9. Study on a Computer Aided Manoeuvring System in Harbours

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Summary

In the present report, an attempt is done to develop a computer aided manoeuvring system for ships in harbours. The system contains two main functions. The first, as a planner, supplies a manoeuvring plan to approach to a berth or to depart from a berth. The second, as a operator, makes it possible to operate a ship along the preformed manoeuvring plan. The manoeuvring plan is built, paying full considerations to the practices of human pilots and the principle of "safety first". The system is successfully evaluated to work well by numerical simulations.

1. Introduction

Ship handling in harbours is one of the most sophisticated and complicated control carried out by human operators. When ships approach to berths, they are usually in the most dangerous situation and they need the largest number of operators over their voyages. On the other hand, there have been a remarkable progress in computer techonlogy. The recent computer technology enables us to design a fully automated control system for much complicated problems. Then, it is eagerly requested from the view-point of saving labour and increasing safety to develop an automatic operating system for harbour manoeuvres.

To develop a computer aided manoeuvring system, harbour manoeuvres operated by pilots have to be investigated first, for a pilot is only the controller to be technically and socially approved at the present. In the present report, the pilots' practices in harbour manoeuvres are widely employed. The manoeuvring plans used widely by pilots, the elemental manoeuvres which are the elements of the manoeuvring plans, the practical procedures to keep manoeuvring safety and such are also realized on the base of the observed pilots' practices.

The mathematical models of manoeuvring motions in harbours are necessary too for realizing the control system. Both of shallow water effects and relatively large lateral motions have to be taken into consideration. It is desirable from the view-point of the accurate control to predict fairly well full-scale ship motions by the mathematical model. But, if too complicated mathematical model is utilized, it is not easy to determine the parameters of the model. In the present report, two kinds of mathematical models of manoeuvring motions are utilized. A simplified mathematical model is built in the system for calculating the tragectories of manoeuvring motions in the plan and for estimating necessary control forces at the stage of leading. Besides, a precise mathematical model is employed for the digital simulations to check the effectiveness of the present control system at the final stage of the present study.

The main aim of the present study is to establish the conceptual design for the computer aided manoeuvring system. Accordingly, the main frame of the developed system is merely discussed. To realize the practical system, many sub-systems such as sensor systems, digital communication systems and so on have to be developed, but these are assumed to be given in the present study.

First of all, the basic framework of the

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computer aided manoeuvring system is described. The system builds first the manoeuvring plan for leading a ship from some point to a berth or vice versa and after checking the safety of the plan, the system executes the planned berthing motions. To realize such functions of the system, several concepts are introduced with reference to the practical pilots' operations in harbours.

In the second, the procedure to build the manoeuvring plan is proposed. To build up the plan, a rough manoeuvring pattern is first selected. The pattern is secondly composed of several kinds of simplified manoeuvres, called elemental manoeuvres in the present study. The concept of the elemental manoeuvres is introduced from the view–point to employ practical procedures of harbour manoeuvres by pilots. After setting the pattern, the manoeuvring trajectories are estimated along the pattern by means of numerical simulation. That is to say, the qualitative decision–making such as the selection of manoeuvring pattern is done in advance and the quantitative estimations are carried out in succession.

In the third, the procedure to lead a ship along the preformed manoeuvring plan is expressed. Two kinds of control laws are introduced for leading the ship to the berth along the designed motions and cancelling effects of external disturbances. Finally, to verify the effectiveness of the present system, digital simulations for berthing manoeuvres of a large tanker with assistance of five tugboats are carried out and successful results are shown.

The co–ordinate system utilized in the present study is shown in Fig. 1.

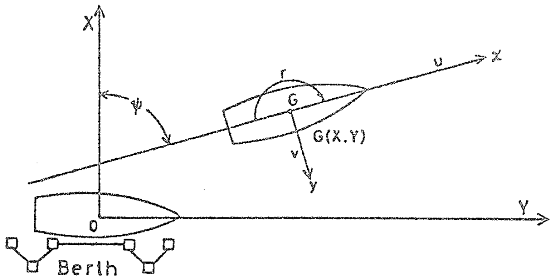

Fig. 1 Co–ordinate system

2. Framework of the Computer Aided Manoeuvring System

The computer aided manoeuvring system is used for leading a ship from some position in a harbour to a berth or vice versa. At present, such operations are carried out by harbour pilots. Then, the short way to realize such an automatic control system is to observe the actual operations by pilots and to transfer the functions of a pilot into a computer system. As the pilot is multi–functional in such operations, many supporting systems are necessary, but the main framework of the system is only discussed here.

