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RISK ANALYSIS OF SHIP'S MANOEUVRES CARRIED OUT ON THE BASIS OF INTEGRATED NAVIGATION SYSTEMS (INS) INDICATIONS

ABSTRACT

In the safety evaluation of manoeuvres carried out on the basis of INS indications, the real ship's dimensions are used to determine navigation safety level. The paper presents a new approach to this problem. The ship's maneuvering area and collision probability were calculated incorporating uncertainty areas of ship's plan geometry at given probability level for typical configuration of navigational equipment applied in existing pilot systems. The widening coefficients of safety factors for each configuration set were determined and discussed. The most economically advantageous configuration of navigation system was chosen.

Keywords:
risk, ship's manoeuvres, navigation.

INTRODUCTION

Presently integrated navigation systems are used more and more often as a basic source of navigation information while reduced visibility. The navigator analyse changes in arrangement of ship-environment based on integrated system indications, with no possibility of visual observation. In most of the cases it takes place on restricted water areas, where increased risk of accident exists. Basic information displayed in navigational systems consists of a graphical representation of ship's position in relation to navigational dangers (fig. 1). Due to the method of determining the ship's position [4] as a geometrical object in a navigational system, this position is uncertain.

Position uncertainty of ship's plan geometry is an area occupied horizontally by the ship whose dimensions can be determined by means of a probabilistic method at an adopted level of probability. The example of uncertainty area, determined at 0,95 confidence level according formula 1 is presented on figure 2.

$$x_{ri} = x_{Ari} + d_i \, sin(\psi_{ri} + \alpha_i);$$

$$y_{ri} = y_{Ari} + d_i\, cos(\psi_{ri} + \alpha_i), \tag{1}$$

where:

x_{ri}, y_{ri} — calculated coordinates of consecutive points of ship's contour;
x_{Ari}, y_{Ar} recorded positions of GPS antenna — assuming north up orientation;
ψ_{ri} heading, d_i — distance between GPS antenna and point of ship's contour;
α_i — angle between GPS antenna and point of ship's contour.

Based on general formula of uncertainty propagation theory the standard uncertainties of input values were determined and covariance matrix of two-dimensional probability density function σ_F presents equitation (2):

$$\sigma_F = \begin{bmatrix} \frac{\partial x_{ri}}{x_{Ari}} & \frac{\partial x_{ri}}{y_{Ari}} & \frac{\partial x_{ri}}{d_i} & \frac{\partial x_{ri}}{\gamma_i} \\ \frac{\partial y_{ri}}{y_{Ari}} & \frac{\partial y_{ri}}{x_{Ari}} & \frac{\partial y_{ri}}{d_i} & \frac{\partial y_{ri}}{\gamma_i} \end{bmatrix} \cdot \begin{bmatrix} \sigma x^2_{Ari} & \sigma_{Ari} y_{Ari} & 0 & 0 \\ \sigma x_{Ari} y_{Ari} & \sigma y^2_{Ari} & 0 & 0 \\ 0 & 0 & \sigma d_i^2 & 0 \\ 0 & 0 & 0 & \sigma \gamma_i^2 \end{bmatrix} \cdot \begin{bmatrix} \frac{\partial x_{ri}}{x_{Ari}} & \frac{\partial y_{ri}}{y_{Ari}} \\ \frac{\partial x_{ri}}{y_{Ari}} & \frac{\partial y_{ri}}{x_{Ari}} \\ \frac{\partial x_{ri}}{d_i} & \frac{\partial y_{ri}}{d_i} \\ \frac{\partial x_{ri}}{\gamma_i} & \frac{\partial y_{ri}}{\gamma_i} \end{bmatrix}, \tag{2}$$

where:

σx^2_{Ar} — variance of latitude coordinate;
σy^2_{Ari} — variance of longitude coordinate;
$\sigma x_{Ari} y_{Ari}$ — covariance of latitude and longitude coordinates;
σd^2_{i} — variance of distance of i-th ship's contour point from antenna location;
$\sigma \gamma^2_i$ — the sum of variances of angle α_i and heading ψ_i.

