fluctuations of external disturbances.

A third series of requirements is also related to human behaviour. As the real manoeuvres are carried out by human controllers in practice, it is the purpose to develop a control algorithm which is able to simulate a human controller as closely as possible, rather than a 'perfect' controller. For this reason, the autopilot should have a *discrete* rather than *continuous* character from several points of view:

- control actions should be taken at discrete time intervals;
- output signals (such as rudder angle, engine setting) should be selected among a number of discrete values;
- input signals which are in practice based on human perception (e.g. lateral position in canal) should be introduced into the autopilot with a limited accuracy.

In a preliminary study performed by Hendrickx [3], an autopilot based on following control algorithm was considered:

$$\delta = K_\gamma \gamma + K_r r + K_\eta \eta_M + K_v v \tag{1}$$

with δ : rudder angle,

γ : angle between ship's longitudinal axis and straight line connecting midship section and point on reference trajectory at distance ξ ahead (see figure 3),

r : rate of turn,

η_M : offset relative to reference trajectory (see figure 3),

v : sway velocity,

with extensions in order to perform engine manoeuvres. It was concluded that this type of autopilot does not lead to satisfactory results in the canal, mainly due to the lack of anticipation of the ship's reaction to external disturbances and to difficulties in determining optimal control coefficients K_γ, K_r, K_η and K_v, and of the look ahead distance ξ.

3 Concept of simulation autopilot

3.1 Principle

A control algorithm meeting the requirements mentioned in 2.2 as much as possible, is represented schematically in figure 4.

Input signals consist of the ship's position (x_0, y_0) and orientation (ψ), velocity components (u, v, r) and acceleration components ($\dot{u}, \dot{v}, \dot{r}$) in the horizontal plane, as well as the present values of the output signals. The latter are the rudder angle δ and the propeller rate n, which is a function of the engine setting.

New control actions are taken at discrete time intervals Δt, see figure 5. The autopilot takes its decisions based on a mathematical manoeuvring simulation model, referred to as 'prediction model'. The latter is applied in order to predict the ship's position after a lapse of time equal to ξ/u, i.e. approximately the time to cover $\xi = \xi' L_{pp}$ times the ship length, as a result of several possible control actions. A prediction for the ship's position is calculated for a discrete number of combinations of δ and n.

The effect of each considered control action is evaluated by means of a cost function C, which is a function of the predicted position. The control action which minimises this cost function is considered as an optimum, and is applied during the following time interval Δt.

Summarized, the control system is determined by the selection of:

- the cost function C;
- the possible combinations of control actions;
- the time interval Δt between two control actions;
- the anticipation length ξ or anticipation time ξ/u;
- the prediction model.

3.2 Case study : selection of autopilot parameters

3.2.1 Control actions

A control action is defined as a combination of the rudder angle δ, taking discrete values $\delta^{(1)}$, ..., $\delta^{(K)}$, and the propeller rate n, taking discrete values $n^{(1)}$, ... ,$n^{(M)}$ according to the engine settings. Originally, the rudder angle was allowed to take values $\delta = 0°, \pm5°, \pm10°$, ..., $\pm30°$, $\pm35°$, but, as a result of discussions with canal pilots, the possible output values were finally limited to 0°, ±10°, ±20°, ±35° only.

Taking account of speed limitations in the canal, engine setting 'slow' (m = 1) was considered to be the most convenient, although actions 'half' (m = 2) and 'full' (m = M = 3) could be taken during restricted time intervals in order to increase rudder induced forces.

For the time interval Δt, 10 seconds was accepted as a realistic value. The rudder angle and propeller rpm at time $t = i\,\Delta t$ are denoted δ_i and n_i, and take values $\delta^{(k)}$ $(1 \le k \le K)$ and $n^{(m)}$ $(1 \le m \le M)$, respectively. Following combinations of δ and n are considered for extrapolation by the prediction model and evaluation by the cost function:

$$\delta = \delta^{(k)}, \delta^{(k\pm1)}, \delta^{(k\pm2)}, \delta^{(k\pm3)} ; \quad n = n^{(m)}$$

If the optimal rudder angle δ_{opt} coincides with an extreme position, i.e. $\delta_{opt} = \delta^{(K)} = +35°$ or $\delta_{opt} = \delta^{(1)} = -35°$, an engine manoeuvre will be carried out, so that following combinations are also taken into consideration:

$$\delta = \delta^{(k)}, \delta^{(k\pm1)}, \delta^{(k\pm2)}, \delta^{(k\pm3)} ; \quad n = n^{(m+1)}$$

Engine manoeuvres (m > 1) have a standard duration of 2 Δt in order to avoid excessive speed increase; for this reason, the variable $\tau^{(m)}$, being the number of time intervals propeller rate $n^{(m)}$ is applied, is introduced in figure 4.

3.2.2 Trajectory prediction

For the prediction model, the full version of the simulation model, as represented schematically in figure 5, can be applied, although a larger value for the integration step can be selected (Dt instead of dt). It is clear that this will result into optimal control actions, but this implies that the control system has a perfect knowledge of the ship's dynamics and reactions to disturbances.

A more realistic control behaviour may be obtained by selecting a coarse, simplified version of the mathematical manoeuvring model. Even an incomplete mathematical model, in which some modules are deleted, may be applied; this allows to consider the effect of ignorance of some particular effects such as bank effects and wind.

