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Signal processing in the hydroacoustic ships berthing aid system

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The berthing of ships is an extremely complicated task that requires decisions on the movement of ships based on a large number of variables: tide, wind, visibility, speed, distance from jetty. Particular difficulties are related to the less maneuverable ships such as very large crude carriers. The presented hydroacoustic ships berthing aid system measures four distances of a ship to the jetty using the sonar echo method. The system computer calculates the bow and stern speed and distances to dolphins from the measured data. The results obtained are simultaneously presented on a large, high luminance display as well as printed out and recorded on computer discs. Additionally the dolphins displacements are measured and the data obtained together with its statistical parameters are recorded.

INTRODUCTION

A ship's berthing maneuver that is performed incorrectly may end in a collision or even a disaster with the vessel itself possibly damaged or both the vessel and the berth. The risk of a collision goes up as the mass of the ship increases. A big ship that hits the berth at a speed even less than 10 cm/s can cause a serious collision. Another action that should be avoided upon berthing are rapid maneuvers of the screw propeller and tubular rudders as they bring about a change of the bottom configuration and weaken the structure of the berths. These risks can be avoided if the pilot in charge of the entire maneuver knows the distance between the ship and the berth as well as its speed. This information is provided by special berthing systems installed at harbor berths. They are laser, radar or hydroacoustic systems. Hydroacoustic systems are most frequently used because of their flawless operations regardless of the atmospheric conditions (fog, rain, snow storm) and do not pose a risk to people's health. Irrespective of the physical principle of the system's operations, the results of distance and speed measurements are shown on a large luminescent display that is visible for the pilot from the bridge of the maneuvering ship.

This article presents a hydroacoustic ships berthing aid system developed and made by the Department of Acoustics at the Technical University of Gdansk and the SONEL company. The system is installed and operated at two berths of the Port Północny in Gdańsk.

THE PRINCIPLES OF THE SYSTEM'S OPERATIONS

Four ultrasonic transducers that are placed at specific points along the berth line (Fig.1) consecutively send out acoustic sounding pulses that are generated in the transmitter. These pulses are reflected from the ship's side and are received by the system's receiver as echo pulses. The receiver measures delay times t_i between the known moments of sending out souhding pulses and the moments of receiving echo pulses. Given the speed of the acoustic wave propagation c, the computer computes the distances d_i between the ship's side from i - of the transducer: $d_i = 0.5\, ct_i$.

This simple principle of the system's operation gets complicated in practice which is a consequence of the required high accuracy of measurements and the acoustic disturbances in the system. The required accuracy of measuring the distance is Δ=10cm and the accuracy of the speed measurement is Δv=1cm/s. As results from the above in order to determine the speed at the necessary accuracy, the time interval

Δt=10s is needed. However, the results of speed and distance measurements should be given approximately every second. Consequently it is necessary to increase the accuracy of the distance measurement (Δd=1cm at best) and/or use methods of data processing that increase the accuracy of the measurements. In the system in question both possibilities were used.

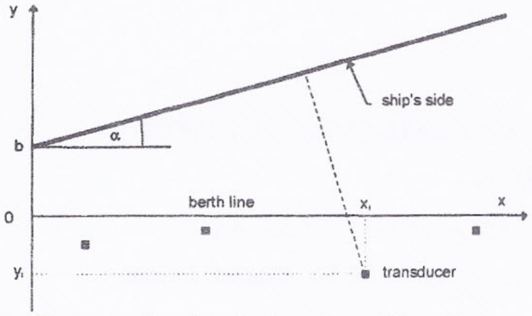

Fig. 1. Diagram showing the location of the ship's side in relation to the transducers and the berth.