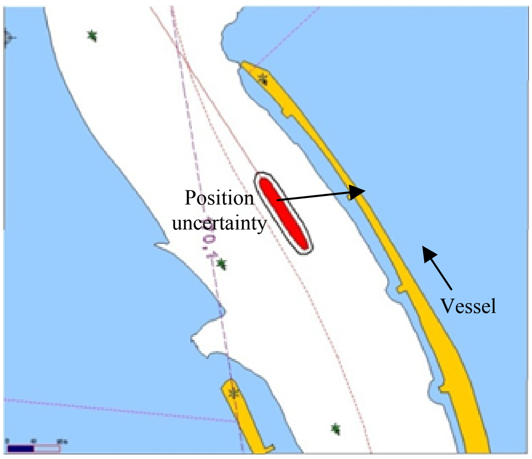

Fig. 1. The ship and her uncertainty area presented in navigation pilot system [5]

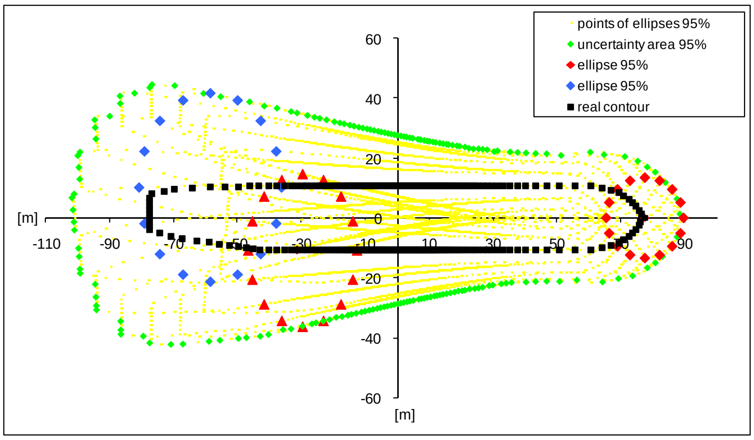

Fig. 2. The uncertainty area of ship's plan geometry around the m/f 'Jan Śniadecki' contour formed after extreme points of error ellipse had been found at 95% confidence level and GPS antenna placed in fore part of the ship

The size of this area reflects uncertainty of defining ship's position in integrated navigation systems, while the distance of its boundaries in relation to navigational dangers may constitute a criterion of the assessment of the safety of maneuvers based on navigational system indications.

Taking into consideration the diversity of INS in the aspect of carried out of GPS measurement techniques (absolute GPS, differential GPS: DGPS, EGNOS, Real-time kinematic — RTK) [4], heading (GPS compass, gyro-compass) or local coordinates of GPS antenna location on the ship's deck it can be concluded that maneuvers carried out based on INS indications are distinguished by different safety level. From the point of INS based maneuvering safety evaluation, the relation between basic safety factors (dimensions of maneuvering area and probability of accident) and various configuration of navigation system is interesting. The safety evaluation problem of maneuvers carried out on basis of INS seems to be especially up to date in the light of worldwide research and the discussion in the European Union concerning the possibility of remote pilotage.

RISK EVALUATION OF SHIP'S MANOEUVRES CARRIED OUT ON THE BASIS OF PILOT NAVIGATION SYSTEM

The most essential problem in determining the restricted areas dimensions is to guarantee safety of navigation on this area. The designer of port, basin etc. is required to estimate risk of accident accompanying each specified ship's manoeuvres.

The risk is defined as combination of probability of accident and its effects and can be expressed as:

$$R = P_A \cdot S_a , \qquad (3)$$

where:

R — risk of accident;

P_A — probability of accident;

S_a — effects of accident.

For research purposes the risk value was assumed at $R = 0{,}07$ level. By means of formula (4) the acceptable probability of accident P_{acc} = 0,00019444 was determined:

$$P_{acc.} = \frac{R_{akc}}{I_R S_a} , \qquad (4)$$

where:

I_R — average intensity of particular manoeuvre in one year period (leaving port, turning, etc.).

