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The system for testing ship manoeuvrability and propulsion properties based on NAVSTAR-GPS global satellite system

SUMMARY

Operating principles of GPS global navigation system and its use possibilities for ship manoeuvre testing are presented in this paper.

The system is based on MX200 receiver, manufactured by Magnavox company, and a complementary system, worked out by Ship Design and Research Centre (CTO).

INTRODUCTION

The International Maritime Organisation (IMO), undertaking efforts for improving marine navigation safety, has passed numerous resolutions on requirements concerning manoeuvre characteristics of vessels (the recent one from November 1993, [1]). Since 1976 such characteristics have been determined in the Baltic Sea area for the needs of North Harbour (Gdańsk), by, among others, AD2 system worked out at the Technical University of Gdańsk. For several years such tests have been carried out by CTO, applying AD2 receiver coupled with IBM PC computer in order to automatically convert hyperbolic co-ordinates and derive the required characteristics.

Since AD2 system is ageing physically and morally (it fails sometimes), there is no hope for its modernisation either, it has become urgent to match the above tests with modern systems for ship position measurement. After the detailed economical and technical analysis (especially concerning accuracy), it has been decided to use DGPS satellite system. The system however requires setting up a coastal reference station, which had to be completed by The Hydrographical Office of Poland (BHRP) in Gdynia by the end of 1993. Starting the station has delayed due to several difficulties. The project however is being realised [2] and the whole electronic equipment for Hel radio beacon is to be bought and soon supplied. When the reference station is started by BHRP Gdynia, the system worked out by CTO and described below is to be implemented.

POSITION DETERMINATION BY NAVSTAR-GPS SYSTEM

NAVSTAR-GPS (Navigation Satellite Timing and Ranging-Global Positioning System) is a navigation system, using the satellites launched by USA Ministry of Defence. The system consisting of 24 satellites distributed on six orbits was completed in 1993. It can be used for navigation and position determination in any part of the earth 24 hours a day.

The satellites of GPS system send two kinds of signals: for military and civil use. Those for military use make it possible to achieve higher accuracy and they are marked as PPS (Precise Positioning Service) or shortly P. They are accessible only with additional codes. Civil navigation can use the signals of SPS type (Standard Positioning Service) called also C/A code (Course Acquisition).

The mentioned PPS and SPS signals are sent within two frequency channels, of about 1.57 GHz and 1.23 GHz, and they are used for the measurements of the distance between a satellite and a receiver on the earth (e.g. a ship).

In order to determine the precise position of receiver on the earth, the distances from four satellites (x, y and z are the three unknowns while the fourth derives from the time shift of receiver regarding the satellite time) should be determined simultaneously. A system of equations with four unknowns should be solved (1):

$$
\begin{aligned}
&(X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = (R_1 - T)^2 \quad \text{and} \quad && R_1 = c\Delta t_1 \\
&(X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = (R_2 - T)^2 && R_2 = c\Delta t_2 \\
&(X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = (R_3 - T)^2 && R_3 = c\Delta t_3 \\
&(X_4 - U_x)^2 + (Y_4 - U_y)^2 + (Z_4 - U_z)^2 = (R_4 - T)^2 && R_4 = c\Delta t_4
\end{aligned}
\tag{1}
$$

where: c - speed of light,

R_i - pseudo-distance from the satellite (i = 1, 2, 3, 4),

X_i, Y_i, Z_i - position of satellites,

U_x, U_y, U_z - position of a user (receiver),

T - the time of the user.

U_x, U_y, U_z and T are the unknowns to be determined and times Δt_i (i=1,2,3,4) are measured by GPS receiver. From the relationship (1) it results that in order to solve the equations it is necessary to know positions of all the satellites. The parameters of their orbits are being observed and corrected by the Control Centre in Colorado Springs, USA, and they are sent to a satellite twice a day. Then, satellites are sending those precise data to the earth in order to be used by Ephemerides and Almanach satellites. Moreover, it results from the equations (1) that GPS receiver should be at least a four-channel receiver. It is impossible to solve those equations directly due to their non-linear character. The recurrent estimation by means of the Kalman filters is therefore used.

