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The Sensitivity of Safe Ship Control in Restricted Visibility at Sea

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ABSTRACT: The structure of safe ship control in collision situations and computer support programmes on base information from the ARPA anti-collision radar system has been presented. The paper describes the sensitivity of safe ship control to inaccurate data from the ARPA system and to process control parameters alterations. Sensitivity characteristics of the multi-stage positional non-cooperative and cooperative game and kinematics optimization control algorithms on an examples of a navigational situations in restricted visibility at sea are determined.

1 SAFE SHIP CONTROL

1.1 *Structure of control system*

The challenge in research for effective methods to prevent collisions has become important with the increasing size, speed and number of ships participating in sea carriage. An obvious contribution in increasing safety of shipping has been application of the ARPA (Automatic Radar Plotting Aids) anti-collision system (Fig. 1).

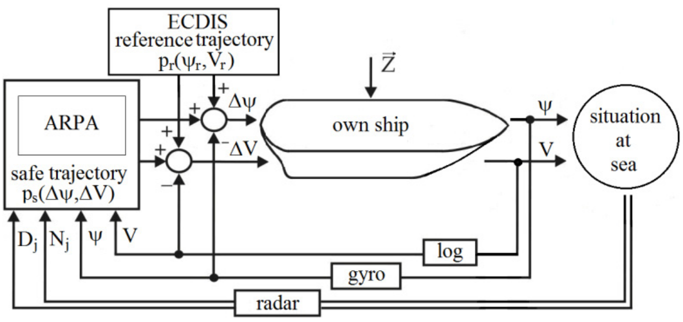

Figure 1. The structure of safe ship control system.

1.2 *Information of the state process*

The ARPA system enables to track automatically at least 20 encountered j objects as is shown on Figure 2, determination of their movement parameters (speed V_j , course ψ_j) and elements of approach to the own ship ($D_{\min}^j = DCPA_j$ - Distance of the Closest Point of Approach, $T_{\min}^j = TCPA_j$ - Time to the Closest Point of Approach) and also the assessment of the collision risk r_j (Bist 2000, Bole 2006).

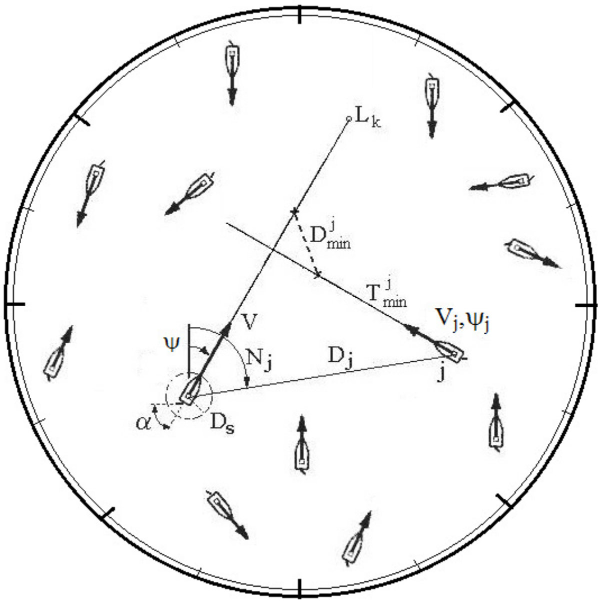

Figure 2. Navigational situation passing of the own ship with j met ship moving with V_j speed and ψ_j course.

The risk value is defined by referring the current situation of approach, described by parameters $D_{\min}^j$ and $T_{\min}^j$, to the assumed evaluation of the situation as safe, determined by a safe distance of approach D_s and a safe time T_s – which are necessary to execute a collision avoiding manoeuvre with consideration of distance D_j to j-th met ship (Cahill 2002).

The functional scope of a standard ARPA system ends with the trial manoeuvre altering the course $\pm\Delta\psi$ or the ship's speed $\pm\Delta V$ selected by the navigator (Cockcroft & Lameijer 2006, Gluver & Olsen 1998).

1.3 *Computer support of navigator*

The problem of selecting such a manoeuvre is very difficult as the process of control is very complex since it is dynamic, non-linear, multi-dimensional, non-stationary and game making in its nature. In practice, methods of selecting a manoeuvre assume a form of appropriate steering algorithms supporting navigator decision in a collision situation. Algorithms are programmed into the memory of a Programmable Logic Controller PLC (Fig. 3) (Lisowski 2008).

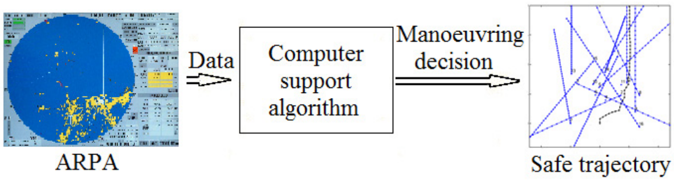

Figure 3. The system structure of computer support of navigator manoeuvring decision in collision situation.

2 COMPUTER PROGRAMMES OF NAVIGATOR SUPPORT

2.1 *Base model of process*

The most general description of the own ship passing the j number of other encountered ships is the model of a differential game of j number of moving control objects (Fig. 4).

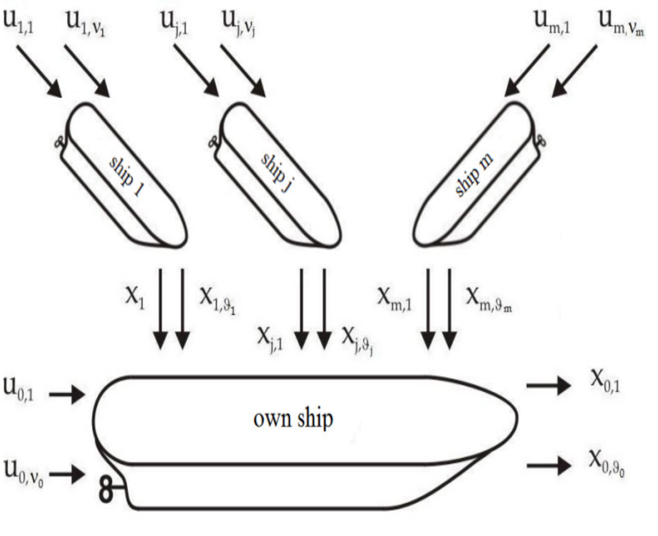

Figure 4. Block diagram of the basic differential game model of safe ship control process.

The properties of control process are described by the state equation:

$$\dot{x}_i = f_i\left[\left(x_{0,\vartheta_0},\ldots,x_{m,\vartheta_m}\right),\left(u_{0,\nu_0},\ldots,u_{m,\nu_m}\right),t\right] \tag{1}$$

where:

$\vec{x}_{0,\vartheta_0}(t)$ - ϑ_0 dimensional vector of process state of own ship determined in time $t\in[t_0,t_k]$,

$\vec{x}_{j,\vartheta_j}(t)$ - ϑ_j dimensional vector of the process state for j-th ship,

$\vec{u}_{0,\nu_0}(t)$ - ν_0 dimensional control vector of own ship,

$\vec{u}_{j,\nu_j}(t)$ - ν_j dimensional control vector of j-th ship (Isaacs 1965, Lisowski 2010, Engwerda 2005).

The constraints of the control and the state of the process are connected with the basic condition for the safe passing of the ships at a safe distance D_s in compliance with COLREG Rules, generally in the following form:

$$g_j(x_{j,\vartheta_j},u_{j,\nu_j}) = \left(D_s - D^j_{\min}\right) \le 0 \tag{2}$$

For the class of non-coalition games, often used in the control techniques, the most beneficial conduct of the own ship as a player with j-th ship is the minimization of her goal function in the form of the payments – the integral payment and the final one:

$$I_{0,j} = \int_{t_0}^{t_k}[x_{0,\vartheta_0}(t)]^2\,dt + r_j(t_k) + d(t_k) \to \min \tag{3}$$

The integral payment represents loss of way by the ship while passing the encountered ships and the final payment determines the final risk of collision $r_j(t_k)$ relative to the j-th ship and the final deflection of the ship $d(t_k)$ from the reference trajectory (Fig. 5) (Modares 2006, Nisan et al. 2007).