In order to examine ship's uncertainty area impact on the safety of manoeuvres executed according to indications of an integrated navigation system, a real experiment was carried out. In the experiment, m/f 'Jan Śniadecki' performed 21 departure passages out of the port of Świnoujście.

For the examined restricted area — a bend — the width of ship's swept path and probability of accident were chosen as criterions of safety assessment of passages. The boundaries of the navigable area for this region were defined by the 8 m depth contour on the starboard side and the crossing of that was assumed as an accident. Safety factors were determined for the different configuration of INS by means of pre-calculated uncertainty areas of 'Jan Śniadecki' plan geometry. Particular variants of configuration are marked according to below description:

GPS_z — GPS autonomus and gyrocompass

GPSSPS_z — GPS autonomus (accuracy published by Standard Positioning Service — SPS) and gyrocompass

DGPSI_z — Differential GPS IALA& gyrocompass

DGPSICG(ng)_z — Differential GPS IALA (accuracy published by American Coast Guard — the worst case) & gyrocompass

DGPSI_GPSV — Differential GPS IALA & compass GPS (CSI Vector)

DGPSICG(ng)_GPSV — Differential GPS IALA (accuracy published by American Coast Guard — the worst case) & compass GPS (CSI Vector)

DGPSI_GPSVP — Differential GPS IALA & compass GPS (CSI Vector), (accuracy published by manufacturer)

DGPSI_2DGPSI — Differential GPS IALA & heading determined between two synchronically measuring DGPS receivers

DGPSICG(nl)_ 2DGPSI — Differential GPS IALA (American Coast Guard — the best case) & heading determined between two synchronically measuring DGPS receivers

EGNOS_z — Differential GPS (EGNOS corrections) & gyrocompass

EGNOSSA(nl)_z — Differential GPS (EGNOS corrections) (accuracy published by –European Space Agency: ESA the best case & gyrocompass

EGNOS_GPSV — Differential GPS (EGNOS corrections) & compass GPS (CSI Vector)

EGNOSSA(nl)_GPSVP — Differential GPS (EGNOS corrections) the Best case compass GPS Vector & compass GPS (CSI Vector), (accuracy published by manufacturer)

RTK_2RTK — Real Time Kinematic GPS & heading determined between two synchronically measuring DGPS receivers.

Determined probabilities of accident for the searched configuration of INS are presented on the figure 3.

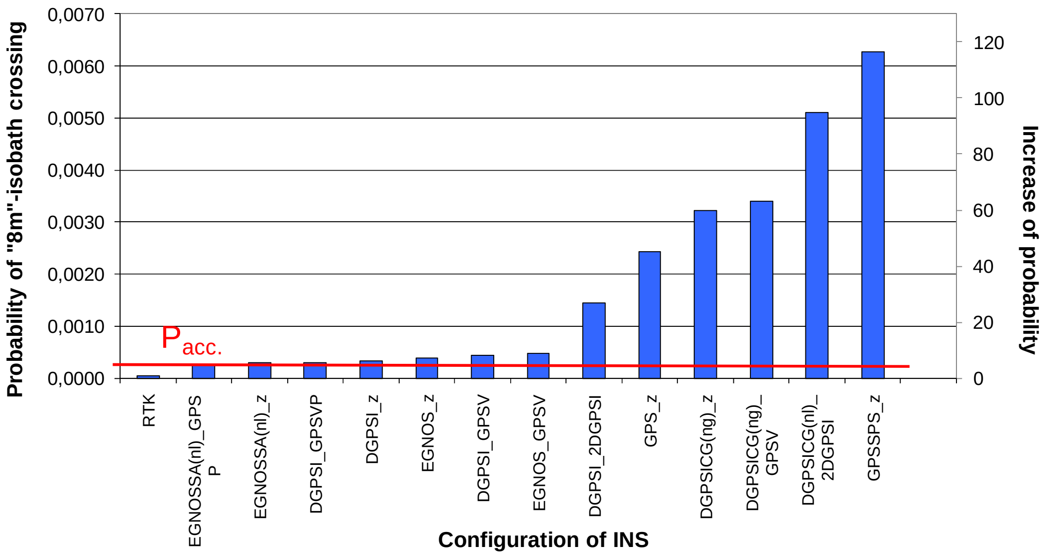

Fig. 3. Probability of navigation accident of m/f 'Jan Śniadecki' leaving Świnoujście near east head of breakwater considering the uncertainty area of ferry plan geometry