A value of 0.8 was selected for the anticipation factor ξ' defined in 3.1. During engine manoeuvres, however, the factor was reduced by 50%, taking account of limitations of such actions in time.

3.2.3 Selection of an optimal control action

A selection of an optimal control action is based on an evaluation by means of a cost function C, which is a function of the predicted position. In the present case, C is a function of the distance of the ship's stern, midship section and bow relative to the prescribed trajectory (see figure 3):

$$C = c_F \Delta \eta_F^2 + c_M \Delta \eta_M^2 + c_A \Delta \eta_A^2 \qquad (2)$$

but this expression can be extended in order to take account of other requirements, e.g. speed limitations, heading.

4 Fast time simulations results

4.1 Introduction

This chapter handles the effect of external disturbances and of the control algorithm on the control actions taken by the simulation autopilot and the trajectory followed by a panamax bulkcarrier (L_{oa} = 265 m, B = 32.2 m, T = 12.25 m) sailing through the canal from Sluiskil (km 9) to Sas van Gent (km 2). The results are presented in figures 6 to 8, displaying

- the propeller rate,
- the rudder angle,
- the swept path occupied by the ship, together with the contours of the canal bottom line at maximum depth (13.50 m),

as functions of the position along the canal.

4.2 Influence of external disturbances

Figure 6 presents simulation runs carried out in following conditions:

(a) no wind, no bank effects (which implies that the prescribed trajectory has to be followed in open shallow water);
(b) no wind, bank effects;
(c) 6 Bf SW wind, bank effects;
(d) 6 Bf NE wind, bank effects.

Statistical data indicate that wind speeds exceeding 6 Beaufort have a frequency of occurrance of only 0.035%, so that it can be concluded that the ship is controlled in a satisfactory way in all practical conditions.

4.3 Influence of prediction model

All simulations in figure 6 were performed with an autopilot which has a perfect knowledge of the ship's manoeuvring behaviour and reactions to external disturbances. In practice, a pilot will develop an idea about these ship characteristics, which can be compared with the 'prediction model'; depending on his skill and experience, this model will more or less be in accordance to reality.

In order to evaluate the importance of a correct prediction, figure 7 compares the control actions and the swept path performed by autopilots applying four different prediction models:

(a) perfect prediction model;
(b) prediction model ignoring wind effects;
(c) prediction model ignoring bank effects;
(d) prediction model ignoring both wind and bank effects;

which implies that all autopilots have a perfect knowledge about the ship's behaviour in open shallow water, but have different ideas about the ship's reaction to external disturbances. All runs were performed in a 6 Beaufort SW wind condition.

A comparison between the runs carried out by the different autopilots indicates that a correct understanding of bank effects (b) is more important than a realistic estimation of wind forces (c), even in severe wind conditions.

4.4 Influence of anticipation factor ξ'

Figure 8 shows the importance of the choice of the anticipation factor ξ. Acceptable values appear to be situated in the range 0.6 - 0.8. Although an optimum is reached for a predicted trajectory of 0.6 ship lengths, 0.8 was selected for the fast time simulation runs, as a further decrease of ξ clearly leads to instable control behaviour; the autopilot was unable to sail the ship through the canal with an anticipation factor $\xi' = 0.4$.

Classical simulation autopilots, based on e.g. control algorithm (1), make use of an anticipation length in the range 1.0 - 1.5 L; it is clear that the acceptable range is much lower in this particular case.

5 Comparison with real time simulations

5.1. Introduction

In order to evaluate the fast time simulation results, the 265 m long ship was sailed along the canal by 8 canal pilots on the real time ship manoeuvring simulator at Flanders Hydraulics. During both kinds of simulations, the same mathematical model was used.

The purpose of the real time simulation program had a rather qualitative character, consisting of gathering the opinion of the pilots on the ship behaviour of the ship on the canal and evaluating the realism of the mathematical model. The number of runs was too low for a statistical evaluation of the swept path: 21 runs were carried out, 10 of which at 6 Beaufort SW wind.

5.2 Comparison with individual simulation runs

Some examples of individual simulation runs are displayed in figure 9(a-c). As expected, the variability between the runs was rather large; in particular, important differences in swept path were observed. This can be explained in several ways.

- The actions of the autopilot were intended to follow the canal centerline as closely as possible. As this is no real aim in reality, several pilots did not try to avoid eccentricity as much as the autopilot did.
- The suction effects at the bend of Sas van Gent (km 4 to 2) were quoted as insufficient by some of the pilots. As the latter tried to use suction effects to start the turning manoeuvre, the ship was kept too much to the starboard side of the fairway at that location. The reason for this apparent shortcoming of the mathematical model could be found in the difference between the real and the theoretical canal cross-sections; soundings show that the inner bend has become too shallow while the outer bend has widened and deepened.

The main difference between the pilots' and the autopilot's control actions concerns the fluctuations of the rudder angle. In the case of the autopilot, figure 7 shows that, to some extent, these fluctuations increase if the prediction model becomes less accurate. One should keep in mind that all prediction models taken into account had a perfect knowledge about the ship's open water steering and manoeuvring characteristics, while the information the pilots received about the ship was of course restricted.