In order to achieve high accuracy of the distance measurement what is necessary is a respectively accurate measurement of time t_i and accurate information on the acoustic wave velocity c. High accuracy of the measurement can be obtained by minimizing the sampling period (in the system in question it is 20μs which is equivalent to the resolution of the distance at about 15mm) and by employing a special method of detecting the leading edge of the echo pulse. The method:

- detects the echo pulse of a maximum energy and maximum slope of the leading edge (echo reflected against the ship's side has the highest energy of all other echoes which can be seen in Fig. 2,
- determines the minimal and maximal value of the slope,
- determines the detection threshold as the mean value of the measured extremes,
- determines the time moment when the slope of the echo pulse exceeds the detection threshold.

The velocity of propagation c is determined on the basis of the measurement of the time of echo reception from the target situated at a known distance from one of the ultrasonic transducers. Measurements taken when the ship was still, when the echo was reflected from a flat ship's side and with no propagation noise present, showed that the measurement error of the distance is about 3cm. If the measurement is taken during the ship's maneuvers, the error can increase significantly.

This is caused by the curvature of the hull and interferences evoked by the operation of the screw propeller, tubular rudders, harbor tugs participating in the maneuvers and a non-laminar flow of water around the hull. Fig. 3 shows an example of a measurement of the velocity and the distance between the ship's side and one of the ultrasonic transducers. The figure shows dispersed results of the measurement which in this case were observed when tubular rudders were on. This is a typical situation that was registered during a berthing maneuver performed by a small ship without help from tug boats.

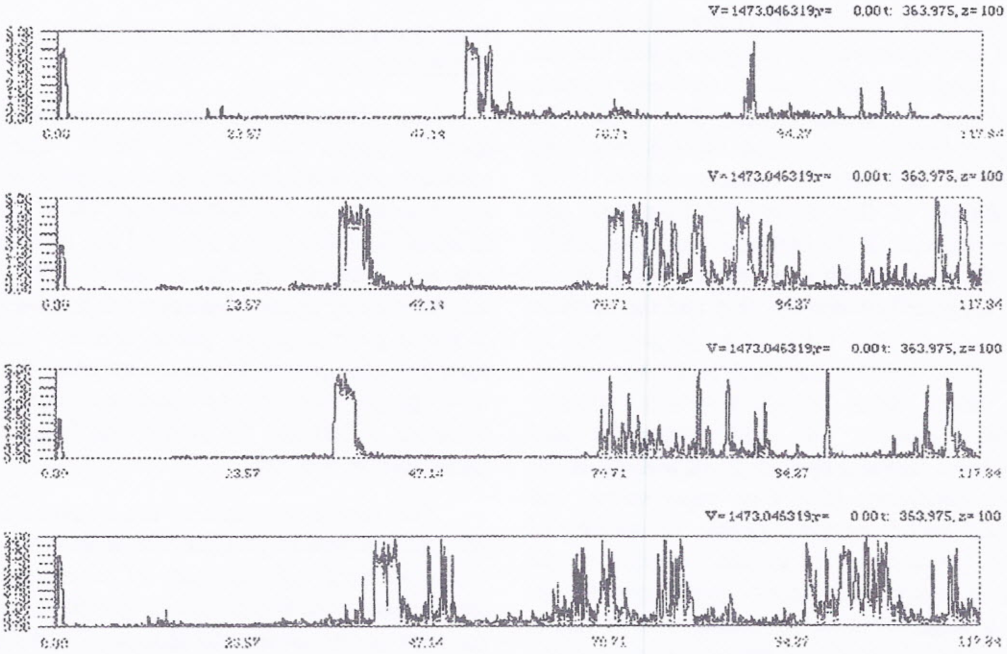

Fig. 2. Echo signals from the ship's side.

