OPERATING ENVIRONMENT THREATS INFLUENCE ON THE MARITIME FERRY TECHNICAL SYSTEM SAFETY – THE NUMERICAL APPROACH

WPLYW ZAGROŻEŃ ŚRODOWISKA EKSPLOATACYJNEGO NA BEZPIECZEŃSTWO TECHNICZNEGO SYSTEMU PROMU MORSKIEGO – PODEJŚCIE NUMERYCZNE

Ewa Kuligowska

Gdynia Maritime University

Abstract: *The material given in this paper delivers the procedure for numerical approach that allows finding the main practically important safety characteristics of the complex technical systems at the variable operation conditions including operating environment threats. The obtained results are applied to the safety evaluation of the maritime ferry technical system. It is assumed that the conditional safety functions are different at various operation states and have the exponential forms. Using the procedure and the program written in Mathematica, the considered maritime ferry technical system main characteristics including: the conditional and the unconditional expected values and standard deviations of the system lifetimes, the unconditional safety function and the risk function are determined.*

Keywords: *safety, operating environment threat, maritime ferry technical system*

Streszczenie: *W pracy przedstawiono procedurę dla podejścia numerycznego, która umożliwia znalezienie głównych charakterystyk bezpieczeństwa złożonych systemów technicznych pracujących w zmiennych warunkach eksploatacji, wraz z uwzględnieniem wpływu zagrożeń środowiska eksploatacyjnego. Uzyskane wyniki zostały zastosowane do oceny bezpieczeństwa technicznego systemu promu morskiego. Zakłada się wykładnicze warunkowe funkcje bezpieczeństwa, różne w różnych stanach eksploatacyjnych. Stosując powyższą procedurę dla danego systemu oraz wykorzystując program napisany w systemie Mathematica, zostały oszacowane główne charakterystyki, w tym: warunkowe i bezwarunkowe wartości oczekiwane i odchylenia standardowe czasów życia systemu, bezwarunkowa funkcja bezpieczeństwa systemu oraz funkcja ryzyka systemu.*

Słowa kluczowe: *bezpieczeństwo, zagrożenia środowiska, techniczny system promu morskiego*

1. Introduction

Most real technical systems are structurally very complex and they often have complicated operation processes. The common safety and operation including operating environment threats analysis of complex technical systems and critical infrastructures is of great value in the industrial practice. The convenient tools for analyzing this problem are the multistate system's safety modeling [7] commonly used with the semi-Markov modeling [6], [10] of the systems operation processes including operating environment threats [2], leading to the construction the joint general safety models of the complex technical systems and critical infrastructures related to their operation process and the operating environment threats influence on their safety structures and their components safety parameters [5].

The paper presents a general procedure for numerical approach applied to determine safety characteristics of the maritime ferry technical system and its components, related to its operation process including operating environment threats. The procedure is based on the model given in [9]. On the basis of the proposed procedure, the computer calculations in *Mathematica* environment determining these characteristics are performed.

2. Maritime ferry technical system operation process related to operating environment threats

The maritime ferry technical system is a series system composed of (Figure 1):

- the navigational subsystem S_1 , composed of one general component $E_{11}^{(1)}$, that is equipped with GPS, AIS, speed log, gyrocompass, magnetic compass, echo sounding system, paper and electronic charts, radar, ARPA, communication system and other subsystems;
- the propulsion and controlling subsystem S_2 , composed of the subsystems:
 - S_{21} , which consist of 4 main engines $E_{11}^{(2)}, E_{12}^{(2)}, E_{13}^{(2)}, E_{14}^{(2)}$;
 - S_{22} , which consist of 3 thrusters $E_{21}^{(2)}, E_{22}^{(2)}, E_{31}^{(2)}$;
 - S_{23} , which consist of twin pitch propellers $E_{41}^{(2)}, E_{51}^{(2)}$;
 - S_{24} , which consist of twin directional rudders $E_{61}^{(2)}, E_{71}^{(2)}$;
- the loading and unloading subsystem S_3 , composed of the subsystems:
 - S_{31} , which consist of 2 remote upper trailer decks to main deck $E_{11}^{(3)}, E_{21}^{(3)}$;
 - S_{32} , which consist of 1 remote fore car deck to main deck $E_{31}^{(3)}$;
- the stability control subsystem S_4 is composed of the subsystems:
 - S_{41} , which consist of an anti-heeling system $E_{11}^{(4)}$, which is used in port during loading operations;

- S_{42} , which consist of an anti-heeling system $E_{21}^{(4)}$, which is used at sea to stabilizing ships rolling;
- the anchoring and mooring subsystem S_5 is composed of the subsystems:
 - S_{51} , which consist of aft mooring winches $E_{11}^{(5)}$;
 - S_{52} , which consist of fore mooring and anchor winches $E_{21}^{(5)}$;
 - S_{53} , which consist of fore mooring winches $E_{31}^{(5)}$.