2.1 System functions of planning and operating

The computer aided manoeuvring system contains two functions. The one is a kind of planner which makes the manoeuvring plan for leading a ship from some point to a berth or vice versa and the other is a kind of operator which operates the ship along the preformed manoeuvring plan. In the present system, the manoeuvring plan is first built and, after checking the safety of the plan, the operation is carried out along the plan. This idea is convenient for increasing the safety and for preparing the necessary supports such as tugboats, rope–handling boats and so on.

Generally speaking, the automatic berthing may be considered as a kind of the optimal control problem to be solved so that some cost function such as berthing time becomes minimum. It is, however, more important to get familiar behaviour which obeys well various traffic rules and customs than to be optimal, for the manoeuvring safety is of the first importance. It is recommendable from the above reason to employ the idea that a ship is led to a berth along the manoeuvring plan to be confirmed previously its safety.

To generate the manoeuvring plan, the manoeuvring pattern is first selected and the trajectories of ship motions are determined afterwards. That is to say, the qualitative decision–making is done at the first and the quantitative one follows. It is important, as

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mentioned previously, to get a familiar manoeuvring motion, obeying the traffic rules and the customs. The idea to separate the qualitative decision–making from the quantitative one is contributive to it.

Making a further comment, both ideas mentioned above are important from the view–point of employing the procedures of artificial intelligence, such as expert systems in the near future. Generally speaking, the more complicated the layout of the harbour, the traffic conditions, the external disturbances, the traffic rules and such become, the more useful the AI procedures are expected to be. Though the AI procedure is not utilized in the present study, the above idea is important for realizing the practical system with highly intelligent capability in decision–making.

2.2 Cares for the principle of "safety first"

Generally speaking, the principle of "safety first" is considered most important in ship operation. There may happens a trouble on a ship's engine, a steering gear, tugboats and so on, or a strong gust of wind may affect seriously a ship near a berth. Accordingly, an actual pilot pays, every time and everywhere, a full attention for ship's safety by every conceivable means. This is one of the most important base of seamanship. The present problem is how to introduce this principle into the computer aided manoeuvring system.

To find practical considerations for safety, many manoeuvring plans in Japanese ports were investigated and pilots' practices for safety were summarized.[1),2)] On the other hand, some considerations are necessary from the viewpoint of solving easily the present control problem. Taking both into consideration, the following two countermeasures for safety are employed in the present study.

The one is the idea of "false goal". It is pointed out from the observation on many manoeuvring plans in Japanese harbours that ships seem to approah once some point located in front of berth and not directly to the real berth. The point is callled as a false goal in the presente study. There is a enough safety distance between the false goal and the berth. When some trouble happens in approach, the distance can prevent the ship from a fatal accident.

Besides, the ship stops once at the false goal. Her heading is adjusted parallel to the berth and her longitudinal position is also adjusted just in front of the berth. Accordingly, if the ship moves only to the lateral direction, she can reach just to the berth. Generally speaking, the number of freedoms in harbour manoeuvres is three and it is not easy to adjust the three motions at a time. The main manoeuvring motion after the false goal is, however, considered to have only one freedom and it can be easily controlled with an enough accuracy.

The other is to keep an enough margin in a control force. If the manoeuvring motions in the plan are estimated by using the half of utilized control forces, a fatal accident such as crush to a berth may be avoided by the use of full power. It is pointed out from the observation on harbour manoeuvres that pilots never use the full power of the control devices near a berth. They usually order "half", "slow", "dead slow" to the control devices. The order of "full" is for the emergency. The margin in the employed control force is very effective for the emergency.

The above two concepts for manoeuvring safety are employed in the present study. It is pointed out that these bring no additional difficulty for solving control problems and it is also convenient that the amount of the safety distance and the margins in control forces can be adjusted according to the level of expected troubles.