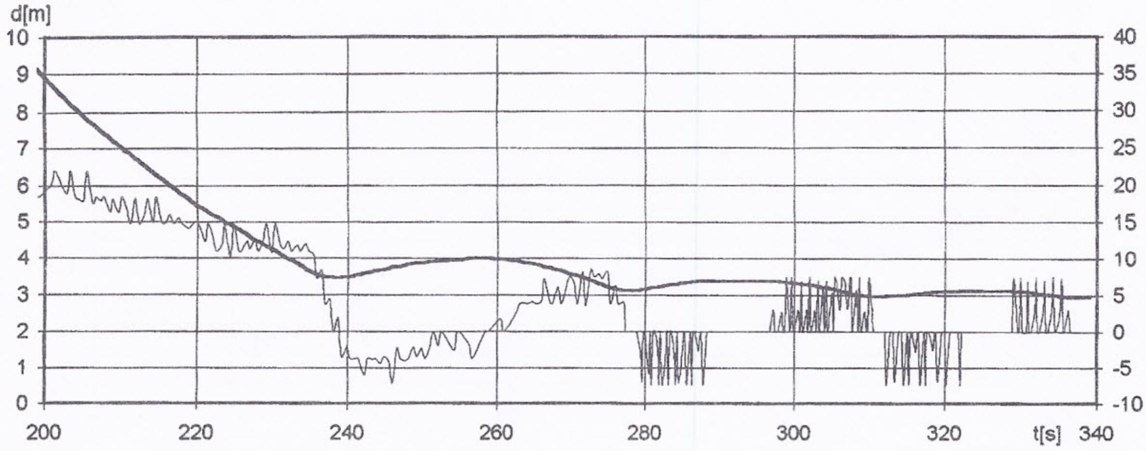

Fig. 3. Distance (*heavy line*) and velocity (*fine line*) of a selected point at the ship's side.

To change the dispersion of the distance and measurement results a method of forming regression line was employed; its position determines the most probable position of the ship's side.

Let us assume that the straight line equation is $y = ax + b$ and that its slope in relation to the berth is at an angle α. Geometric relations shown in Fig.1 show that the distance δ_i of the i-th transducer from the straight line y is:

$$\delta_i = x_i\cos\alpha + (b + y_i)\cos\alpha$$

The difference between the measured distance d_i from the actual distance δ_i is the measurement error Δ_i. The straight line should be drawn in such a way so that the mean square dispersion of the measurement errors is the smallest. By marking:

$$\Delta^2 = \sum_{i=1}^{4} \Delta_i^2$$

and differentiating dispersion Δ in relation to b and α we obtain a set of two equations with two unknowns b and α. As the result of solving these equations we obtain:

$$2D\sin^2\alpha - B\sin\alpha + \cos\alpha(A + C\sin\alpha) - D = 0\,,$$

where $A=4D_x - DX$, $B=4D_y - DY$, $C=4Y_2-4X_2+X^2 - Y^2$, $D=4X_y - XY$ and

$$X = \sum_{i=1}^{4} x_i \quad Y = \sum_{i=1}^{4} y_i \quad D = \sum_{i=1}^{4} d_i \quad D_x = \sum_{i=1}^{4} x_i d_i$$

$$D_y = \sum_{i=1}^{4} y_i d_i \quad X_y = \sum_{i=1}^{4} x_i y_i \quad X_2 = \sum_{i=1}^{4} x_i^2 \quad Y_2 = \sum_{i=1}^{4} y_i^2$$

The above trigonometric equation is first solved as a square equation, assuming that $\cos\alpha=1$. The obtained angle α is substituted into $\cos\alpha$ and the solution of the square equation is repeated. After two such operations the error of the solution can be ignored. Given the angle α, $a=\text{tg}\alpha$ is computed and finally:

$$b = \frac{D - X\sin\alpha - Y\cos\alpha}{4\cos\alpha}$$

Using the straight line equation $y=ax+b$ the distances between the ship's side and the dolphin are determined. These distances are given on a display and used to determine the speed at which the ship is nearing the dolphins. Fig. 4 shows the velocity and the distances between the ship's side and the dolphins computed on the basis of regression line. For the purpose of a better comparison of the effects of error minimization, diagrams in Fig. 3 and 4 are based on the same maneuver of berthing. As you can see the diagrams obtained from a regression line are smoother and consequently with smaller errors.