Fig. 1 The detailed scheme of the maritime ferry system structure

In this report, we assume that the maritime ferry technical system operation process and safety may depend on its operating environment threats and we distinguish the following 3 unnatural threats: ut_1 – a human error, ut_2 – a terrorist attack and ut_3 – a heavy sea traffic.

Taking into account expert opinions on the operation process without of separation of the operating environment threats of the considered system, in [1], there were distinguished seven operation states. In this case, according to (3.7) in [1], the maximum value of the number of operation states v' of the maritime ferry technical system operation process $Z'(t)$ related to its operating environment threats is 144 [2]. Taking into account expert opinions on the varying in time operation process $Z'(t)$ of the considered system and assuming that the threats are disjoint, according to (2.12)-(2.15) in [2], we distinguish the following as its 72 operation states (input data for *Mathematica*: *numberofstates* = 72), respectively marked by:

$$z'_b = z_1, \text{ for } b = 1, z'_b = z_2, \text{ for } b = 5, \dots, z'_b = z_{18}, \text{ for } b = 69; \quad (1)$$

where z'_b , $b = 1, 5, \dots, 69$, are the operation states without including operating environment threats ut_1 , ut_2 , ut_3 and

$$z'_b, \text{ for } b = 2, 3, 4, 6, 7, 8, \dots, 70, 71, 72. \quad (2)$$

are the operation states including state z_b , $b = 1, 2, \dots, 18$, and successively the threats ut_1 , ut_2 , ut_3 .

The influence of the above system operation states changing on the changes of the maritime ferry technical system safety structure is similar to that described in Section 2.3 of [1]. For the new operation states numeration, we have the following system structures (there are listed the subsystems with the operation process impact on system safety) [5]:

- at the system operation states z'_b , $b = 1, 2, 3, 4, 29, 30, \dots, 36, 69, 70, 71, 72$, the system is composed of series subsystems S_3 and S_4 ;
- at the system operation states z'_b , $b = 5, 6, 7, 8, 25, 26, 27, 28, 37, 38, 39, 40, 65, 66, 67, 68$, the system is composed of series subsystems S_1 , S_2 (which contains a "2 out of 4" subsystem S_{21} , a parallel-series subsystem S_{22} , among others) and S_5 ;
- at the system operation states z'_b , $b = 9, 10, 11, 12, 41, 42, 43, 44, 57, \dots, 64$, the system is composed of series subsystems S_1 and S_2 (which contains a "2 out of 4" subsystem S_{21} , a parallel-series subsystem S_{22} , among others);
- at the system operation states z'_b , $b = 13, 14, \dots, 20, 45, \dots, 56$, the system is composed of series subsystems S_1 , S_2 (which contains a "2 out of 4" subsystem S_{21} , among others) and S_4 ;
- at the system operation states z'_b , $b = 21, 22, 23, 24$, the system is composed of series subsystems S_1 , S_2 (which contains a "2 out of 4" subsystem S_{21} , a parallel-series subsystem S_{22} , among others) and S_4 .

Considering expert opinions (MSRSG, GMU, MOG) that at all operation states z_b , $b = 1, 2, \dots, 18$, of the maritime ferry technical system, the probability of a human error, a terrorist attack and of a heavy sea traffic can be approximately and respectively evaluated as [2]

$$P_b(ut_1) = P(ut_1) = 0.0006, \quad P_b(ut_2) = P(ut_2) = 0, \quad P_b(ut_3) = P(ut_3) = 0.0004. \quad (3)$$

According to [2], it was possible to predict the limit transient probabilities p'_b , $b = 1, 2, \dots, 72$, of the maritime ferry technical system operation process $Z(t)$ including operating environment threats at particular states given in the list below (input data for *Mathematica*):

$$\begin{aligned} \text{limit}_{pb} = \{ & 0.037, 0.0006, 0, 0.0004, 0.001, 0.0006, 0, 0.0004, 0.025, 0.0006, 0, 0.0004, \\ & 0.035, 0.0006, 0, 0.0004, 0.362, 0.0006, 0, 0.0004, 0.025, 0.0006, 0, 0.0004, \\ & 0.004, 0.0006, 0, 0.0004, 0.015, 0.0006, 0, 0.0004, 0.036, 0.0006, 0, 0.0004, \\ & 0.001, 0.0006, 0, 0.0004, 0.002, 0.0006, 0, 0.0004, 0.015, 0.0006, 0, 0.0004, \\ & 0.35, 0.0006, 0, 0.0004, 0.033, 0.0006, 0, 0.0004, 0.023, 0.0006, 0, 0.0004, \\ & 0.002, 0.0006, 0, 0.0004, 0.004, 0.0006, 0, 0.0004, 0.012, 0.0006, 0, 0.0004 \}. \end{aligned} \quad (4)$$