3. Procedure to Build Manoeuvring Plan

Pilots build roughly their manoeuvring plans before starting to approach to a berth. In the present system, the manoeuvring plan from some point in a harbour to a berth is first built. The procedure for making the manoeuvring plan is expressed here.

The manoeuvring plan is built through the following two steps. The first is to choose a

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suitable manoeuvring pattern and the second is to estimate the trajectories of ship motions along the pattern. That is to say, the qualitative decision–making is first done and the quantitative one next.

3.1 Determination of the manoeuvring pattern

It is first pointed out that the manoeuvring pattern depends on the level of control devices. For example, the manoeuvring pattern is very complicated for the ship with her own propeller and rudder and without sidethrusters and tugboats. For such a ship have no means to supply an enough lateral force on her fore body and she is sometimes compelled to use the effects of wind, current and reversing propeller for getting the lateral force. On the contrary, the patterns are rather simple for the ship which can get many effective supports from tugboats. Then, it is concluded as mentioned previously that the manoeuvring pattern have to be individually determined, depending on the level of control devices.

The manoeuvring patterns are now discussed for a tanker assisted by five tugboats. Fig. 2 shows the typical manoeuvring patterns for a tanker in a port with a relatively wide waterway in front of a berth. In both shown in Fig. 2, the ship approaches once to the false goal and after stopping there, moves again to the real berth. The manoeuvring patterns from the starting point to the false goal depend on the conditions in the harbours, especially on the distance between both points. In the pattern (1), the ship approaches to the false goal by shifting her position to the false goal and adjusting her heading parallel to the berth at the same time. In the pattern (2), the ship turns first to the false goal, runs ahead to the false goal, stops at the false goal and adjusts finally her heading parallel to the berth. The pattern to be employed can be selected by considering the distance or the traveling time between both points. The pattern (1) is applied for the case that the above distance is short and the pattern (2) is for the long distance.

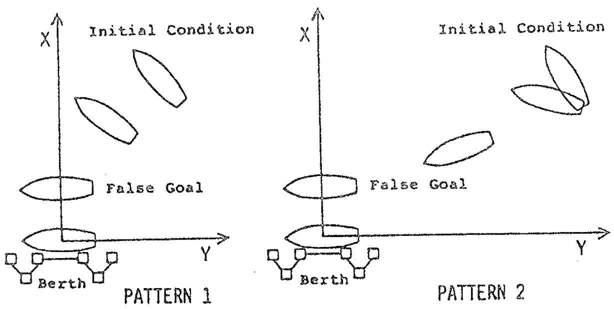

Fig. 2 Typical patterns for approaching to berth

It is now assumed to choose the pattern (2) and to use five tugboats as control devices. The arrangement of the tugboats are shown in Fig. 3. In this case, two tugboats are stationed at the fore position and the aft for supplying the lateral forces to the ship and a tugboat is placed at the midship for the longitudinal force.

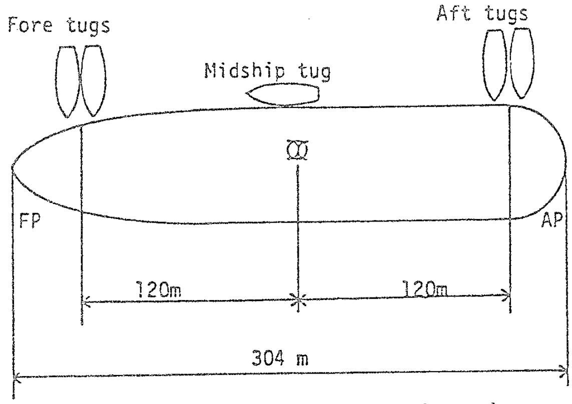

Fig. 3 Arrangement of 5 tugboats for tanker

In the pattern (2), the ship is first turned for facing to the false goal. If the turning angle is large, both of the fore and aft tugboats are ordered to work for turning. After the angle decreases to some level, the aft tugboats are stopped and the fore ones continue to push for both of turning and accelerating the ship to the false goal. After the ship faces roughly to the false goal, the midship tugboat starts pushing the ship to the false goal and the tugboats for lateral forces brakes the ship to turn. At the next stage, the ship approaches to the false goal, keeping her heading or course line by the fore and aft tugboats and adjusting her longitudinal speed by the midship tugboat. After reaching near the false goal, the midship tugboat starts decelerating the ship and the

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fore and aft ones adjust her heading parallel to the berth. After adjusting her longitudinal position and heading, the fore and aft tugboats start pushing the ship to the berth and the midship one adjusts her longitudinal position. Near the berth, the ship is decelerated and finally stopped just in front of the berth. The above is the story to lead the ship to the berth.