5.3 Comparison with average trajectory

A comparison between some individual runs and the fast time simulations demonstrates some resemblance; this becomes more clear, however, if the average values of control actions taken by the pilots and of the swept path performed by the ship during the real time simulation runs are displayed as a function of the position in the canal, figure 9(d).

Pilots and autopilot both appear to require engine actions in the same part of the trajectory (bend at Sas van Gent: km 4 to km 2).

Peaks in rudder action are of course determined by the position of the bends; nevertheless, a comparison with the fast time simulation runs displayed in figure 7 reveals a rather fair agreement between the average real time rudder actions and the performance of the autopilot making use of a prediction model (c) without anticipation of bank effects. Maximum deviations from the canal centerline also occur at the same position along the canal, but are less for the average real-time simulation trajectory.

6. Conclusion

An autopilot for use in fast time ship manoeuvring simulation runs was proposed, which bases its decisions on a mathematical prediction model evaluating the result of several possible control actions by means of a cost function. This method offers the advantages to take full account of the ship's manoeuvring characteristics and to anticipate predictable external reactions, as would an experienced pilot do. Other characteristics which give the automaton a human touch, concern the discrete character of control commands.

This type of autopilot can be applied for assessing the influence of ship characteristics or external disturbances on the feasibility of specific manoeuvres, but also allows to investigate the effect of ignorance or limited estimation by a (human or artificial) control system of the ship's manoeuvring behaviour or reactions to external influences. Such an approach may lead to conclusions concerning the relative importance of a correct knowledge of several aspects affecting the execution of a specific ship manoeuvre.

Acknowledgements

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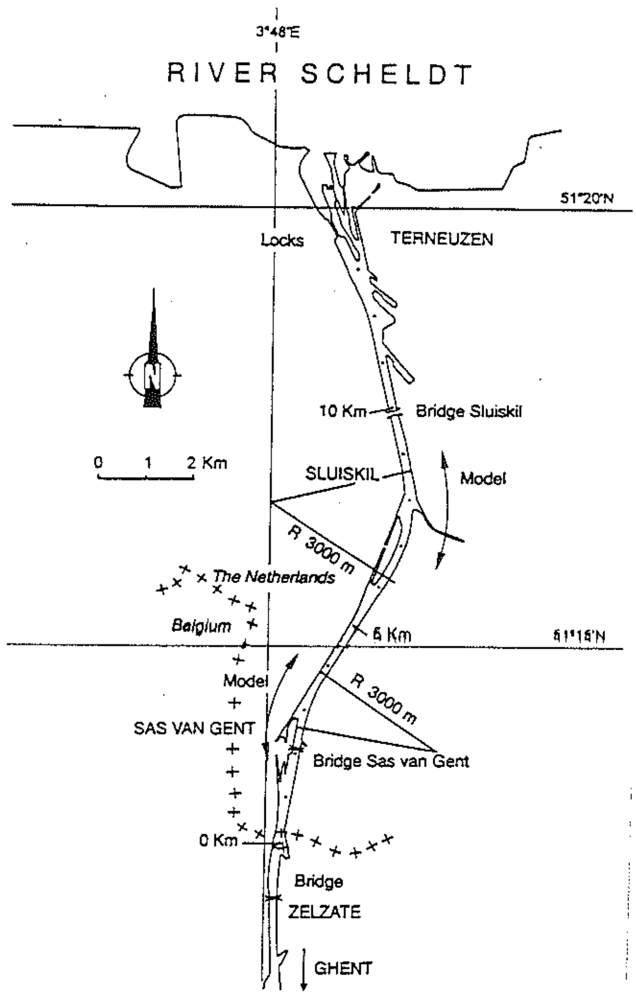

Figure 1 Canal Terneuzen - Ghent : situation plan ([1], [2])

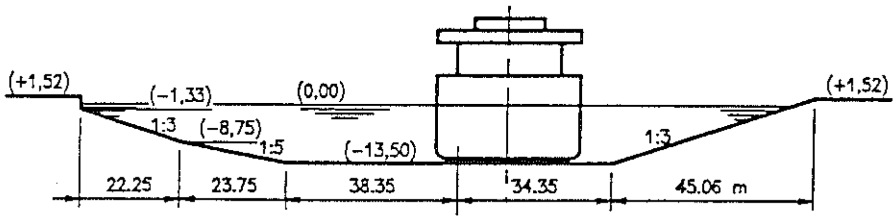

Figure 2 Canal Terneuzen - Ghent : standard cross-section ([1], [2])