In all searched configuration variants probability of accident exceeded the acceptable probability value.

The uncertainty of ship's plan geometry in INS causes the broadening of safe maneuvering area. Considering this the safety margin coefficient of safe maneuvering area was determined at a given confidence level for m/f 'Jan Śniadecki' maneuvering carried out on the basis of particular configuration of INS (fig. 4).

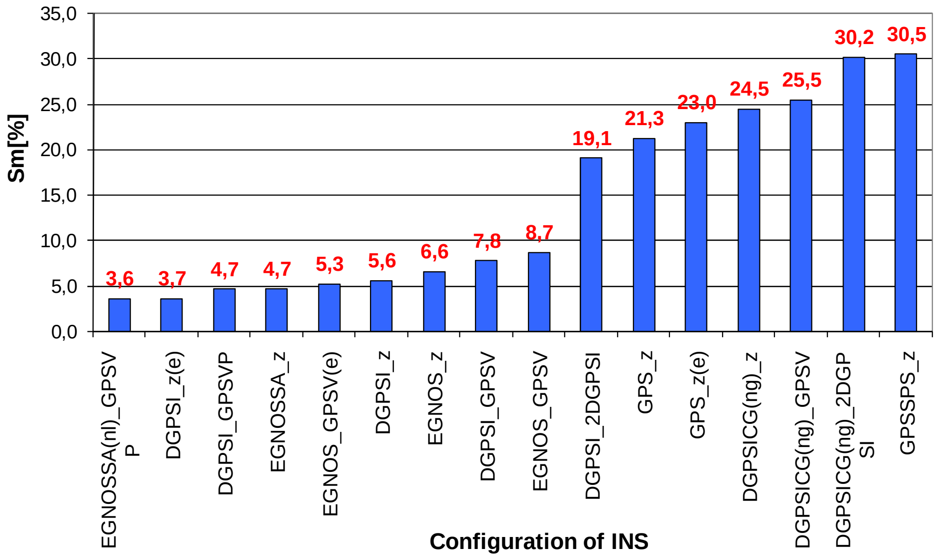

Fig. 4. The safety margin coefficient of m/f 'Jan Śniadecki' safe manoeuvring areas for different configurations of INS

Safety margin was expressed according the below formula:

$$S_m[\%] = \frac{S_i}{S_{wz}} 100\% - 100\%, \tag{5}$$

where:

S_i — ship's safe maneuvering areas determined for particular configuration of INS;

S_{wz} — ship's maneuvering area determined for real ship's contour without uncertainty; area allowance.

The width of the maneuvering area in particular sections can be described by the sum of distances of extreme ship's waterplane outline points to the left and right of the reference fairway axis. Statistically, at the specified, confidence level, it can be defined by the following formula:

$$d_{ws(c)} = \left(d_{slav} + k\sigma_{sl}\right) + \left(d_{srav} + k\sigma_{sr}\right), \quad (6)$$

where:

$d_{ws(c)}$ — width of the manoeuvring area at *c* confidence level in reference to the *s*-section point of the fairway axis;

d_{slav}, d_{srav} — average distances of extreme ship's waterplane outline points to the left and right of the reference axis;

k — coefficient dependent on accepted confidence level;

d_{sl}, d_{sr} — variables' distribution (eg. $k \approx 2$ for normal distribution at confidence level 0.95);

σ_{sl}, σ_{sr} — standard deviations of distances to the left and right of the reference axis.