To complete the manoeuvring pattern as shown in the above story, the procedures to manoeuvre a ship in a harbour have to be given by a computer. Manoeuvring motions of ships operated by pilots in Japanese harbours have been analyzed by the authors. The results of the analysis show that the manoeuvring motions observed in harbours are divided into elemental motions which have relatively simplified aims. The elemental motions observed there are separated into several kinds, such as course–keeping, course–changing, turning without a longitudinal speed and drifting. In other words, a series of manoeuvring motions from some point to a berth can be composed of the above elemental manoeuvres[2).

Pilots realize the elemental manoeuvres, taking both of ship manoeuvring characteristics and procedures to operate control devices into consideration. Every elemental manoeuvre have many varieties, depending on the differences in the control procedures. The authors tried to specify the varieties, being based on the observed harbour manoeuvres by pilots and the theoretical consideration on ship manoeuvrability. To generate the manoeuvring plan, the varieties of elemental manoeuvres are built in a computer system. It is needless to say that the control procedures are determined by choosing elemental manoeuvres, for the procedures to handle control devices are stored as the specifications of elemental manoeuvres in a computer system.

3.2 Estimation of the manoeuvring trajectories

After completing the manoeuvring pattern, the trajectories of the manoeuvring motions are estimated. To estimate them, the control laws have to be determined. In the present study, the the previously mentioned idea of the elemental manoeuvres is employed for the purpose. For the control laws are programmed for every elemental manoeuvre in the computer system.

To estimate the trajectories of manoeuvring motions, the mathematical model of manoeuvring motions have to be employed.

$$m(\dot{u}-vr)=\frac{\rho}{2}L^3g(-m_x{}^*\dot{u}^*+m_y{}^*v^*r^*+X_{|u|u}{}^*|u^*|u^*+X_{tug}{}^*+X_e{}^*)$$

$$m(\dot{v}-ur)=\frac{\rho}{2}L^3g(-m_y{}^*\dot{v}^*-m_x{}^*u^*r^*+Y_{|v|v}{}^*|v^*|v^*+Y_{tug}{}^*+Y_e{}^*)$$

$$I_{zz}\dot{r}=\frac{\rho}{2}L^4g(-J_{zz}{}^*\dot{r}^*+N_{|r|r}{}^*|r^*|r^*+N_{tug}{}^*+N_e{}^*)$$

tug : tug force
e : external disturbance

where

$$m_x{}^*,\ m_y{}^*=m_x,\ m_y/\frac{\rho}{2}L^3g,$$

$$J_{zz}{}^*=J_{zz}/\frac{\rho}{2}L^5g$$

$$u^*,\ v^*=u,\ v/\sqrt{Lg}\ ,\ r^*=r/\sqrt{g/L}$$

$$\dot{u}^*,\ \dot{v}^*=\dot{u},\ \dot{v}/g,\ \dot{r}^*=\dot{r}L/g$$

If a detailed model is used, the manoeuvring motions can be estimated with good accuracy. It is, however, not easy to develop such a model without a lot of cost and time. The above simplified model is now utilized.

The concept of safety margin in control power was introduced previously from the view–point of safety. If the half of the full control power is considered as a margin, the manoeuvring motions to be induced for approaching to the berth have to be restricted so that the ship speed can be decreased to zero before some expected stopping–points by the half braking power. The expected stopping–points mean a false goal, a berth, shallow places

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and such. The problem is how to estimate such manoeuvring motions. Fig. 4 shows the phase plane trajectory of ship motion to be braked by the half power Th and Ps is the distance that the ship with some speed v runs before stopping. The above means that the ship with the speed v at P is equivalent to the ship with zero speed at Pe=P+Ps. Such a point Pe is called an equivalent point in the present study. The relation between v and Ps can be easily estimated by the mathematical model of manoeuvring motions. In the present study, the position to be stopped, named Po, is considered as a kind of false goal with some safety distance from real dangerous points. It is accordingly concluded that the manoeuvring trajectories are estimated by applying the bang–bang control law or the quantized linear control law with respect to the distance (Po−Pe).