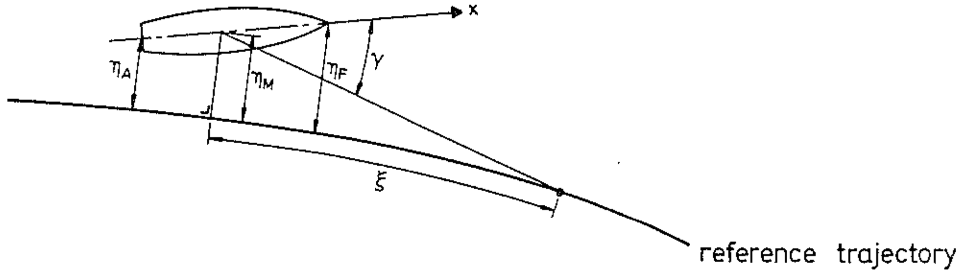

Figure 3 Track keeping autopilot (1) : conventions

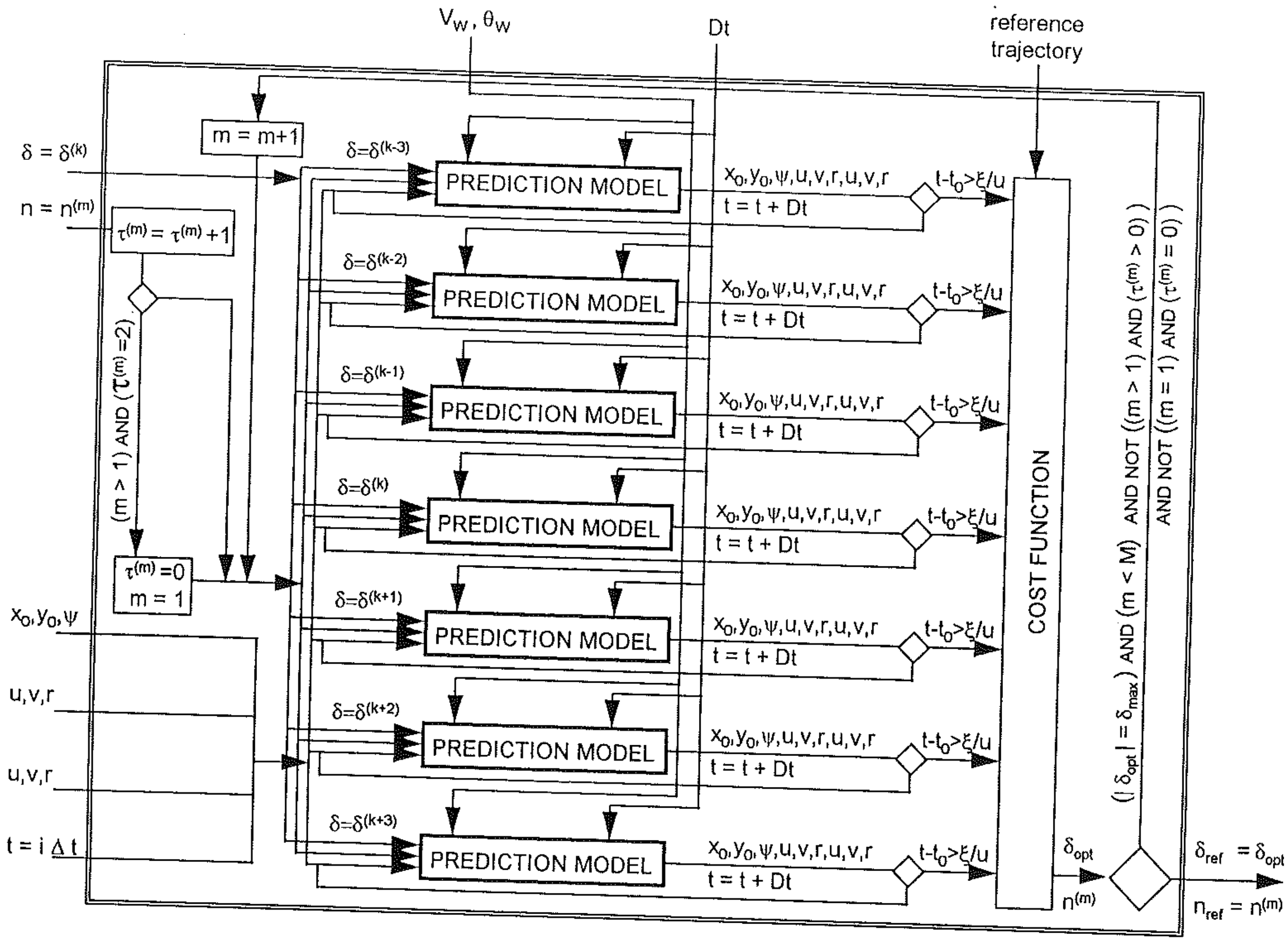

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Figure 4a Autopilot based on cost function : principle