3. Safety of maritime ferry technical system related to its operating process including operating environment threats

Maritime ferry technical system safety parameters

After discussion with experts, taking into account the safety of the operation of the ferry, we fix 5 ($z = 5$) safety states of the ferry technical system and we distinguish the following safety states:

- a safety state 4 – the ferry operation is fully safe,
- a safety state 3 – the ferry operation is less safe and more dangerous because of the possibility of environment pollution,
- a safety state 2 – the ferry operation is less safe and more dangerous because of the possibility of environment pollution and causing small accidents,
- a safety state 1 – the ferry operation is much less safe and much more dangerous because of the possibility of serious environment pollution and causing extensive accidents,
- a safety state 0 – the ferry technical system is destroyed.

Moreover, by the expert opinions, we assume that there are possible the transitions between the components' safety states only from better to worse ones.

Considering the assumptions and agreements from Section 4, we assume that the components of the subsystem S_ν , $\nu = 1, 2, 3, 4, 5$, at the system operation states z'_b , $b = 1, 2, \dots, 72$, have the exponential safety functions, i.e. the coordinates of the vector (1) given in [9] are determined in *Mathematica* using the formula

$$S[\lambda] := \text{Exp}[-\lambda * t], t \in (0, \infty) \quad (5)$$

where λ is the ageing intensity of the maritime ferry technical system component at the system operation process state z'_b , $b = 1, 2, \dots, 72$.

According to expert opinions, changing the maritime ferry operation process states including operating environment threats have influence on changing the system safety structures and its selected components' safety parameters as well. For this system, the intensities of components departure from the safety states subset $\{1, 2, 3, 4\}$, $\{2, 3, 4\}$, $\{3, 4\}$, $\{4\}$, without of operation impact (the input data for *Mathematica*), are given as follows:

- for the series-connected elements:

$$\begin{aligned} \lambda_1 &= \{ 0.015, 0.010, 0.010, 0.010, 0.010, 0.010, 0.010, 0.010, \\ &\quad 0.010, 0.015, 0.015, 0.010, 0.010, 0.010 \}; \\ \lambda_2 &= \{ 0.020, 0.015, 0.015, 0.015, 0.015, 0.015, 0.025, 0.025, \\ &\quad 0.025, 0.030, 0.030, 0.020, 0.020, 0.020 \}; \\ \lambda_3 &= \{ 0.022, 0.020, 0.020, 0.020, 0.020, 0.020, 0.030, 0.030, \\ &\quad 0.030, 0.045, 0.045, 0.030, 0.030, 0.030 \}; \\ \lambda_4 &= \{ 0.025, 0.025, 0.025, 0.025, 0.025, 0.025, 0.040, 0.040, \\ &\quad 0.040, 0.050, 0.050, 0.040, 0.040, 0.040 \}, \end{aligned} \quad (6)$$

Maritime ferry technical system safety characteristics

In [7], it is fixed that the maritime ferry technical system safety structure and its subsystems and components safety depend on its changing in time operation states. The influence of the system operation states changing on the changes of the system safety structure and its components safety functions is given in [2], [5]. Thus, in the case when the operation time is large enough, according to (1) given in [9], the maritime ferry technical system unconditional safety function is given by the vector

$$S'(t, \cdot) = [1, S'(t,1), S'(t,2), S'(t,3), S'(t,4)], t \in <0, +\infty), \quad (10)$$

and considering the maritime ferry technical system operation process transient probabilities at the operation states given by (4), the vector coordinates are given respectively for $t \in <0, +\infty)$, $u = 1,2,3,4$, by