2.2 *Programme of multi-stage positional non-cooperative game MSPNCG*

The optimal steering of the own ship $u_0^*(t)$, equivalented for the current position p(t) to the optimal positional steering $u_0^*(p)$. The sets of acceptable strategies $U_j^0[p(t_k)]$ are determined for the encountered ships relative to the own ship and initial sets $U_0^{jw}[p(t_k)]$ of acceptable strategies of the own ship relative to each one of the encountered ship. The pair of vectors u_j^m and u_0^j relative to each j-th ship is determined and then the optimal positional strategy for the own ship $u_0^*(p)$ from the condition (4).

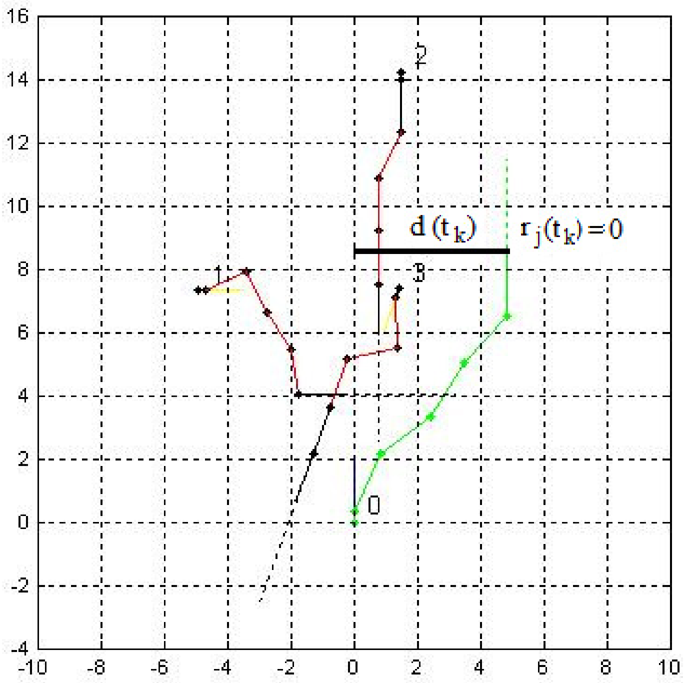

Figure 5. The final risk of collision $r_j(t_k)$ relative and the final deflection $d(t_k)$ from the reference trajectory in situation passing of three met ships.

$$I_0^* = \min_{u_0 \in \bigcap_{j=1}^{m} U_0^j} \; \max_{u_j^m \in U_j} \; \min_{u_0^j \in U_0^j} \int_{t_0}^{t_{L_k}} u_0(t)\,dt = S_0^*(x_0, L_k) \tag{4}$$

The function S_0 refers to the continuous function of the manoeuvring goal of the own ship, characterising the distance of the ship at the initial moment t_0 to the nearest turning point L_k on the reference $p_r(t_k)$ route of the voyage (Millington & Funge 2009, Osborne 2004).

The optimal control of the own ship is calculated at each discrete stage of the ship's movement by applying the Simplex method to solve the problem of the triple linear programming, assuming the relationship (4) as the goal function and the control constraints (2).

Using the function of *lp – linear programming* from the Optimization Toolbox Matlab, the positional multi-stage game non-cooperative manoeuvring MSPNCG program has been designed for the determination of the own ship safe trajectory in a collision situation (Lisowski 2010).

2.3 *Programme of multi-stage positional cooperative game MSPCG*

The quality index of control (4) for cooperative game has the form:

$$I_0^* = \min_{u_0 \in \bigcap_{j=1}^{m} U_0^j} \; \min_{u_j^m \in U_j} \; \min_{u_0^j \in U_0^j} \int_{t_0}^{t_{L_k}} u_0(t)\,dt = S_0^*(x_0, L_k) \tag{5}$$

2.4 *Programme of non-game kinematic optimization NGKO*

Goal function (4) for kinematics optimization has the form:

$$I_0^* = \min_{u_0 \in \bigcap_{j=1}^{m} U_0^j} \int_{t_0}^{t_{L_k}} u_0(t)\,dt = S_0^*(x_0, L_k) \tag{6}$$

3 THE SENSITIVITY OF SAFE SHIP CONTROL

3.1 *Definition of safe control sensitivity*

The investigation of sensitivity of game control fetch for sensitivity analysis of the game final payment (3) measured with the relative final deviation of $d(t_k)=d_k$ safe game trajectory from the reference trajectory, as sensitivity of the quality first-order.

Taking into consideration the practical application of the game control algorithm for the own ship in a collision situation it is recommended to perform the analysis of sensitivity of a safe control with regard to the accuracy degree of the information received from the anti-collision ARPA radar system on the current approach situation, from one side and also with regard to the changes in kinematical and dynamic parameters of the control process (Lisowski 2009, Straffin 2001).

Admissible average errors, that can be contributed by sensors of anti-collision system can have following values for:

- radar,
  - bearing: ±0,22°,
  - form of cluster: ±0,05°,
  - form of impulse: ±20 m,
  - margin of antenna drive: ±0,5°,
  - sampling of bearing: ±0,01°,
  - sampling of distance: ±0,01 nm,
- gyrocompas: ±0,5°,
- log: ±0,5 kn,
- GPS: ±15 m.

The algebraic sum of all errors, influent on picturing of the navigational situation, cannot exceed for absolute values ±5% or for angular values ±3°.

3.2 *The sensitivity of safe ship control to inaccuracy of information from ARPA system*

Let $X_{0,j}$ represent such a set of state process control information on the navigational situation that:

$$X_{0,j} = \{V, \psi, V_j, \psi_j, D_j, N_j\} \tag{7}$$

Let then $X_{0,j}^{ARPA}$ represent a set of information from ARPA system containing extreme errors of measurement and processing parameters:

$$X_{0,j}^{ARPA} = \{V \pm \delta V, \psi \pm \delta\psi, V_j \pm \delta V_j, \psi_j \pm \delta\psi_j, D_j \pm \delta D_j, N_j \pm \delta N_j\} \tag{8}$$

Relative measure of sensitivity of the final payment in the game s_{inf} as a final deviation of the ship's safe trajectory d_k from the reference trajectory will be:

$$s_{\inf} = (X_{0,j}^{ARPA}, X_{0,j}) = \frac{d_k^{ARPA}(X_{o,j}^{ARPA})}{d_k(X_{0,j})} \tag{9}$$

$$s_{\inf} = \{s^V, s^\psi, s^{V_j}, s^{\psi_j}, s^{D_j}, s^{N_j}\} \tag{10}$$

3.3 *Sensitivity of safe ship control to process parameters alterations*

Let X_{param} represents a set of parameters of the state process control:

$$X_{param} = \{t_m, D_s, \Delta t_k, \Delta V\} \tag{11}$$

Let then X'_{param} represents a set of information containing extreme errors of measurement and processing parameters:

$$X'_{param} = \{t_m \pm \delta t_m, D_s \pm \delta D_s, t_k \pm \delta t_k, \Delta V \pm \delta\Delta V\} \tag{12}$$

Relative measure of sensitivity of the final payment in the game as a final deflection of the ship's safe trajectory d_k from the assumed trajectory will be:

$$s_{dyn} = (X'_{param}, X_{param}) = \frac{d'_k(X'_{param})}{d_k(X_{param})} \tag{13}$$

$$s_{dyn} = \{s^{t_m}, s^{D_s}, s^{t_k}, s^{\Delta V}\} \tag{14}$$

where:

t_m - advance time of the manoeuvre with respect to the dynamic properties of the own ship,

t_k - duration of one stage of the ship's trajectory,

D_s – safe distance,

ΔV - reduction of the own ship's speed for a deflection from the course greater than 30^{o} (Baba & Jain 2001).