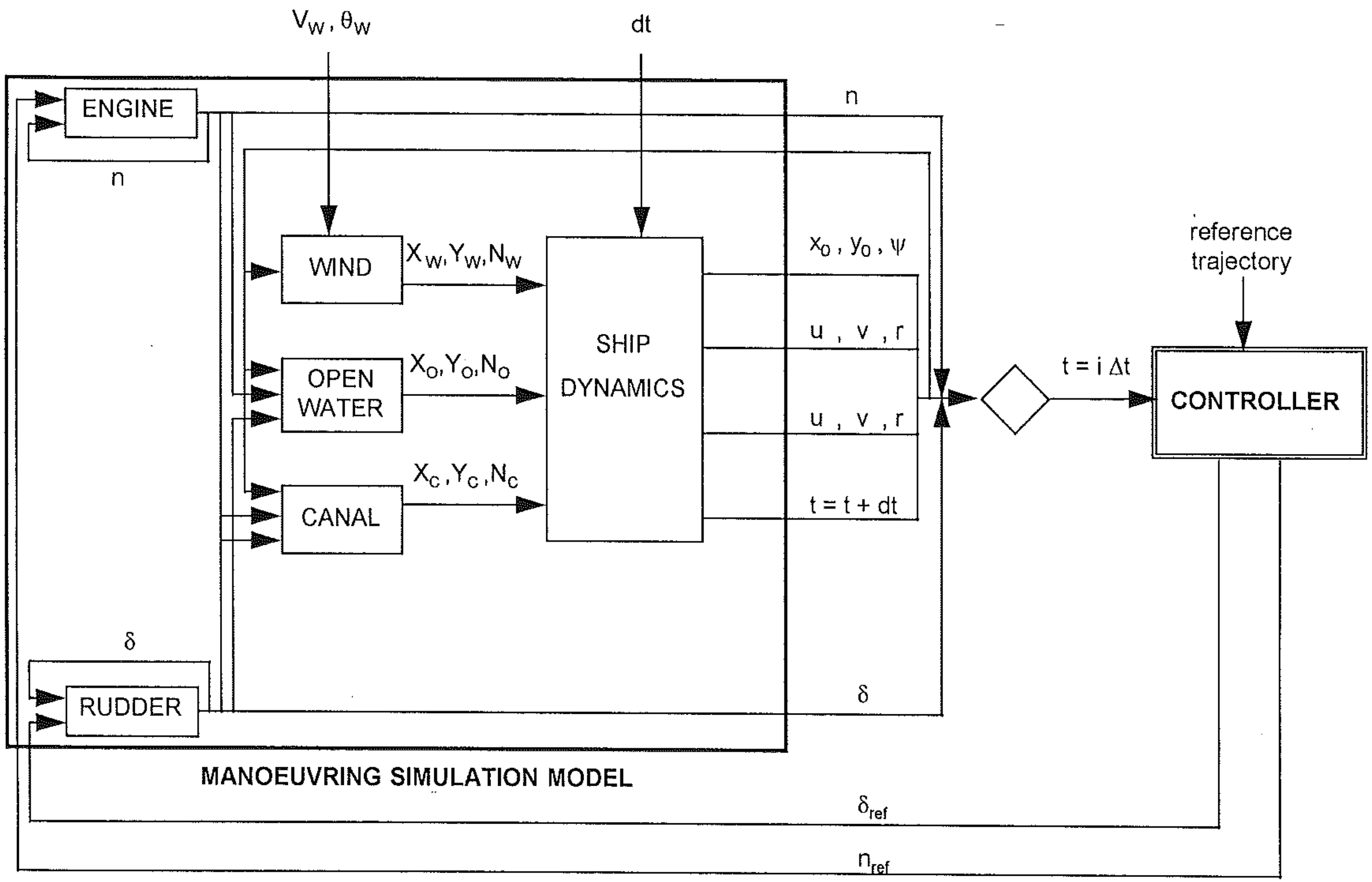

Figure 4b Fast time simulation model

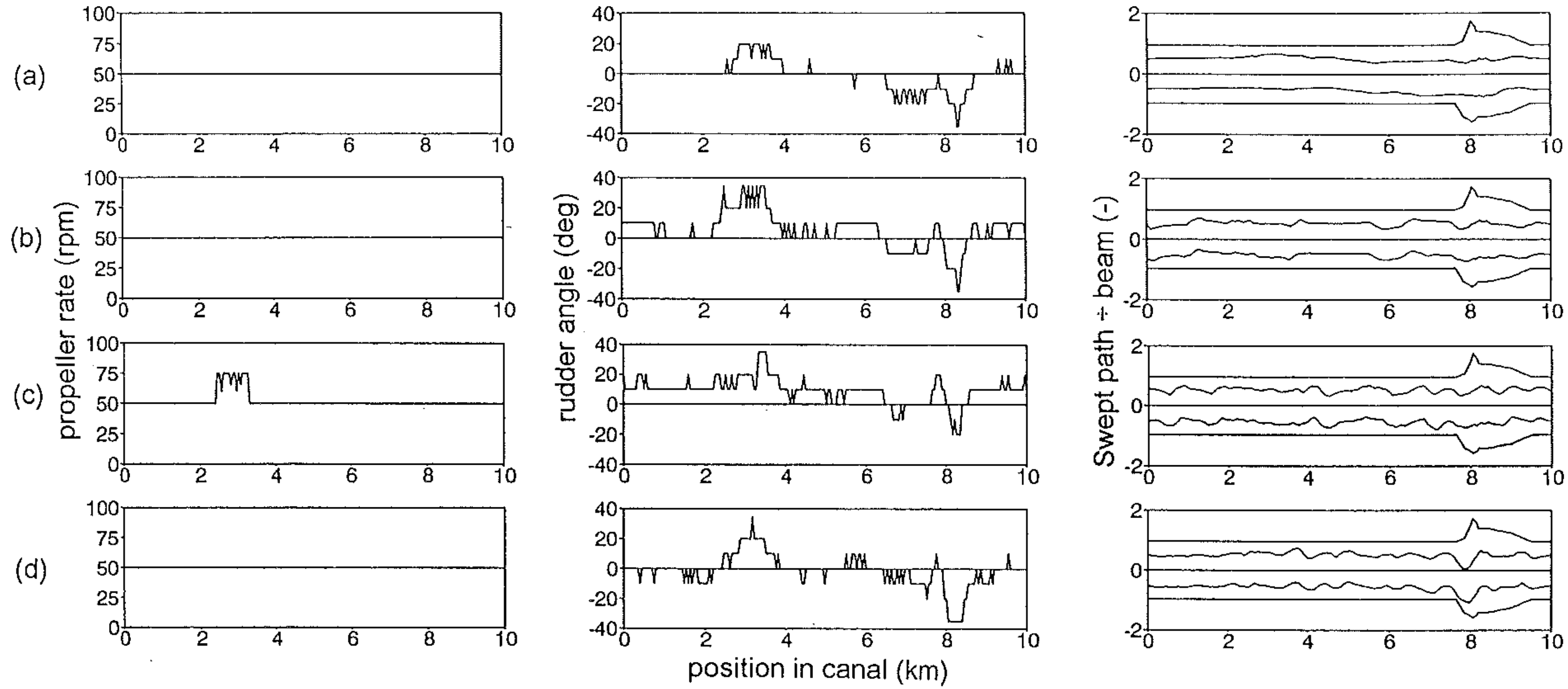

Figure 5 6 Fast time simulation runs with panamax bulkcarrier (L_{oa} = 265 m, B = 32.2 m, T = 12.25 m) controlled by autopilot with perfect prediction model, ξ = 0.8 L. Influence of external disturbances:

(a) no wind, no banks;
(b) no wind, bank effects;
(c) 6 Bf SW wind, bank effects;