The benefits of this regression line are even more evident on diagrams of the ship's speed. Despite a significant reduction of the errors, the dispersion of speed measurements continues to exceed the required limit of $\Delta v=1\text{cm/s}$. To reduce the speed measurements errors further, the method of a double averaging of the measurement results was used. The averaging is the following:

We mark i-th speed determined on the basis of simple regression as v_i. The first cycle of averaging is done according to the formula:

$$v_n = \sum_{i=n}^{i=n+N} v_i$$

where N is the number of measurements being averaged.

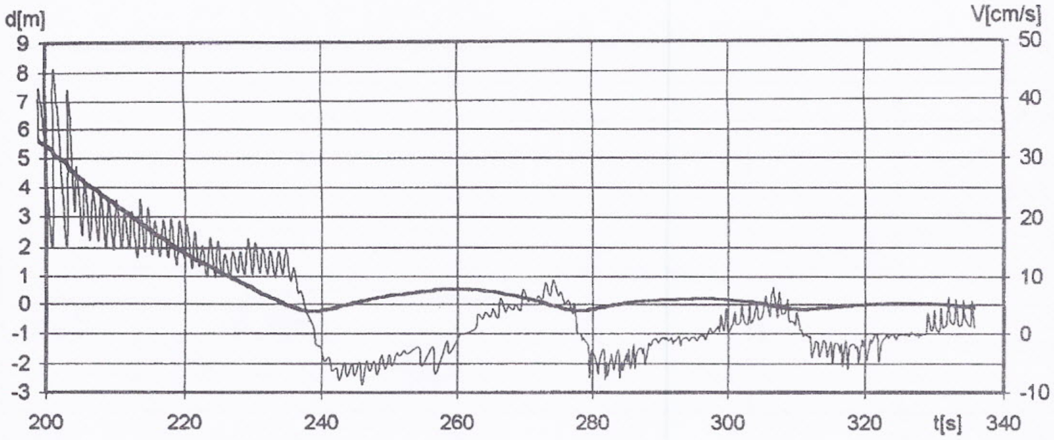

Fig. 4. Distance and velocity of the ship computed on the basis of regression line.

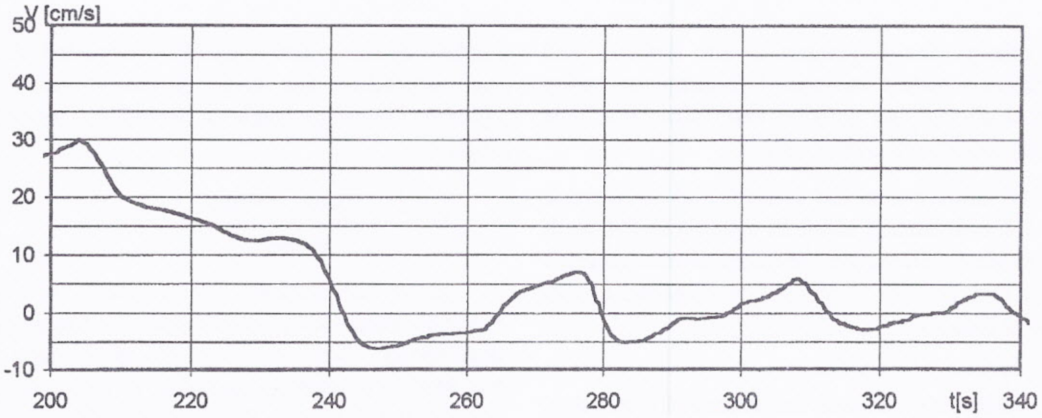

Fig. 5. Diagram of an averaged velocity of the ship's side.

In the second cycle we compute:

$$v_m = \sum_{n=m}^{n=m+M} v_n$$

where M is the number of speeds v_n being averaged.