The conclusion is that maximum difference between safe manoeuvring areas obtained from studies without allowance for uncertainty area of ship's plan geometry and studies with such allowance can reach approximately 30% in Świnoujście harbour area for the 'GPSSPS_z' configuration used. The determined safety margin coefficient values are in the range between 3,6% for 'EGNOSSA(nl)_GPSVP' and 30% for 'GPSSPS_z'.

With the knowledge of the cost of an average navigation accident for a given area, the cost of purchase and maintenance of the system as well as the probability of the occurrence of different types of navigation accidents, it is possible to select the most economically advantageous navigation system for a specific ship and area. In the investigated case the target function took the shape of:

$$f(x) = K_z = K_w + K_s \rightarrow min$$
$$K_w = P_A I_R \quad (7)$$

at limitation:

$$P_A \leq P_{akc}$$

where:

K_w —cost of accident;

K_s —cost of navigation system;

P_{acc} —acceptable risk of accident;

I_R —an average yearly intensity of maneuvers (e.g. leaving the port).

The function which is the sum of cost of accident function and cost of navigation system function presents figure 5.

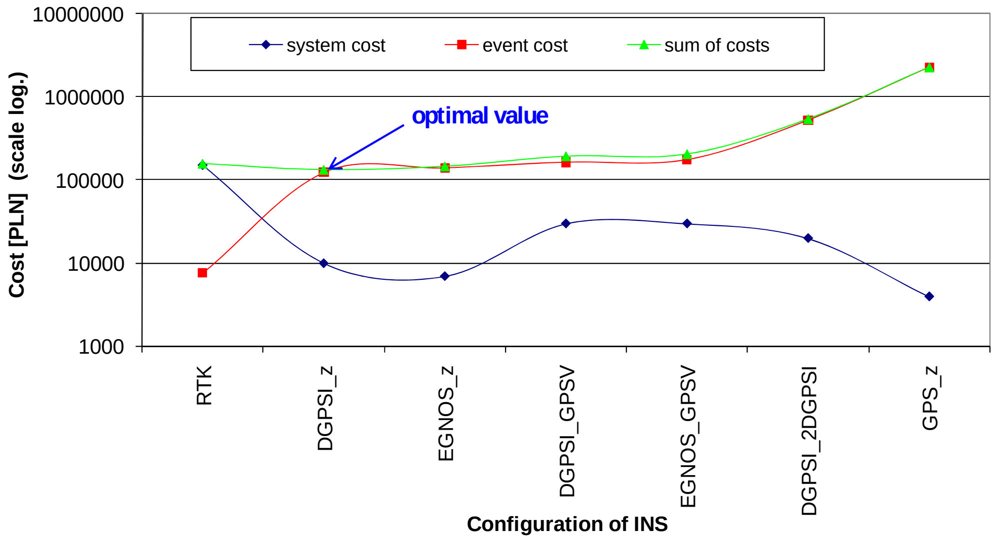

Fig. 5. Optimization of the most economically advantageous system

Function minimum was defined in a point for the variant (DGPS IALA and gyrocompass). It can be thus concluded that taking into consideration the safety of navigation (accident probability) and the cost of the purchase of the system, the most economically advantageous is the system whose operation is based on the DGPS receiver with the IALA differential station (Dziwnow) and gyrocompass.

CONCLUSIONS

The experiment performed has proved the necessity of uncertainty area of ship's plan geometry consideration in safety evaluation of manoeuvres carried out on based of INS. There are statistically significant differences in the manoeuvring area dimensions between different configuration of common navigation devices the INS is consisted of. That's why the method incorporating the idea to include probabilistic ship's contour dimensions is suggested to take precedence in the process of evaluation of manoeuvres safety. This method always requires preliminary research of the navigation system used or recommended in the studied area, but the resultant safety measures are more reliable. In the carried experiment the approx. 30% difference in safety criterion was noted between measurement (RTK) method and uncertainty area inclusive method. The difference has been obtained also in probability of accident value (the increase of 120).

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