4 SENSITIVITY CHARACTERISTICS OF SAFE SHIP CONTROL IN RESTRICTED VISIBILITY AT SEA

Computer simulation of MSPNCG, MSPCG and NGKO algorithms, as a computer software supporting the navigator manoeuvring decision, were carried out on an example of a real navigational situations of passing j=3, 12 and 20 encountered ships. The situations were registered in Kattegat Strait on board r/v HORYZONT II, a research and training vessel of the Gdynia Maritime University, on the radar screen of the ARPA anti-collision system Raytheon (Figs 6-7).

Figure 6. The place of identification of navigational situations in Kattegat Strait.

Figure 7. The research-training ship of Gdynia Maritime University r/v HORYZONT II.

4.1 *Navigational situation for j=3 met ships*

Computer simulation of MSPNCG, MSPCG and NGKO programmes was carried out in Matlab/Simulink software on an example of the real navigational situation of passing *j=3* encountered ships in Kattegat Strait in restricted visibility when $D_s = 2$ *nm* and were determined sensitivity characteristics for the alterations of the values $X_{0,j}$ and X_{param} within ±6% or ±3° (Figs 8-14).

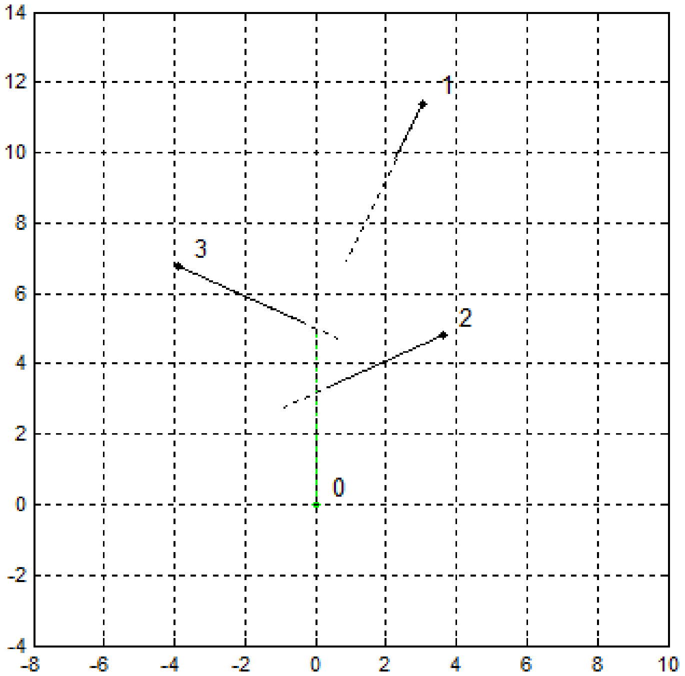

Figure 8. The 12 minute speed vectors of own ship and 3 encountered ships in situation in Kattegat Strait.

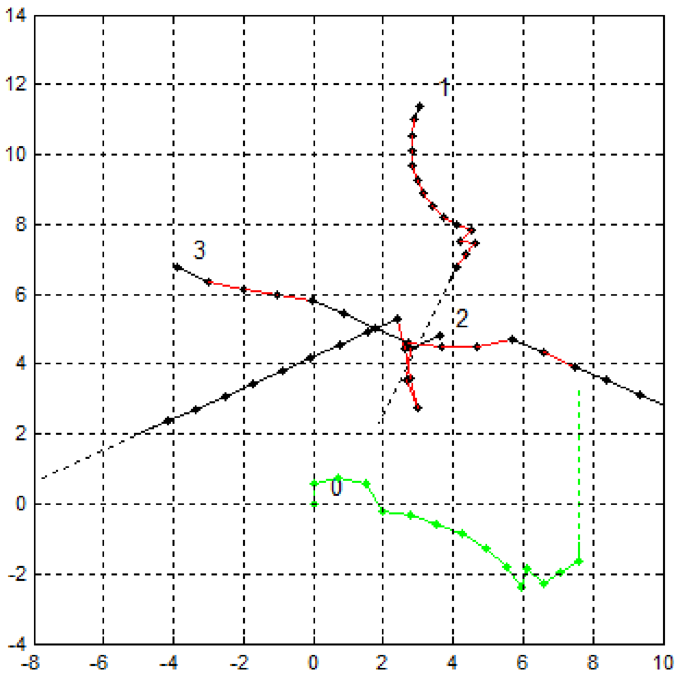

Figure 9. The safe trajectory of own ship for MSPNCG algorithm in restricted visibility $D_s=2$ *nm* in situation of passing $j=3$ encountered ships, $r(t_k)=0$, $d(t_k)=7.60$ *nm*.

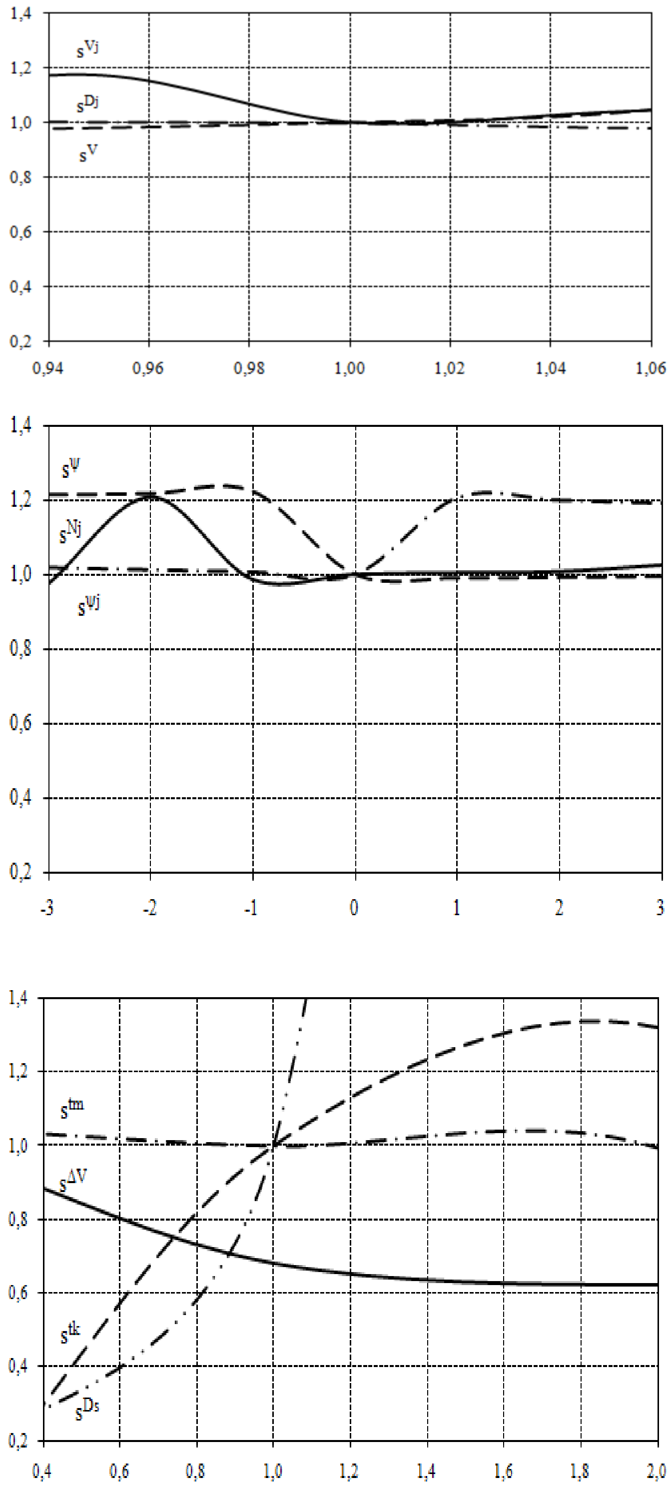

Figure 10. Sensitivity characteristics of safe ship control according to MSPNCG programme on an example of the navigational situation $j=3$ in the Kattegat Strait.