For practical use, it is interesting that applying the option with two signals of SPS standard code the accuracy of position determination of about 100 m (probability = 95%) is achieved. It means that GPS system is the most precise global system of positioning.

Furthermore, the system makes it possible to use dGPS technique (differential GPS), which allows to obtain 20 times higher accuracy of position determination. An additional reference station is necessary for dGPS system, whose real position is precisely determined, and which is provided also with a GPS receiver. The reference station determines its position by means of the satellites, and compares it with the real position, determining at the same time the position error. The position difference is transmitted to other dGPS receivers within the range of hundreds of kilometres. All the receivers which are to use corrections, should be provided with additional signal receivers, acquiring signals from the reference station, and a software proper for dGPS technique. The messages on correction are transmitted according to RTCM-104 format (Radio Technical Commission for Maritime Service) within 283.5 - 325.0 kHz frequency range (picked with the 500 Hz interval).

DGPS RECEIVER OF MX200 TYPE

The dGPS system, owned by CTO, is a system made by Magnavox Company, consisting of:
- GPS receiver of MX200 type with a software of differential version,
- DGPS signal radio receiver of MX-50R type,
- compound aerial.

It is made as a portable system of Magna-Pak type in a water proof case,of 8 Kg weight.

MX200 receiver characteristics

- number of input channels	- 6
- sensitivity	- 143 dBm
- position read-out	- every one second
- position accuracy	
- without dGPS	- 40 - 100 m
- with dGPS	- 2 - 5 m
- accuracy of 3 miles distance determination:	
- without dGPS	- 0.5 - 1.2%
- with dGPS	- 0.022 - 0.056%
- time measurement accuracy	- 0.01 sec
- instantaneous speed:	
- without dGPS	- 0.1 m/s (0.2 kn)
- with dGPS	- 0.05 m/s (0.1 kn)
- accuracy of speed determination within the distance of 3 miles:	
- without dGPS	- 0.6 - 1.2%
- with dGPS	- 0.02 - 0.06%
- graphical display	- 6 inches (152 mm)
- keyboard	- 25 keys
- navigation quality display	-LEDs:
- red	- lack of navigation (less than 3 satellites followed)
- yellow	- disadvantageous position of satellites
- green	- optimum navigation.

Types of MX200 receiver modes of operation

1. NAVIGATE (3 screens) - COG, SOG, BRG, DIST (navigation abbreviations) etc,
2. SAIL PLAN - it can remember up to 200 route points and 20 routes,
3. OPTIMIZE - counter, stopper, the possibility of fuel consumption measurement,
4. PLOTTER (2 screens) - it depicts a square up to: 128x128 miles,
5. SETUP - setting the input/output parameters and data,
6. POSITION (4 screens) - position, speed and time display,
7. CALC. (calculator) - co-ordinates and time recalculating,
8. ALARM - possibility of 9 alarms set-up (15 alarms after connecting additional sensors),
9. MOB - „Man overboard" manoeuvre servicing.

MX-50R receiver characteristics

- frequency retune range	- 283.5 - 325.0 kHz every 0.5 kHz,
- input signal level	- 5mV - 100 mV,
- signal modulation	- MSK (Minimum Shift Keying),
- decoding	- digital, with Costy double loop,
- transmission speed	- 25, 50, 100 or 200 bit/sec.

SYSTEM FOR MANOEUVRE AND SHIP SPEED TESTING

Block diagram of the system for manoeuvre and ship speed testing, working on the basis of GPS satellite system, is presented in Fig. 1.

