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A Particular Model of Redundancy Useful in the Assessment of Operational Reliability and Safety of a Dynamic Positioning System of an Offshore Vessel

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Abstract

Differences in definitions of offshore dynamically positioned *(DP)* vessels' equipment classes are presented. The definitions of particular classes according to the International Maritime Organization (IMO) and some classification societies are given. Tables with measures describing the requirements for the construction of DP sub-systems are presented. A decomposition of dynamic positioning system structures and a description of redundancy using a complex plane have been proposed. For these, the values of measures are given in a table form describing the construction requirements concerning particular DP subsystems in compliance with various recommendations.

Keywords: technical system, dynamic positioning, redundancy, spare components, offshore vessel, vessel safety and reliability

Introduction

Among a variety of offshore vessels there is a group of ships operating as construction support craft in crude oil and natural gas production. These ships are fitted with dynamic positioning (DP) systems used to maintain automatically ship's defined position and heading. In order to ensure a certain level of safety and reliability most of the DP subsystems are subject to redundancy [1, 2]. Basic components in DP system have been shown in Fig. 1.

The dynamic positioning system is characterized by all types of redundancy, *i.e.* some components are generally redundant while others are separately redundant. Therefore, the *DP* system can be said to be a system with mixed redundancy. For instance, generator sets of the marine power plant have separate redundancy, while diesel power plants are redundant in general, *i.e.* general redundancy is applied. Besides, diesel generator sets in some operating states run in a system where there are more basic components than redundant ones, with each redundant diesel generator set being capable of replacing any of the basic generator sets (shifting redundancy). As far as failure intensity is concerned, systems usually feature hot spare (thruster redundancy) or warm spare (electric power stations) in order to ensure very fast switch-over in case a basic component is damaged.

Further part of this article will present a generalized model of a dynamic positioning structure and will propose the use of complex plane for the description of redundancy in these systems.

Definitions of Equipment Classes of Dynamic Positioning Vessels

The equipment of vessels with dynamic positioning, that is vessels capable of maintaining a given position and heading in a required range while performing technological operations at sea has to comply with certain regulations and requirements. *IMO* regulations apply to ships built after 1 June 1994 and divide ships with automatic positioning into three classes. The IMO classification does not cover ships with manual or semi-automatic position control. Levels of redundancy are defined in an IMO circular [4] and subsequent detailed guidelines published by the International Marine Contractors' Association (*IMCA*) [5].