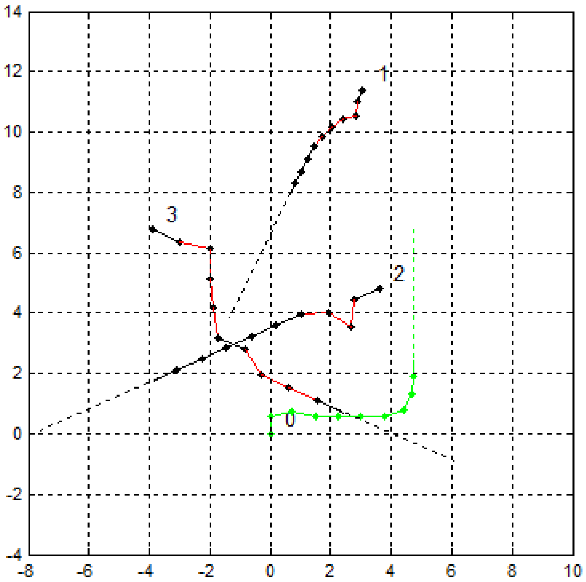

Figure 11. The safe trajectory of own ship for MSPCG algorithm in restricted visibility $D_s=2$ *nm* in situation of passing $j=3$ encountered ships, $r(t_k)=0$, $d(t_k)=4.71$ *nm*.

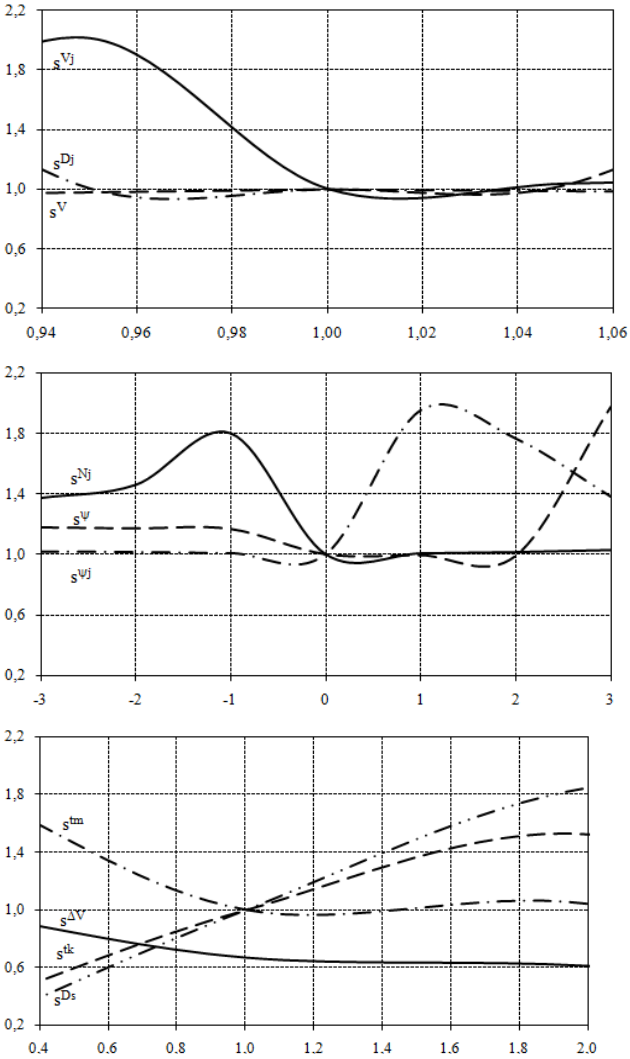

Figure 12. Sensitivity characteristics of safe ship control according to MSPCG programme on an example of the navigational situation $j=3$ in the Kattegat Strait.

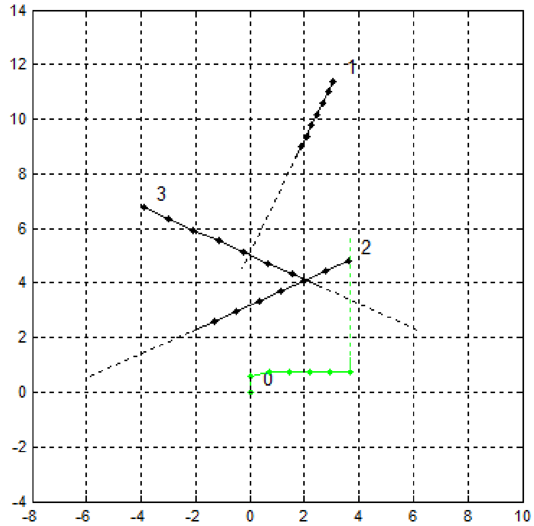

Figure 13. The safe trajectory of own ship for NGKO algorithm in restricted visibility $D_s=2$ *nm* in situation of passing $j=3$ encountered ships, $r(t_k)=0$, $d(t_k)=3.70$ *nm*.

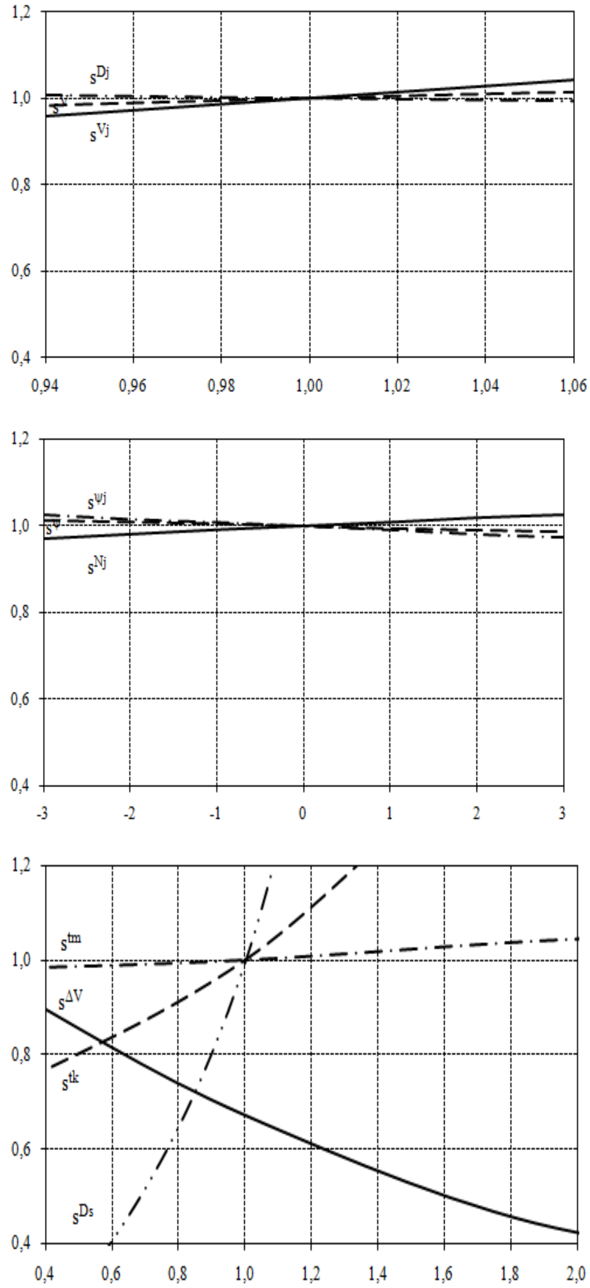

Figure 14. Sensitivity characteristics of safe ship control according to NGKO programme on an example of the navigational situation $j=3$ in the Kattegat Strait.