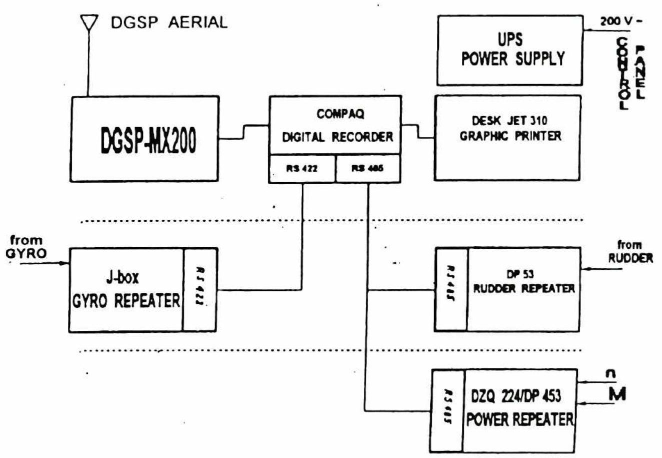


Fig. 1. Block diagram of the system for manoeuvre and ship speed testing

A DGPS receiver of MX200 type transmits information about position and instantaneous speed to a recorder of COMPAQ type. Moreover, signals from a gyro repeater and a rudder repeater are sent to the digital recorder. Signals from rotational speed (n) and torque (M) repeaters are delivered additionally to the recorder from the main shaft of the ship's power plant.

MORZE program, worked out by CTO, controls all the information transmitted to the digital recorder. MORZE program includes several menu options such as:

ship speed measurement, standard manoeuvres measurements: circulation, free inertia trial , man overboard manoeuvre, break-down stop, zigzag trial. For each of those options, the program performs appropriate computations, displays current test running on 11 - inch screen monitor, and lists appropriate (required and declared) tables and diagrams, sending them to a graphic printer.

An important feature of the system is that all the repeaters use digital signals and serial joints, which makes it possible to transmit data over long distances (up to about 500 m). Furthermore, a ship's power repeater was designed and manufactured to filter torsional vibrations occurring on a measuring shaft. The repeater may be connected to the equipment, measuring engine torque and speed, manufactured by other than CTO companies.

All the repeaters shown in Fig. 1, were designed by CTO using the devices marked in the figure,appropriately to the needs of a system for testing ship manoeuvrability properties.

Other parameters, also important for manoeuvrability testing [1], and for ship propulsion properties testing [4], such as: water depth, wind speed and direction, sea state, speed and direction of sea currents and ship load condition, are not directly measured by the system. They should be taken down from devices and other data available on the ship board, and added to the test report.

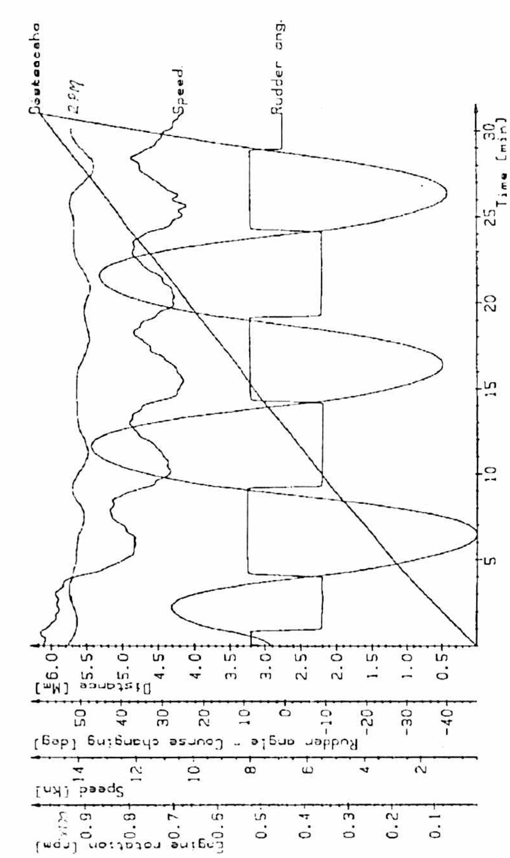
PRESENTATION OF RESULTS AND TEST REPORT

Due to delay in starting the coastal reference station it was impossible to carry out tests with the use of a dGPS receiver, in Gulf of Gdańsk, up to the time that paper was written (April 1994). As a result of that, it is impossible to present a report of the results of such tests. For several years, however, such tests have been carried out by AD2 system. The test are serviced by the previous version of MORZE program. The report is similar to that using dGPS. The most important difference is that in the case of AD2 system the results are processed after the voyage. With dGPS version, the results will be on-line computed and directly delivered during sea trials to graphic printer. Such a program optimisation has been required by shipowners and shipyards.