$$\begin{aligned} S'(t,u) = & 0.037 [S'(t,u)]^{(1)} + 0.0006 [S'(t,u)]^{(2)} + 0.0004 [S'(t,u)]^{(4)} \\ & + 0.001 [S'(t,u)]^{(5)} + 0.0006 [S'(t,u)]^{(6)} + 0.0004 [S'(t,u)]^{(8)} \\ & + 0.025 [S'(t,u)]^{(9)} + 0.0006 [S'(t,u)]^{(10)} + 0.0004 [S'(t,u)]^{(12)} \\ & + 0.036 [S'(t,u)]^{(13)} + 0.0006 [S'(t,u)]^{(14)} + 0.0004 [S'(t,u)]^{(16)} \\ & + 0.362 [S'(t,u)]^{(17)} + 0.0006 [S'(t,u)]^{(18)} + 0.0004 [S'(t,u)]^{(20)} \\ & + 0.025 [S'(t,u)]^{(21)} + 0.0006 [S'(t,u)]^{(22)} + 0.0004 [S'(t,u)]^{(24)} \\ & + 0.004 [S'(t,u)]^{(25)} + 0.0006 [S'(t,u)]^{(26)} + 0.0004 [S'(t,u)]^{(28)} \\ & + 0.015 [S'(t,u)]^{(29)} + 0.0006 [S'(t,u)]^{(30)} + 0.0004 [S'(t,u)]^{(32)} \\ & + 0.036 [S'(t,u)]^{(33)} + 0.0006 [S'(t,u)]^{(34)} + 0.0004 [S'(t,u)]^{(36)} \\ & + 0.001 [S'(t,u)]^{(37)} + 0.0006 [S'(t,u)]^{(38)} + 0.0004 [S'(t,u)]^{(40)} \\ & + 0.002 [S'(t,u)]^{(41)} + 0.0006 [S'(t,u)]^{(42)} + 0.0004 [S'(t,u)]^{(44)} \\ & + 0.015 [S'(t,u)]^{(45)} + 0.0006 [S'(t,u)]^{(46)} + 0.0004 [S'(t,u)]^{(48)} \\ & + 0.350 [S'(t,u)]^{(49)} + 0.0006 [S'(t,u)]^{(50)} + 0.0004 [S'(t,u)]^{(52)} \\ & + 0.033 [S'(t,u)]^{(53)} + 0.0006 [S'(t,u)]^{(54)} + 0.0004 [S'(t,u)]^{(56)} \\ & + 0.023 [S'(t,u)]^{(57)} + 0.0006 [S'(t,u)]^{(58)} + 0.0004 [S'(t,u)]^{(60)} \\ & + 0.002 [S'(t,u)]^{(61)} + 0.0006 [S'(t,u)]^{(62)} + 0.0004 [S'(t,u)]^{(64)} \\ & + 0.004 [S'(t,u)]^{(65)} + 0.0006 [S'(t,u)]^{(66)} + 0.0004 [S'(t,u)]^{(68)} \\ & + 0.012 [S'(t,u)]^{(69)} + 0.0006 [S'(t,u)]^{(70)} + 0.0004 [S'(t,u)]^{(72)}, \end{aligned} \quad (11)$$

where $[S'(t,u)]^{(b)}$, $u = 1,2,3,4$, $b = 1,2,...,28$, are given in [5].

The graph of the three-state maritime ferry technical system safety function is presented in Figure 2.

Fig. 2 The graph of the maritime ferry system safety function $S'(t, \cdot)$ coordinates

The expected values and standard deviations (in years) of the system unconditional lifetimes in the safety state subsets $\{1,2,3,4\}$, $\{2,3,4\}$, $\{3,4\}$, $\{4\}$, calculated from the above results given by (11), respectively are:

$$\mu'(1) \cong 5.79, \quad \mu'(2) \cong 3.16, \quad \mu'(3) \cong 2.34, \quad \mu'(4) \cong 1.88, \quad (12)$$

$$\sigma'(1) \cong 5.57, \quad \sigma'(2) \cong 3.08, \quad \sigma'(3) \cong 2.28, \quad \sigma'(4) \cong 1.83, \quad (13)$$

and further, considering (12), the mean values (in years) of the unconditional lifetimes in the particular safety states 1, 2, 3, 4 respectively are:

$$\bar{\mu}'(1) = 2.63, \quad \bar{\mu}'(2) = 0.82, \quad \bar{\mu}'(3) = 0.46, \quad \bar{\mu}'(4) = 1.88, \quad (14)$$

Since the critical safety state is $r = 2$, then the system risk function is given by

$$r'(t) = 1 - S'(t, 2), \text{ for } t \in <0, +\infty), \quad (15)$$

where $S'(t, 2)$ is given by (11). Hence, the moment when the system risk function exceeds a permitted level, for instance $\delta = 0.05$, is

$$\tau = r'^{-1}(\delta) \cong 0.17 \text{ year.} \quad (16)$$

The graph (the fragility curve) of the maritime ferry technical system risk function $r'(t)$ is presented in Figure 3.

Fig. 3 The graph of the maritime ferry technical system risk function $r'(t)$

4. Conclusions

The predicted safety characteristics of the maritime ferry technical system operating at the variable conditions including operating environment threats are different from those determined for the considered system without of considering the impacts of operating environment threats on their safety [3]. This fact justifies the sensibility of considering real systems at the variable operation conditions that is appearing out in a natural way from practice. This approach makes the systems safety prediction much more precise.

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Ewa Kuligowska MSc Eng., is an Assistant at Department of Mathematics of the Faculty of Navigation in Gdynia Maritime University. Her field of interest is Monte Carlo simulation analysis of complex systems safety and reliability. She has published over 30 papers in scientific journals and conference proceedings.