(d) 6 Bf NE wind, bank effects.

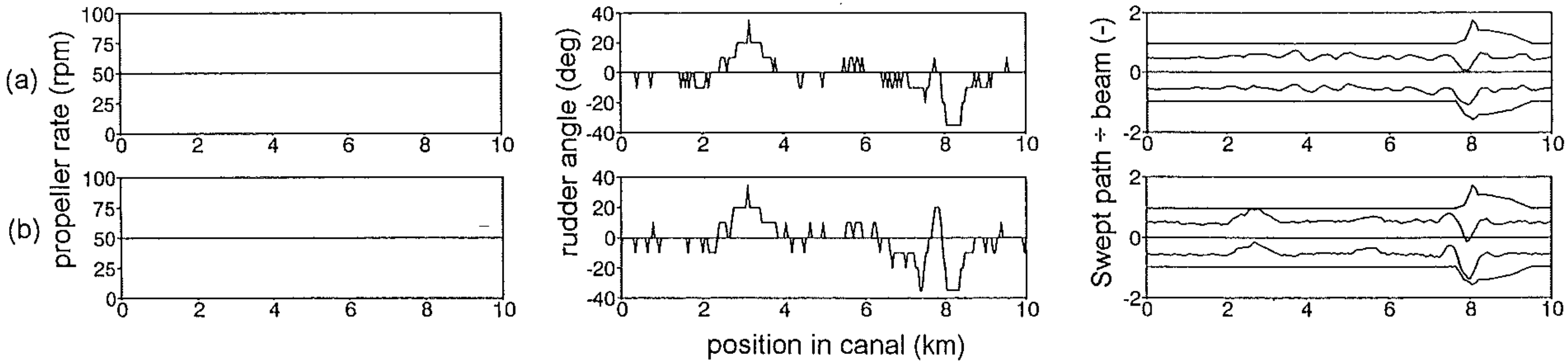

Figure 7 Fast time simulation runs with panamax bulkcarrier (L_{oa} = 265 m, B = 32.2 m, T = 12.25 m) controlled by autopilot at 6 Bf NE wind, ξ = 0.8 L : propeller rpm, rudder angle, swept path as functions of longitudinal position in the canal. Influence of prediction model:

(a) perfect prediction model;

(b) prediction model ignoring both wind and bank effects.