Several pages of a report with results of ship's manoeuvrability trials, prepared with the use of MORZE program, and application of AD2 system are presented in Fig. 2 as examples. The results of tests carried out by the use of GPS system are also available, but as yet not published, because the system was not completed at the moment this paper was written.

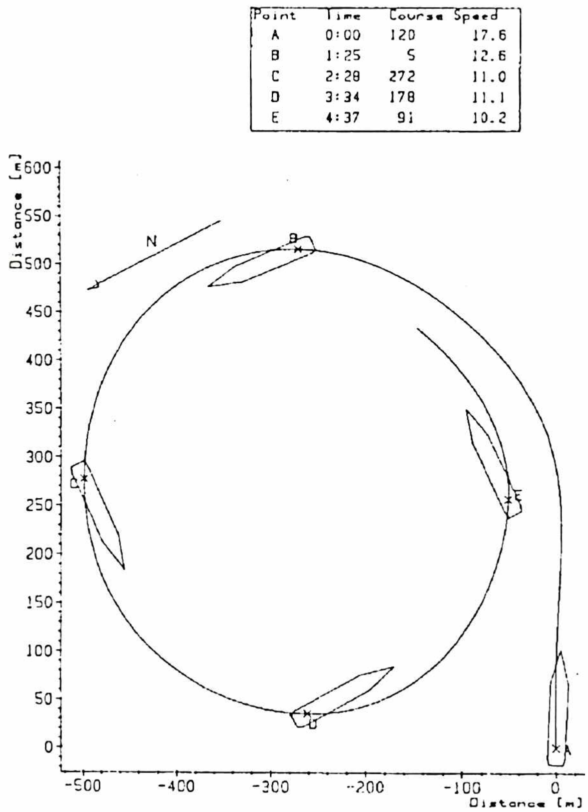
Test report No:RK-94/	Sheet 41/126

ZIG-ZAG TEST No 1

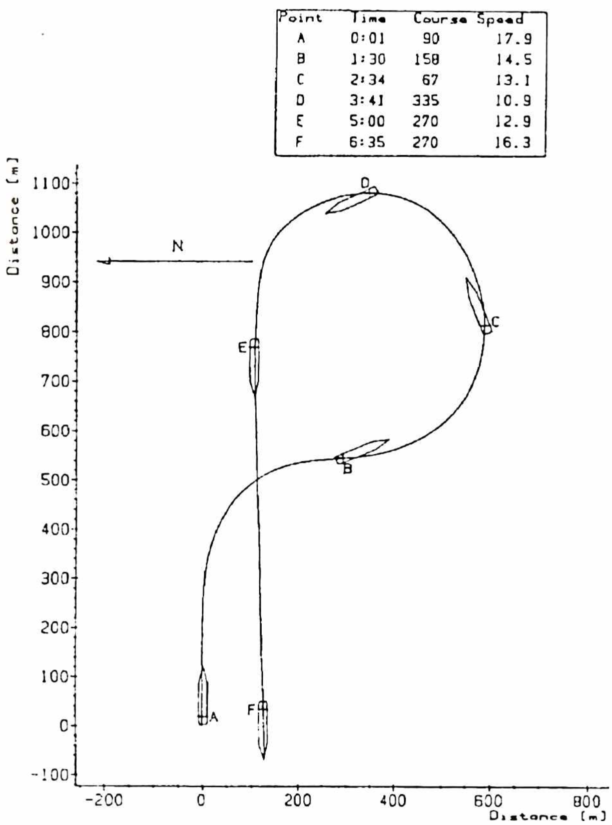


TURNING TEST No 1

TO THE LEFT



MAN OVERBOARD RESCUE No 1



Test report No: RK-94/	Sheet 5/126

Kind of test	SPEED TEST					
Date	1994.06.04 - 05					
Hour	2307-0230					
Draught fore - marks [m]	12.2					
Draught aft - marks [m]	12.2					
Run No	1	2	3	4	5	6
Strength of wind [m/s]	3	4	4	3	3	3
Direction of wind [°]	270	270	270	270	270	270
Sea state [°]	2	2	2	2	2	2
Barom. pressure [hPa]	1005	1005	1005	1005	1005	1004
Ambient temperature [°C]	11	11	11	11	11	11
Sea temperature [° C]	10	10	10	10	10	10
Depth of water [m]	104	104	104	105	105	105
Direction [°]	350	170	350	170	350	170
Course deviation [m]	5.2	10.9	6.1	11.4	14.0	8.2
Road [Nm]	1.991	2.023	2.037	2.027	2.039	2.012
Time [s]	440.78	466.70	480.53	500.11	537.70	563.47
Run time of 1 Nm [s]	221.44	230.67	235.91	246.78	263.77	280.03
Speed [knots]	16.26	15.61	15.26	14.59	13.65	12.86
Load indicator	6.5	6.7	6.0	6.0	5.0	5.0
Revolutions [1/min]	96.2	96.2	89.9	89.9	79.9	79.9
Average revolutions [1/min]	96.2		89.9		79.9	
Power [kW]	11773	12036	9514	9719	6785	6853

Fig. 2. Pages selected from test report on ship speed and manoeuvrability

FINAL CONCLUSIONS

From the experience gained during starting dGPS system, and of operation and observation of GPS system, and also on the basis of available reports, it results that the system is reliable and it guarantees the offered accuracy.

It may be successfully used for determining ship manoeuvre and speed characteristics. It ensures also very high accuracy of those tests. Since many countries all over the world have already provided their coasts with reference stations, the system might be applied in many regions of the world.

Moreover, coupling dGPS system with a graphic printer makes it possible to receive statistical data of position in geographic co-ordinates with the higher accuracy than GPS system provides.

Quality system corresponding to West Europe standards of EN 45000 series for testing laboratories (ISO 9000 standard equivalent), and to requirements of Polish Centre of Testing and Certification will be soon implemented in CTO for the area of selected tests and measurements, including the described ones.

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THE COMPUTER PROGRAM FOR DETECTION OF VORTEX CAVITATION ON MARINE PROPELLERS