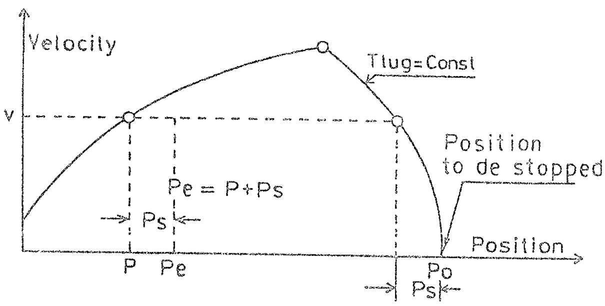

Fig. 4 Concept of equivalent position

The manoeuvring motions are the coupled ones of shifting in two directions and turning. In the present study, however, the above control laws are individually applied to each motion at the first stage. The errors to be arisen by neglecting the coupled characteristics are taken into consideration at the next stage of calculations and the final trajectories are given by a sort of iteration procedure. The example of estimated path and time–histories of three motions are given in Fig. 5 and Fig. 6.

After building the manoeuvring plan, its safety in forecasted environmental conditions have to be checked. If the margin in cotrol forces is estimated to be less from the expected level, the number of tugboats have to be increased, or the allowable limits of external disturbances have to be set lower.

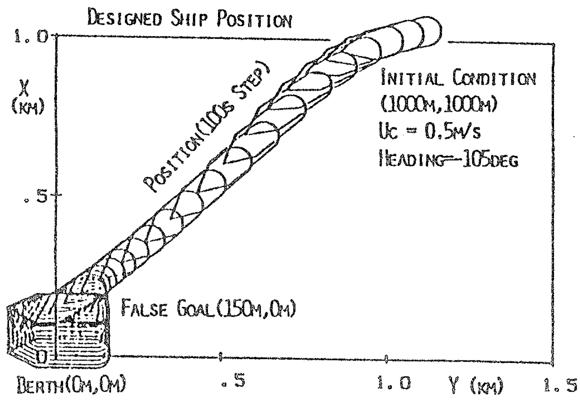

Fig. 5 Example of designed path to berth

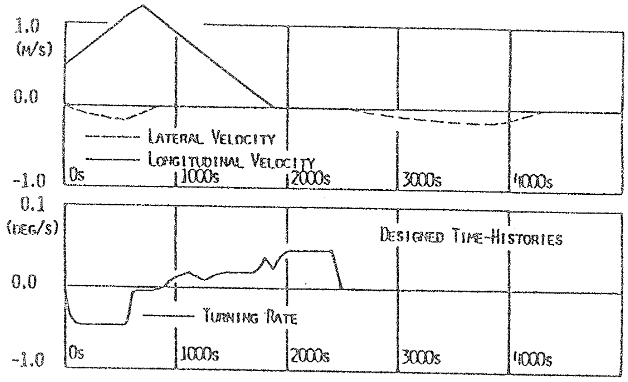

Fig. 6 Example of designed time–histories of ship

4. Procedure for Leading Ship to Berth

After a ship arrives at some point in a port and the conditions of environments, control devices and so on are checked, the system starts to lead a ship to a berth. It is of course that the safety is examined, step by step and time after time, after starting to lead. Though these problems for safety are important, further discussions are omitted on account of limited space. In the present system, the ship is led along the plan to be built previously. The problem is the control law to lead the ship to the berth. Fig. 7 shows the control algorithm employed in present study. The feedforward control is first employed for cancelling the effects of external disturbances and for leading the ship to the planned point.. The linear feedback controls with respect to the errors in positions and velocities are also utilized.