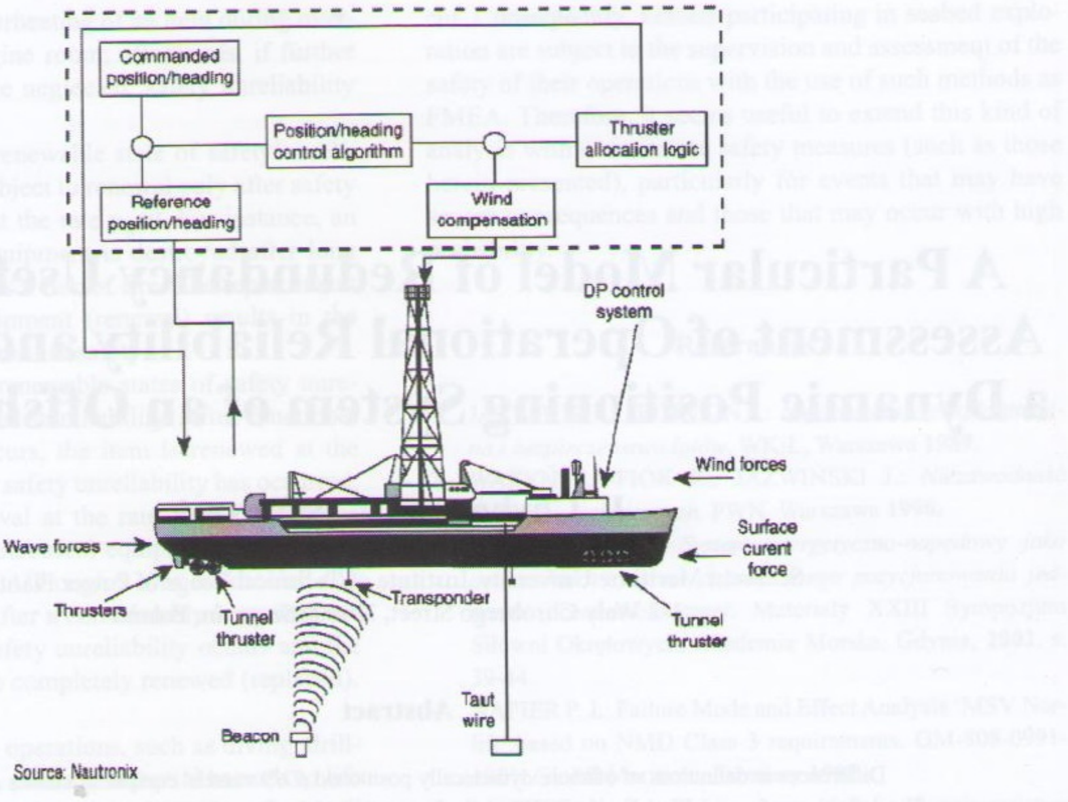

Fig. 1. General outline of dynamic positioning system [3].

Equipment classes for DP vessels as defined by IMO are as follows: Class 1 – loss of position (drifting off a given position and/or heading due to a DP system failure) may occur in the event of a single fault. Class 2 – loss of position (drifting off a given position and/or heading due to a DP system failure) should not occur from a single fault of an active component or system such as generators, thruster, switchboards, remote controlled valves *etc.* But may occur after failure of a passive component such as cables, pipes, manual valves *etc.* Class 3 – loss of position (drifting off a given position and/or heading due to a DP system failure) should not occur from any single failure including a completely burnt fire sub-division (*e.g.* one of the power plants) or flooded watertight engine room compartment. Single faults also include single inadvertent act by any person on board the DP vessel

Classification societies define particular classes in a different manner. For example, the *American Bureau of Shipping* defines the following classes [7]: DPS-0 – vessels with this class are equipped with a DP system which ensures manual position control and automatic heading control under specified maximum environmental conditions; DPS-1 – vessels with this class are equipped with a DP system which ensures automatic position and heading control under specified maximum environmental conditions, with an independent stand for manual position control while heading is controlled automatically; DPS-2 – vessels with this class are equipped with a DP system which ensures automatic position and heading control under specified maximum environmental conditions, during and following any single fault excluding loss of an engine room compartment or compartments; DPS-3 – vessels with this class are equipped with a DP system which ensures automatic position and heading control under specified maximum environmental conditions, during and following any single fault including loss of an engine room compartment due to fire or flood.

The Norwegian classification society *DNV* (*Det Norske Veritas*) distinguishes an additional DP class, and classifies vessels with dynamic positioning into five equipment classes, namely [9]: DYNPOS T – semi-automatic system of position control without redundancy; AUTS – automatic position control system without redundancy. This class corresponds in professional publications to either DPS-0 or DPS-1 classes; AUT – automatic position keeping system with redundancy in technical design, *i.e.* remote thrust control back up and a position reference back up; AUTR – automatic position control system with redundancy in technical design; AUTRO – automatic position control system with redundancy in technical design and physical arrangement of subsystems (necessity of using separate compartments).

The LRS (*Lloyds Register of Shipping*) is another classification society which has its own notation for the four classes of DP vessel equipment [10]: DP(CM) – notation assigned to systems for ships with a centralized remote manual standby positioning with specific systems of reference sensors, environmental sensors and machinery arrangements; DP(AM) – notation assigned to systems in ships with automatic and standby manual controls for positioning keeping and with position reference system(s), environmental sensor(s) and machinery arrangements; DP(AA) – notation assigned to systems in ships with an automatic main and standby controls for position keeping and with position reference system(s), environmental sensor(s) and machinery arrangements; DP(AAA) – notation assigned to systems in ships fitted with automatic main and standby controls for position keeping together with an additional/emergency automatic control unit located in a separate compartment and with position reference system(s), environmental sensor(s) and machinery arrangements.

The Structure of Dynamic Positioning Systems

A general structure of dynamic positioning systems can be schematically presented as in the diagram shown in Fig. 2.

The dynamic positioning system consists of [11]:

$$S=\{E_{S1}, E_{S2}, E_{S3}, E_{S4}, E_{S5}, E_{S6}\} \quad (1)$$

where: E_{S1} – automatic system of dynamic positioning supervision; E_{S2} – ship's electric power plant; E_{S3} – ship's propulsion system; E_{S4} – emergency electric power supply; E_{S5} – reference sensors system; E_{S6} – the other components of DP system.