In 1994 Prof. T. Koronowicz of the Ship Propeller Department has developed the KAWIR computer program for detection of vortex cavitation on marine propellers, which is one of the main sources of propeller induced acoustic emission. A low level of this emission is an important design requirement for naval ships, research vesseles, passenger liners and fishing boats. The KAWIR computer program enables detection and elimination of troublesome vortex cavitation at the design stage of a ship.

The program is based on the results of own theoretical research on the modified vortex model of propeller blades. This research has led to the new original method of numerical simulation of the process of tip vortex formation behind propeller blades. Contrary to the traditional approach, where the Rankine vortex model is used in connection with empirical data, KAWIR calculates the pressure field around a deforming and dissipating system of free vortices, which are shed independently from both sides of the blade. For this purpose the blade itself is modelled by the original Double Layer Lifting Surface theory. In the initial stages of deformation a small kernel is formed, where the concentration of vorticity is high enough to produce pressure sufficiently low to burst cavitation nuclei contained in the oncoming flow. This kernel acts as a „factory" of nuclei which, depending on the parameters of the flow, may form either a street of isolated, pulsating bubbles or a cavitating tube of varying diameter. Both these forms may extend quite far downstream from the propeller blades and both may be a source of acoustic emission.

The KAWIR program employs vorticity distribution on the blades determined by the well known unsteady lifting surface program UNCAVN developed in IFFM about 10 years ago, which is widely used in the Polish and foreign ship hydrodynamics centres. Application of the new program requires information about propeller geometry and the non-uniform inflow velocity field. As a result of calculation the information about tip vortex cavitation inception is produced and in the case when cavitation is present, the dominating frequency of the acoustic signal is determined. Moreover, the program determines the harmonic amplitudes of the acoustic pressure induced by the varying diameter of the cavitating tip vortices in the prescribed points of space. This variation results from operation of the propeller in the non-uniform velocity field. The program may be used on PC386/486 computers with minimum CPU memory 4kB. The development of the program was funded by the Scientific Research Committee (KBN) grant no. 99421 92 03.