A simplified mathematical model of manoeuvring motions is used for estimating the control forces to be supplied to the ship. The

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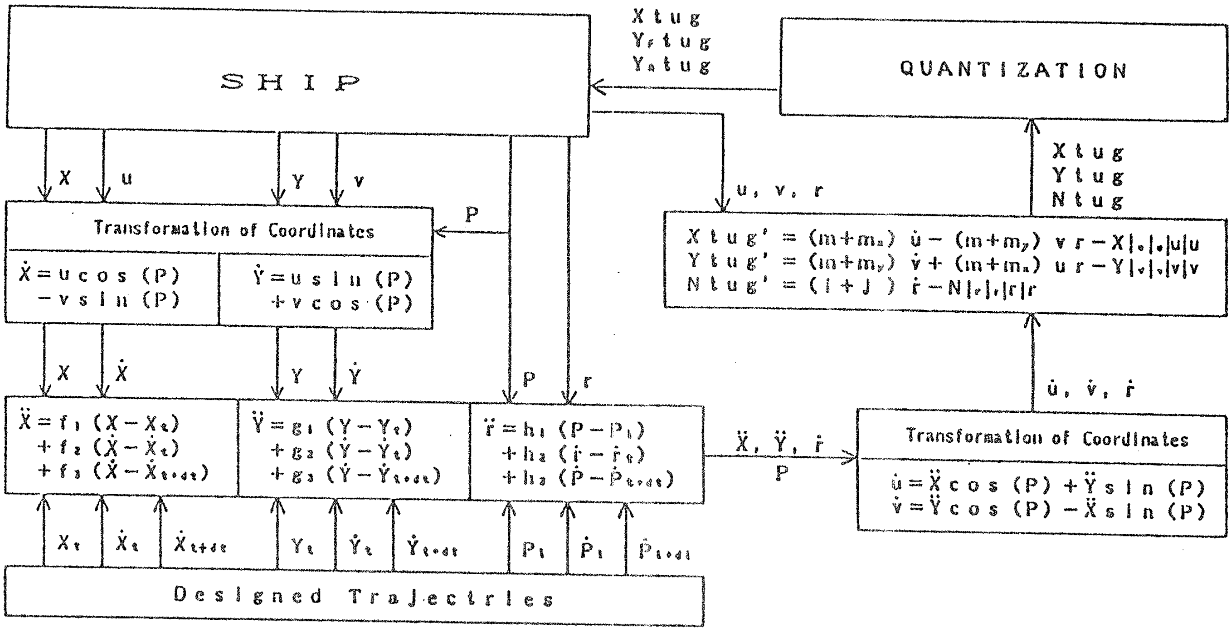

Fig. 7 Control system diagram for leading ship along planned motions

same model used in planning is utilized again. As the large tanker is taken into consideration as a example, it is assumed, as mentioned previously, to supply all of the control forces by five tugboats in the present study. The typical arrangement of tugboats was given in Fig. 3. It is assumed that the maximum towing or pushing force of each tugboat is 50 tons and the output of 1/1, 1/2, 1/4 and 1/8 of the maximum force can be ordered in the special quantized form.

Taking the above into account, the system estimates the longitudinal and lateral forces and the moment to be supplied by tugboats. The forces and the moment are finally converted into the individual forces of five tugboats.

5. Simulations of Berthing Manoeuvres of Tanker

The main aim of the present study is to develop the conceptual design for the computer aided manoeuvring system. To examining the effectiveness of the present system, simulation studies on the berthing manoeuvres are carried out.

The detailed mathematical model of manoeuvring motions is employed for the simulations. The model is modified a little from the well–known MMG model for covering manoeuvring motions in harbours and shallow water effects on hydrodynamic forces acting on a ship are taken into account[3].

$$m(\dot{u}-vr)=\frac{\rho}{2}L^3g[-m_x{}^*\dot{u}^*+(X^*{}_{vr}+m_y{}^*)v^*r^*+X_{|u|u}{}^*|u^*|u^*+X_{vv}{}^*u^*v^{*2}/U^*+X_{tug}{}^*+X_e{}^*]$$

$$m(\dot{v}-ur)=\frac{\rho}{2}L^3g[-m_y{}^*\dot{v}^*-m_x{}^*u^*r^*+Y_v{}^*U^*v^*+Y_{|v|v}{}^*|v^*|v^*+Y_r{}^*r^*+Y_{ur}{}^*u^*r^*+Y_{vvr}{}^*v^{*2}r^*u^*/U^{*2}+Y_{tug}{}^*+Y_e{}^*]$$