4.2 *Navigational situation for j=12 met ships*

Computer simulation of MSPNCG, MSPCG and NGKO programmes was carried out in Matlab/Simulink software on an example of the real navigational situation of passing *j=12* encountered ships in Kattegat Strait in restricted visibility when $D_s=2$ *nm* and were determined sensitivity characteristics for the alterations of the values $X_{0,j}$ and X_{param} within ±6% or $\pm 3^{o}$ (Figs 15-21).

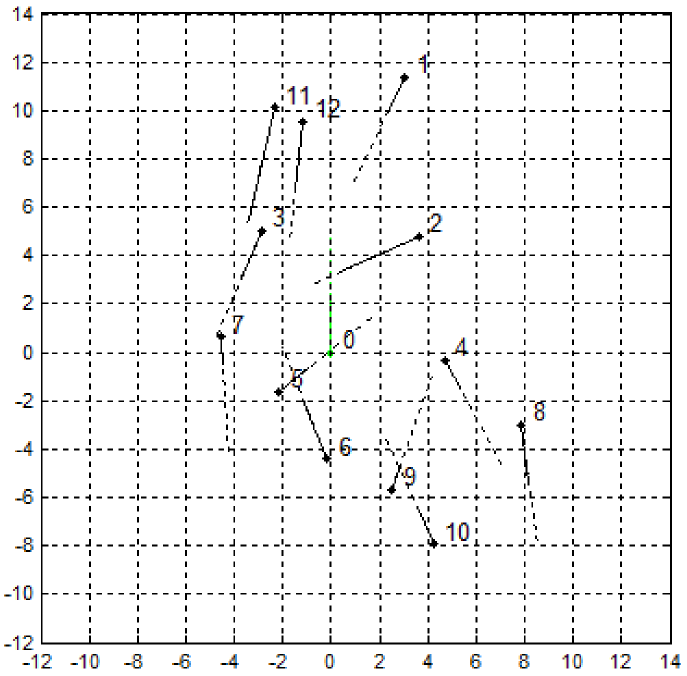

Figure 15. The 12 minute speed vectors of own ship and 12 encountered ships in situation in Kattegat Strait.

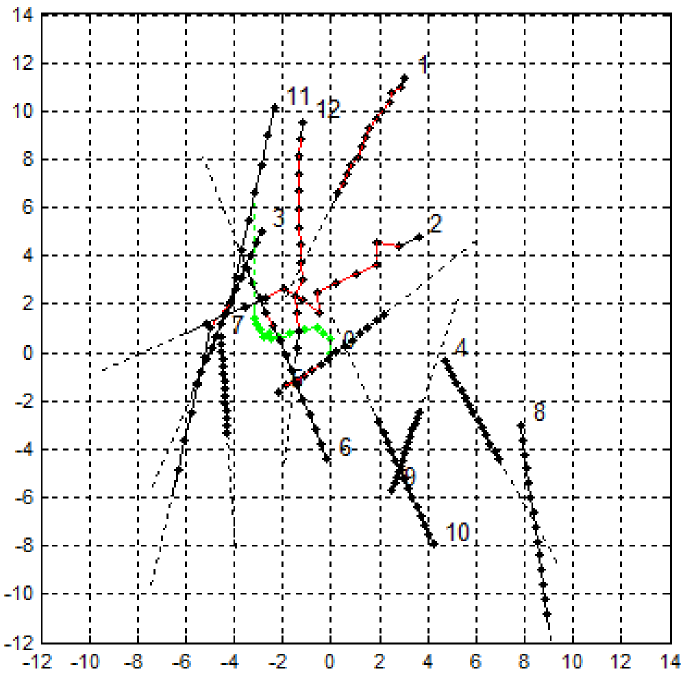

Figure 16. The safe trajectory of own ship for MSPNCG algorithm in restricted visibility $D_s=2$ *nm* in situation of passing *j=12* encountered ships, $r(t_k)=0$, $d(t_k)=3.20$ *nm*.

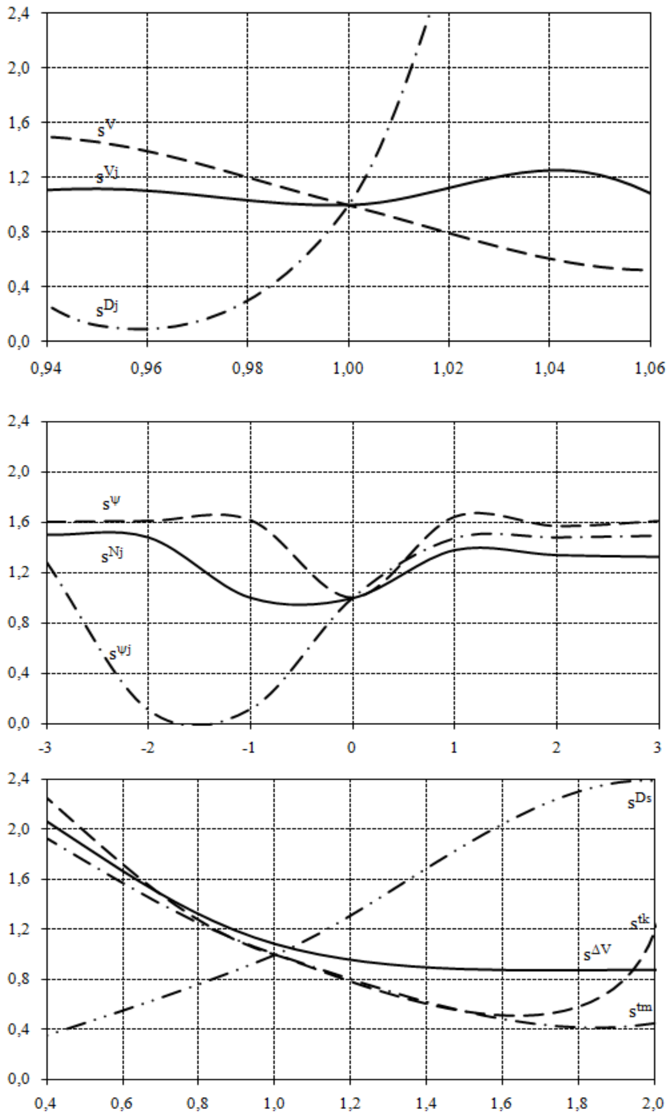

Figure 17. Sensitivity characteristics of safe ship control according to MSPNCG programme on an example of the navigational situation *j=12* in the Kattegat Strait.

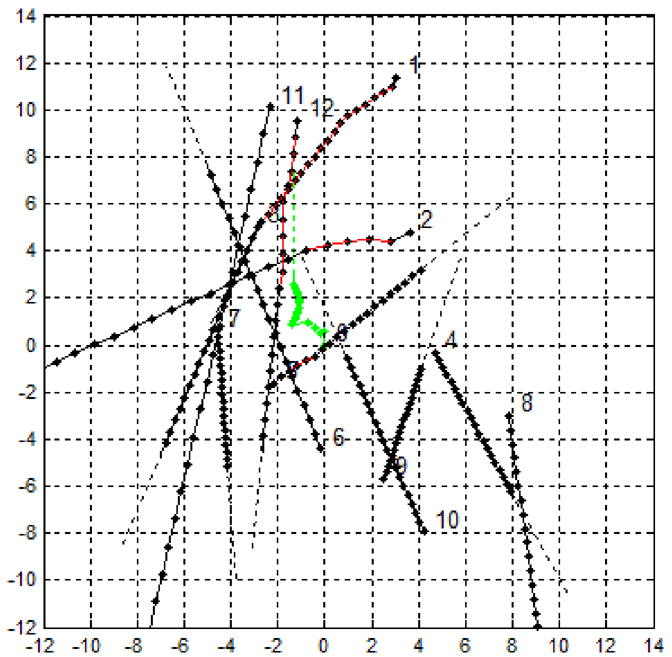

Figure 18. The safe trajectory of own ship for MSPCG algorithm in restricted visibility $D_s=2$ *nm* in situation of passing *j=12* encountered ships, $r(t_k)=0$, $d(t_k)=1.40$ *nm*.