The above subsystems, in turn, are composed of:

$$E_{S1} = \{E_{S1\text{-}1}, E_{S1\text{-}2}, E_{S1\text{-}3}, E_{S1\text{-}4}\} \quad (2)$$

where: $E_{S1\text{-}1}$ – DP control unit; $E_{S1\text{-}2}$ – DP supervision station; $E_{S1\text{-}3}$ – manual control system; $E_{S1\text{-}4}$ – the other systems connected with positioning operations supervision;

$$E_{S2} = \{E_{S2\text{-}1}, E_{S2\text{-}2}, E_{S2\text{-}3}, E_{S2\text{-}4}, E_{S2\text{-}5}\} \quad (3)$$

where: $E_{S2\text{-}1}$ – diesel generator sets of the main power plant; $E_{S2\text{-}2}$ – main switchboard and power distribution management system; $E_{S2\text{-}3}$ – auxiliary machinery of the main power plant; $E_{S2\text{-}4}$ – mains switchboard buses; $E_{S2\text{-}5}$ – the remaining systems related to power generation and distribution;

$$E_{S3} = \{E_{S3\text{-}1}, E_{S3\text{-}2}, E_{S3\text{-}3}, E_{S3\text{-}4}, E_{S3\text{-}5}\} \quad (4)$$

where: $E_{S3\text{-}1}$ – ship's main propulsion unit with the propeller; $E_{S3\text{-}2}$ – rudder of the main propulsion with propulsion and control system; $E_{S3\text{-}3}$ tunnel thrusters with propulsion; $E_{S3\text{-}4}$ – azimuth thrusters with propulsion; $E_{S3\text{-}5}$ – the remaining systems related to thruster system;

$$E_{S4} = \{E_{S4\text{-}1}, E_{S4\text{-}2}, E_{S4\text{-}3}, E_{S4\text{-}4}\} \quad (5)$$

where: $E_{S4\text{-}1}$ – uninterrupted power supply; $E_{S4\text{-}2}$ – battery set; $E_{S4\text{-}3}$ – emergency power plant; $E_{S4\text{-}4}$ – the remaining systems related to emergency power supply;