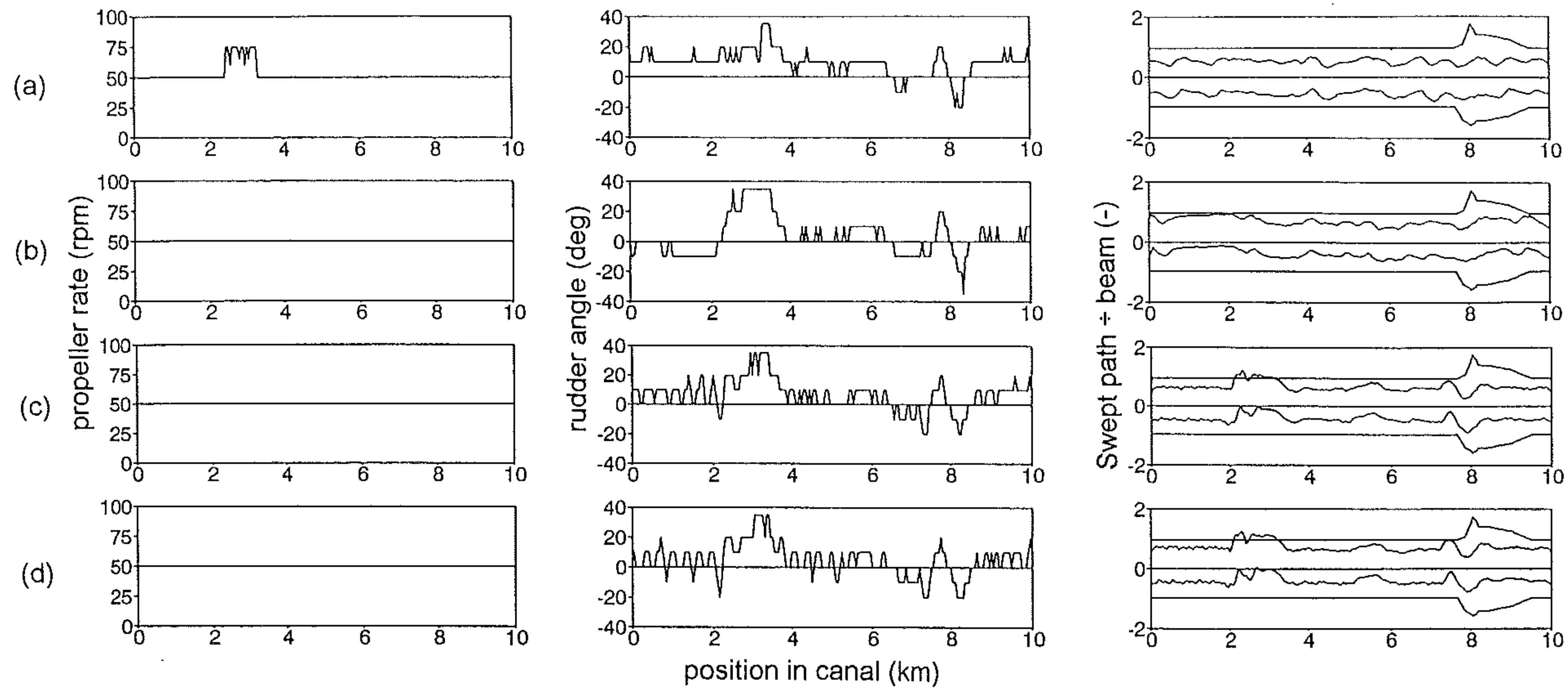

Figure ~~6~~ 7 Fast time simulation runs with panamax bulkcarrier (L_{oa} = 265 m, B = 32.2 m, T = 12.25 m) controlled by autopilot at 6 Bf SW wind, $\xi = 0.8$ L : propeller rpm, rudder angle, swept path as functions of longitudinal position in the canal. Influence of prediction model:

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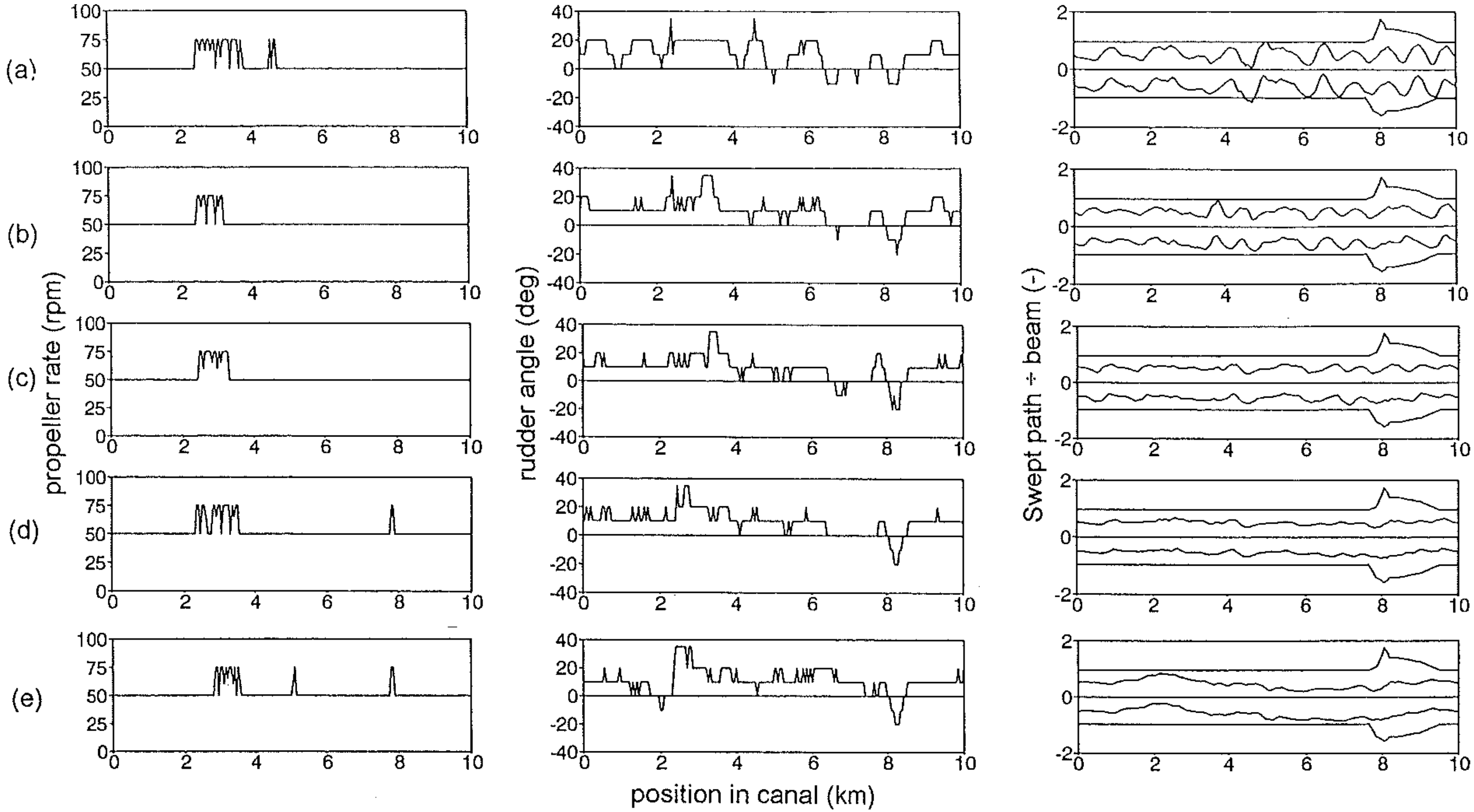