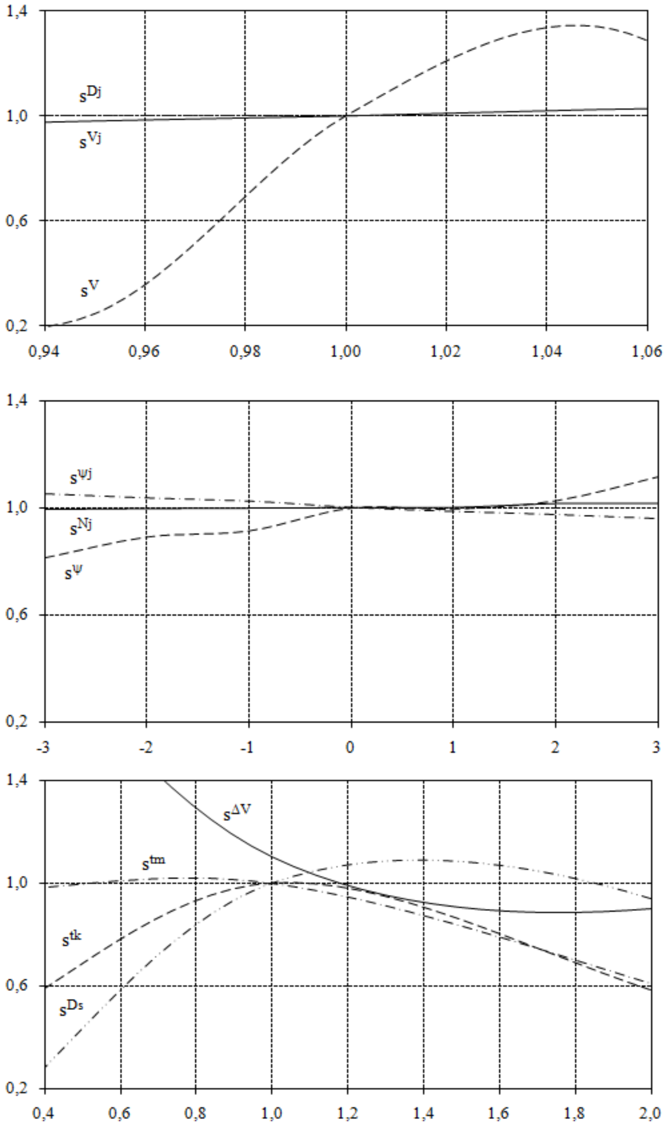

Figure 19. Sensitivity characteristics of safe ship control according to MSPCG programme on an example of the navigational situation *j=12* in the Kattegat Strait.

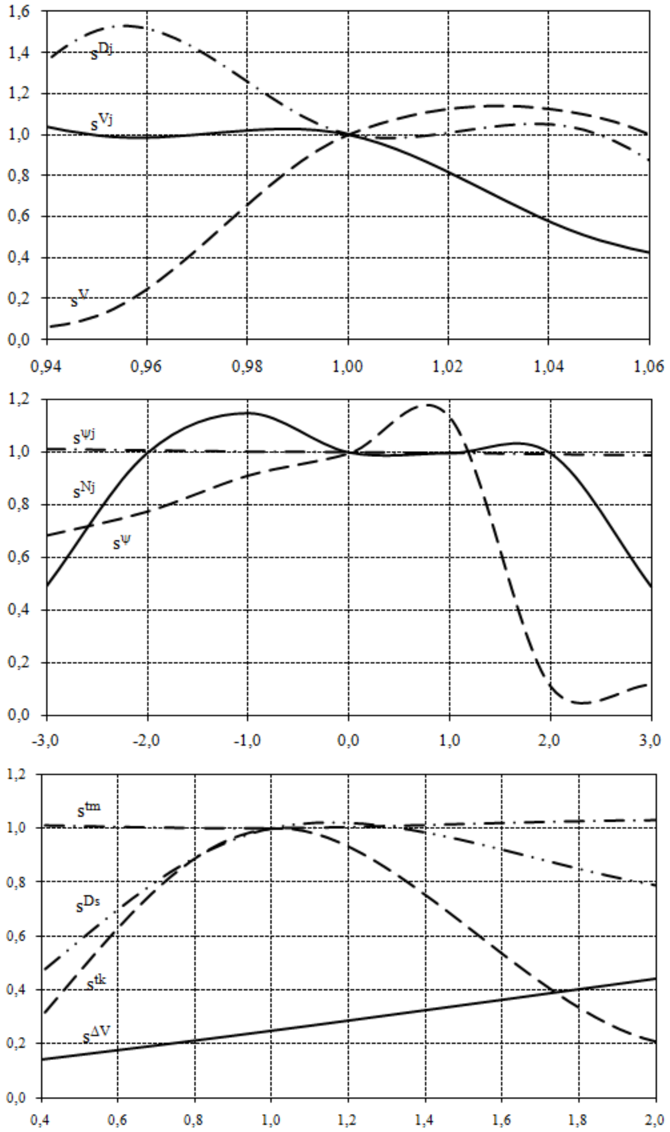

Figure 21. Sensitivity characteristics of safe ship control according to NGKO programme on an example of the navigational situation *j=12* in the Kattegat Strait.

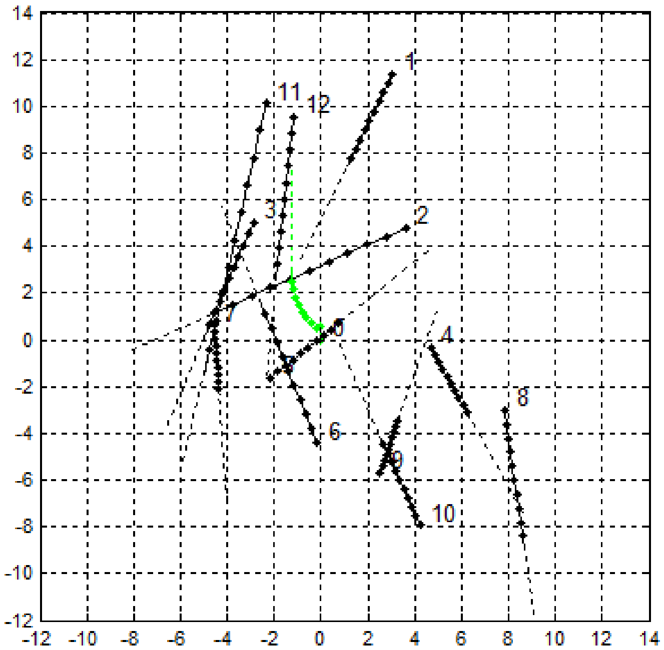

Figure 20. The safe trajectory of own ship for NGKO algorithm in restricted visibility $D_s=2$ *nm* in situation of passing *j=12* encountered ships, $r(t_k)=0$, $d(t_k)=1.23$ *nm*.