$$I_{zz}\dot{r}=\frac{\rho}{2}L^4g[-J_{zz}{}^*\dot{r}^*+N_{uv}{}^*u^*v^*+N_r{}^*r^*+N_{rrr}{}^*r^{*3}+N_{ur}{}^*u^*r^*+N_{vvr}{}^*v^{*2}r^*+N_{tug}{}^*+N_e{}^*]$$

where

$$U^{*2}=u^{*2}+v^{*2}$$

Berthing manoeuvres of the typical large

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tanker was simulated. Five tugboats were employed to help the tanker. Actual depth of the waterways was taken into consideration but external disturbances were not. It was assumed that the positions and the velocities of the tanker were measured without any noise.

Fig. 8 shows the results of the simulations and Fig. 9 gives the time histories of the berthing manoeuvres. The manoeuvring plan to be previously built is shown in Fig. 5.

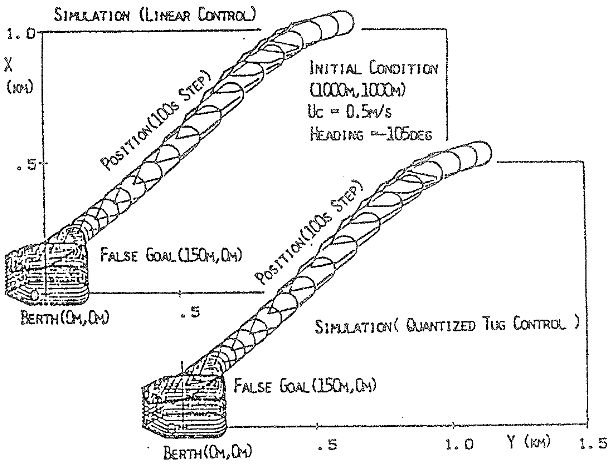

Fig. 8 Examples of simulated path of tanker controlled by present system

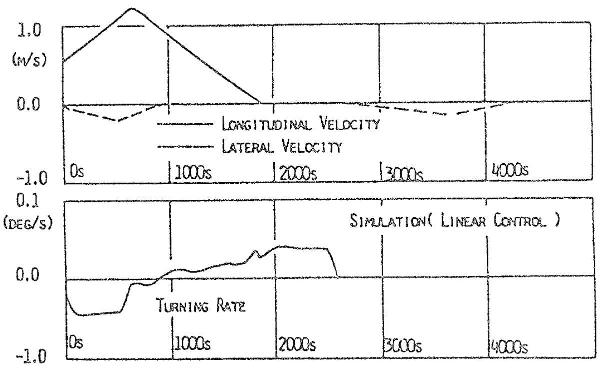

Fig. 9 Example of simulated time—histories

It is pointed out from the above results that the present system can lead successfully the tanker to the berth. Though many subsystems have to be developed for realizing the practical manoeuvring system, the basic idea of the present study is proved effective. There is, however, a few problem to be considered. The one is the procedure of feedback control. In the present study, the control errors are defined in the space co—ordinates. The hydrodynamic properties of a ship are, however, determined in the co—ordinates fixed to the ship. As the gains of feedback controls have close relations with the manoeuvring properties of the ship, the present procedure to define the control errors should be modified. The other is related to the mathematical models of manoeuvring motions. The simplified mathematical model was utilized in the computer aided manoeuvring system from the practical view—point and the detailed model was for the simulations. The effects of the differences between both models are cancelled by the feedback controls in the present system. Further considerations on the allowable simplification for the model built in the control system may be necessary, for there may be some limits for the allowable values of feedback gains.

6. Conclusions

In the present report, an attempt was done to develop the computer aided manoeuvring system. The system contains the following two functions. The one is the planner which makes the manoeuvring plan. The planner was designed from the view—point that the functions of human pilots were built in the computer system. The other is the operator which lead a ship from some point to the berth. In the operation, both of feedback and feedforward controls were employed. It can be successfully pointed out from the simulation studies that the basic idea of the present system works well for the berthing manoeuvres of a large tanker.

To realize a practical control system, efforts are requested for establishing a highly intelligent decision—making system by the employment of artificial intelligence technique and for developing many sub—systems.

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