A disadvantage of this averaging method is a delay in the exposition of the results in relation to the time of the measurement and - as has been found - a slight bias of the speed estimate. Positive effects are visible in Fig.5 which shows a diagram of the ship's speeds relating to the above example of a maneuver.

PREVENTING PROPAGATION INTERFERENCES

In the majority of maneuvers the above procedures are quite successful. The errors of measurements fit within the demanded ranges, and the results shown on the display are a solid picture of the actual parameters of the ship's movements. Sporadically, however, there are some situations where these procedures fail. They happen practically in the case of small and not loaded ships using their own propulsion during maneuvers. Even though such vessels do not pose any risks to berths, additional procedures were accounted for which help to expose insufficient data on their movement. And so in the case when no data is available from the extreme end transducers or in the case of data loaded with too big errors, the system determines the distances exclusively on the basis of measurements from two middle transducers. For obvious reasons the determined regression line does not minimize the errors of the measurements then. In spite of that the results of the measurements are displayed, however with a warning for the pilot in the form of pulsating digits which define the speeds of the bow's and strn's movement. When the measurements from three transducers carry extensive errors, only the distance and speed from the dolphin next to the transducer is calculated. The display shows pulsating information about the movement of the bow only or stern only.

During the measurements, sometimes momentary outages of the signals or a short-term increase in the errors are observed. Then the system

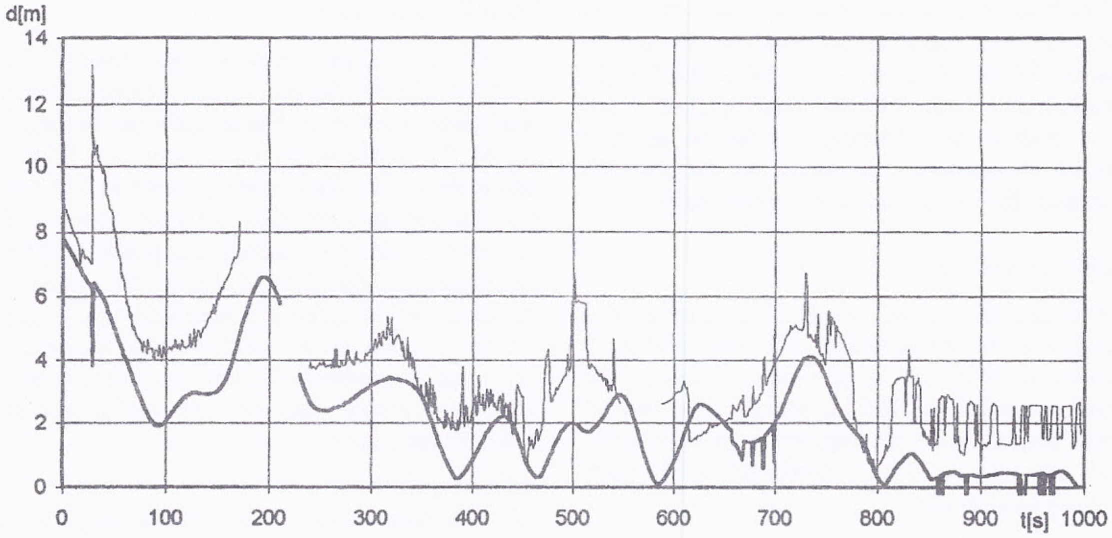

Fig. 6. Effect of strong propagation disturbances

realizes a short-term prediction of the ship's movement and the display shows projected distances and speeds of the bow and stern. If this state continues beyond the possible limit, the system enters procedures that were allocated for strong and long disturbances. An example of a maneuver registration in the presence of strong propagation disturbances is iluustrated in Fig.6.