Figure 8 Fast time simulation runs with panamax bulkcarrier (L_{oa} = 265 m, B = 32.2 m, T = 12.25 m) controlled by autopilot at 6 Bf SW wind, perfect prediction model: propeller rpm, rudder angle, swept path as functions of longitudinal position in the canal. Influence of anticipation length: (a) $\xi' = 1.2$; (b) $\xi' = 1.0$; (c) $\xi' = 0.8$; (d) $\xi' = 0.6$; (e) $\xi' = 0.5$.

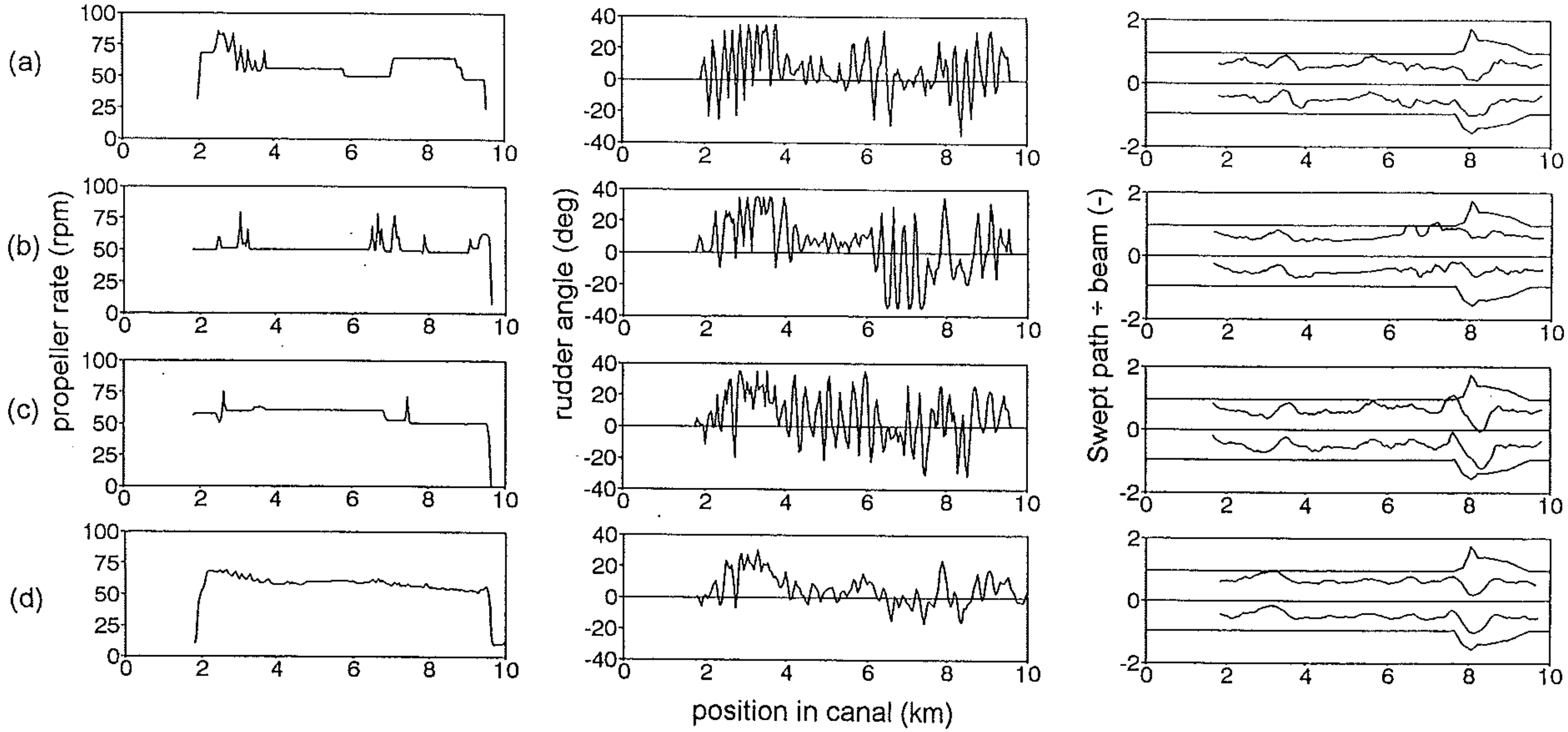

Figure 9 Real time simulation runs with panamax bulkcarrier (L_{oa} = 265 m, B = 32.2 m, T = 12.25 m) controlled by canal pilots at 6 Bf SW wind: propeller rpm, rudder angle, swept path as functions of longitudinal position in the canal.
(a); (b), (c) individual examples;
(d) average values (10 runs).