4.3 *Navigational situation for j=20 met ships*

Computer simulation of MSPNCG, MSPCG and NGKO programmes was carried out in MATLAB/SIMULINK software on an example of the real navigational situation of passing *j=20* encountered ships in Kattegat Strait in restricted visibility when $D_s=2$ *nm* and were determined sensitivity characteristics for the alterations of the values $X_{0,j}$ and X_{param} within ±6% or ±3° (Figs 22-28).

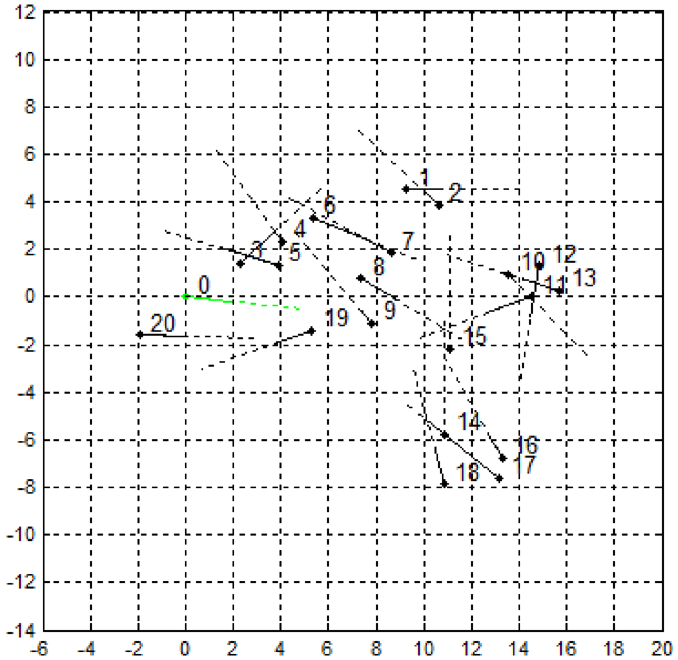

Figure 22. The 12 minute speed vectors of own ship and 20 encountered ships in situation in Kattegat Strait.

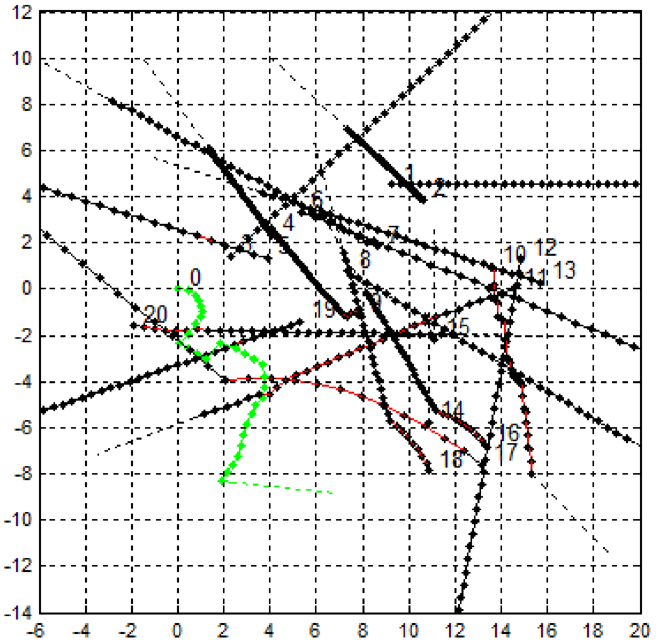

Figure 23. The safe trajectory of own ship for MSPNCG algorithm in restricted visibility $D_s=2$ *nm* in situation of passing *j=20* encountered ships, $r(t_k)=0$, $d(t_k)=8.06$ *nm*.

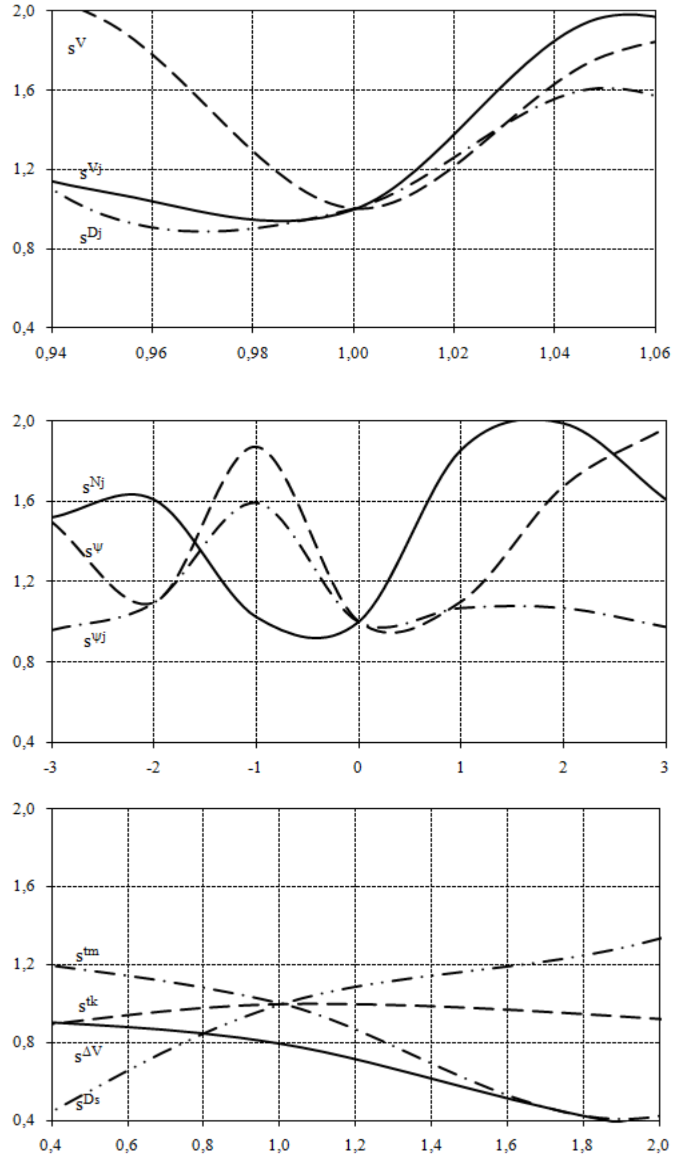

Figure 24. Sensitivity characteristics of safe ship control according to MSPNCG programme on an example of the navigational situation *j=20* in the Kattegat Strait.

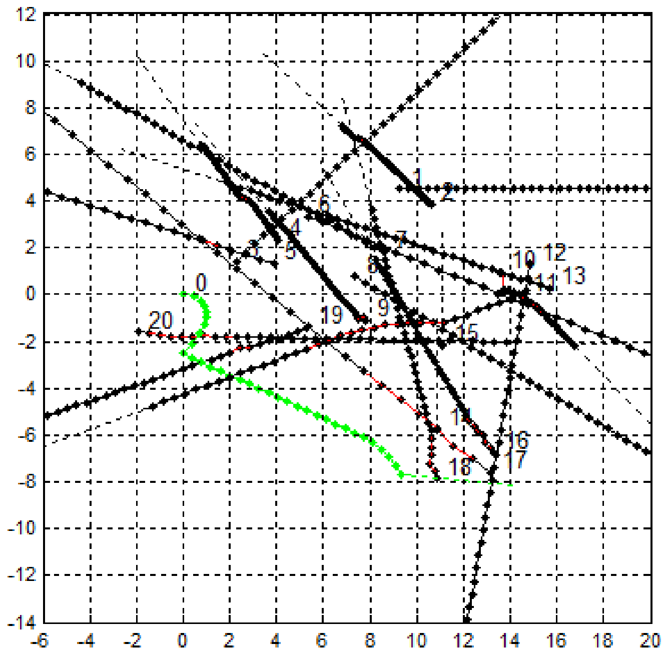

Figure 25. The safe trajectory of own ship for MSPCG algorithm in restricted visibility $D_s=2$ *nm* in situation of passing *j=20* encountered ships, $r(t_k)=0$, $d(t_k)=6.64$ *nm*.