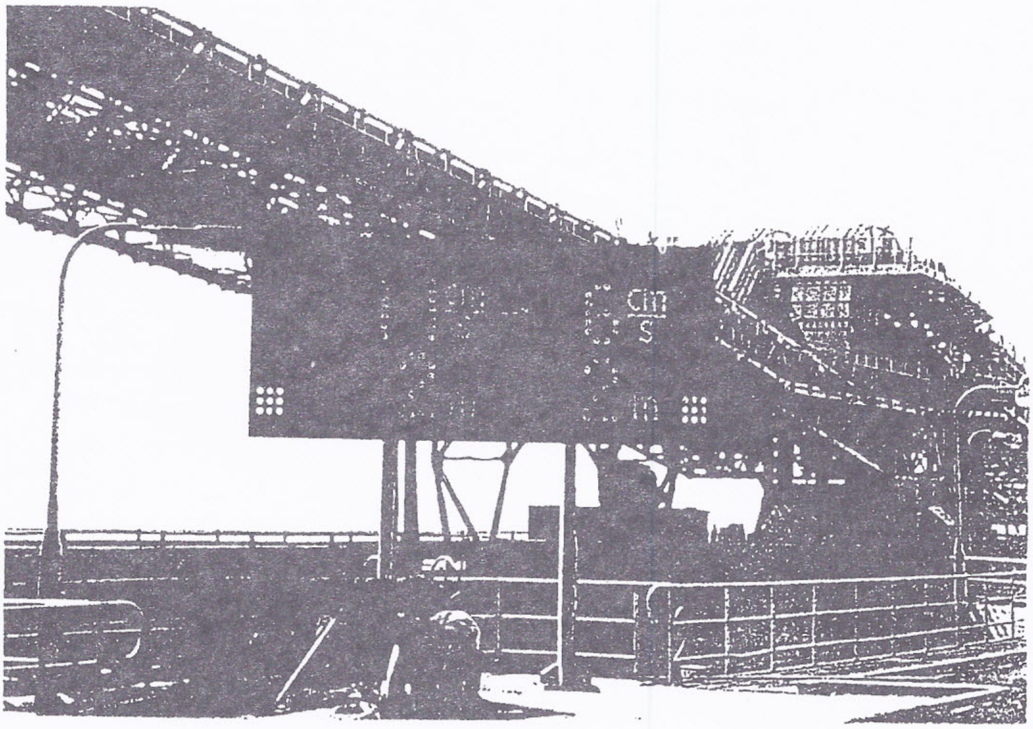

Fig. 7 . View of the display board installed in Port Północny in Gdańsk.

Practical experience showed that the most frequent cause of measurement errors are the curved shapes of the hull of short ships, too small draught and turbulences evoked by the screw propeller and tubular rudders upon braking. So far no negative effects of atmospheric conditions on the system's performance have been observed (waves, frost).

RECORD KEEPING

The data are stored so that the course of a collision can be reconstructed. It also enables a systematic examination of the risk to berths and especially to dolphins. The registered movements of dolphins help to assess the exposure over long period of time. Using this as a basis, prediction can be made about the technical state.

The computer disk stores the files of collected measurement data supplemented by data about maneuvering ships. Additionally a statistics is run on the maximal deflections of dolphins during successive maneuvers.

RECAPITULATION

The use of the above systems, apart from the intended effects (higher safety, easier maneuvers, predictions on the technical state of berths), also caused the pilots to be more cautious. Given full information about the current position and velocity of the ship and knowing that the entire course of the maneuver is being registered, the pilots perform the maneuvers with the demanded ease. They avoid rapid maneuvers of the screw propeller and tubular rudders and are more precise at controlling the tug boats that assist the maneuvers. It influences positively the behavior of harbor basin bottoms configurations and hydrotechnical constructions.

REFERENCES

1.R. Salamon, et. al. „Hydroacoustic ships berthing aid system for Northern Harbour of Gdańsk". Proc. of the XIII Symposium on Hydroacoustics, Gdynia 1996.

2.R. Salamon et. al. „Measurement errors in acoustical docking system". Proc. of the XLIII Open Seminar on Acoustics, Gliwice 1996.