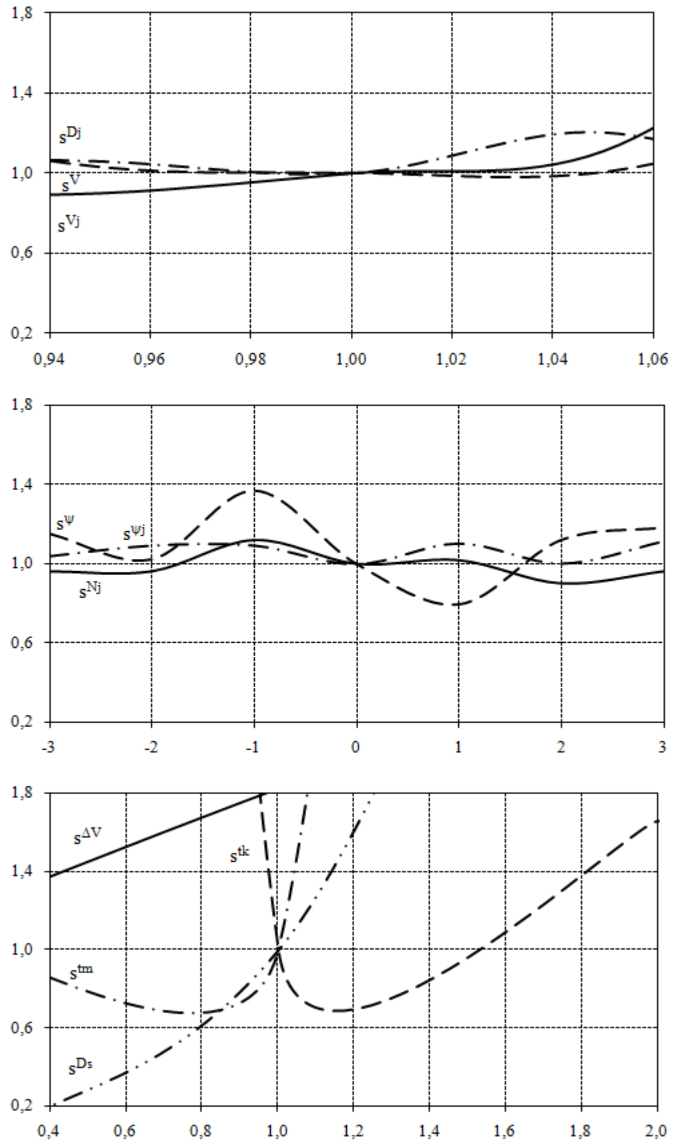

Figure 26. Sensitivity characteristics of safe ship control according to MSPCG programme on an example of the navigational situation *j=20* in the Kattegat Strait.

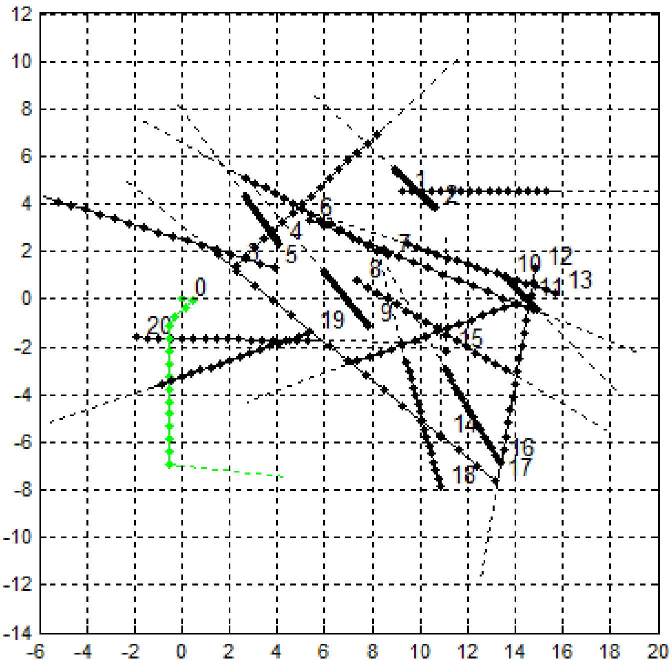

Figure 27. The safe trajectory of own ship for NGKO algorithm in restricted visibility $D_s=2$ *nm* in situation of passing *j=20* encountered ships, $r(t_k)=0$, $d(t_k)=6.94$ *nm*.

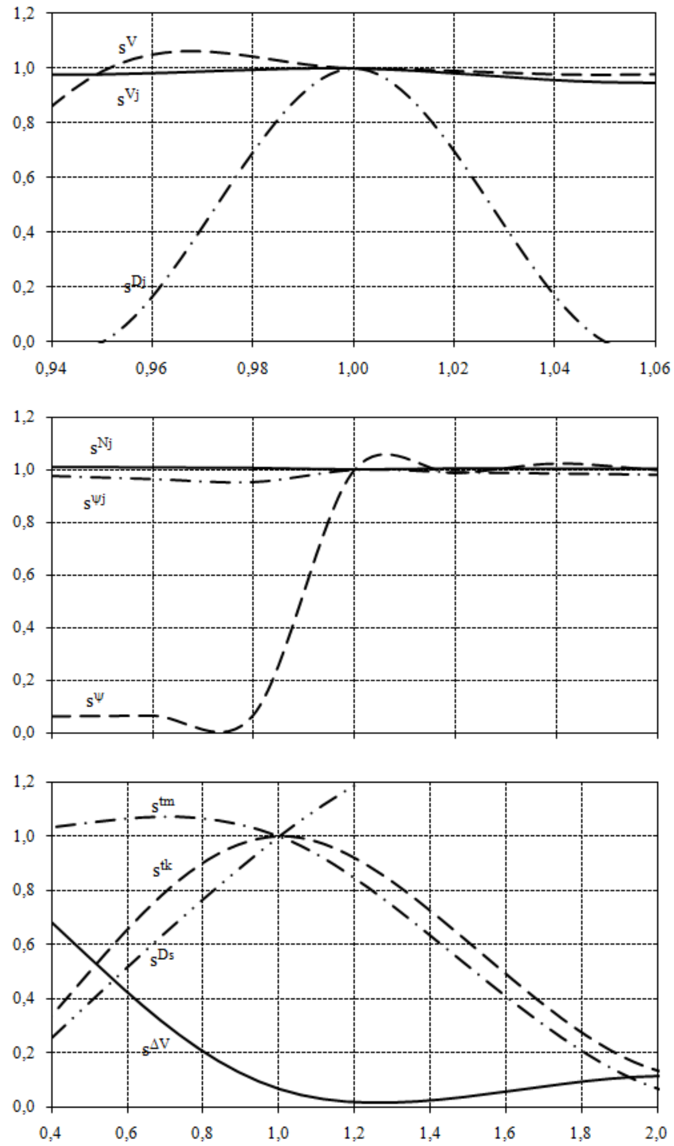

Figure 28. Sensitivity characteristics of safe ship control according to NGKO programme on an example of the navigational situation *j=20* in the Kattegat Strait.

5 CONCLUSIONS

The sensitivity of the final game payment:

- is least relative to the sampling period of the trajectory and advance time manoeuvre,
- most is relative to changes of the own and met ships speed and course,
- it grows with the degree of playing character of the control process and with the quantity of admissible strategies.

The less sensitivity of safe ship control in collision situations is represented by NGKO algorithm and highest by MSPNCG algorithm.

The considered control algorithms are, in a certain sense, formal models of the thinking process of navigator steering of the ship motion and making manoeuvring decisions.

Therefore they may be applied in the construction new model of ARPA system containing the computer supporting of navigator decisions.

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