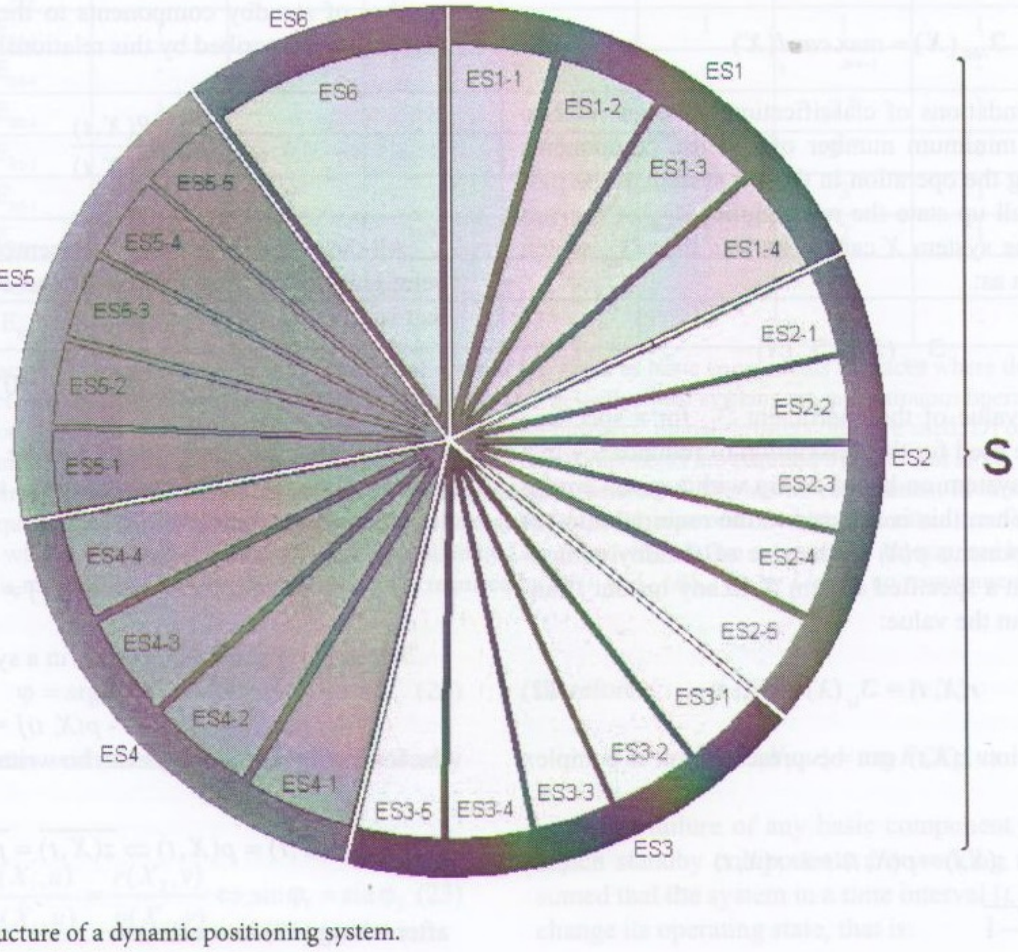

Fig. 2. General structure of a dynamic positioning system.

$$E_{S5} = \{E_{S5\text{-}1}, E_{S5\text{-}2}, E_{S5\text{-}3}, E_{S5\text{-}4}, E_{S5\text{-}5}\} \quad (6)$$

where: $E_{S5\text{-}1}$ – gyrocompass; $E_{S5\text{-}2}$ – anemometer; $E_{S5\text{-}3}$ – ship position reference unit; $E_{S5\text{-}4}$ – vertical reference unit /*VRU*/; $E_{S5\text{-}5}$ – the remaining DP sensor systems.

In order to model the redundancy in the system *X* the transformation $z(X, t)$ was introduced, which resulted in a pair of numbers, which is, respectively, equal to the number of basic components $p(X, t)$ and the number of standby components $r(X, t)$ w in the system *X* at the time *t*:

$$z(X,t) = (p(X, t), r(X, t)) \quad (7)$$

For a given moment of time $t \geq 0$ the total number of components $\Im(X,t)$ in the system *X* equals:

$$\Im(X,t) = p(X, t) + r(X, t) = \Im(X,0) - \Im_{REST}(X, t) \quad (8)$$

where: $\Im(X,0)$ – size of the system *X* with the assumed preset full availability of the system at the time $t=0$ equal to:

$$\Im(X,0) = \underset{t=0}{card}(X) = p(X,0) + r(X,0) \quad (9)$$

where: $\Im_{REST}$ – number of components of the system *X* that have been damaged till the time t.

A comparison of redundancy level in *DP* systems on ships belonging to any of the equipment class is possible through, *e.g.* the introduction of the coefficient $\Im_{real}$, that is equal to the maximum number of system components in the up state that could be observed during their operation:

$$\Im_{real}(X) = \max_{t \to \infty} \underset{t}{card}(X) \quad (10)$$

Recommendations of classification societies refer to the required minimum number of specific components $\Im_{kr}$, *i.e.* during the operation in the DP system at the moment of its full up state the real amount $\Im_{real}$ of a given sub-unit in the system *X* cannot be less than $\Im_{kr}$, which can be written as:

$$\Im_{real}(X) \geq \Im_{kr}(X) \quad (11)$$

Thus the value of the coefficient $\Im_{kr}$ for a specified system can be used for the description of redundancy in a specified subsystem on board a ship with a given equipment class. When this is referred to the required number of basic components $p(X, t)$, the size of standby components $r(X, t)$ in a specified system *X*, in any instant *t* cannot be less than the value:

$$r(X, t) = \Im_{kr}(X) - p(X, t) \quad (12)$$

The function $z(X,t)$ can be presented on a complex plane as:

$$z(X,t) = p(X, t) + i \cdot r(X, t) \quad (13)$$

where: $i = \sqrt{-1}$

After substituting for the relation (12) we obtain a formula connected with the standard measure $\Im_{kr}$ which has this form:

$$z(X,t) = p(X, t) + i \cdot [\Im_{kr}(X) - p(X, t)] \quad (14)$$

The required minimum size of particular components of dynamic positioning systems $z(X,t)$ are presented in Table 1. For the adopted notations of particular subsystems the values of measures referring to various classes of DP equipment are presented. The lowest values for $\Im_{kr}(X)$ are given.

Redundancy Models of Various DP Equipment Classes

Due to strictly defined integer values, contained in specified ranges of the data above, redundancy models of particular DP system structures can be located in specific points of the complex plane. The individual structures of DP subsystems were assigned to specified points of the complex plane [11] according to the relationship (14). The particular points correspond to these values:

$$p(X, t=0) = \text{re}\,[z(X,t=0)] \quad (15)$$

$$r(X, t=0) = \text{im}\,[z(X,t=0)] \quad (16)$$

The order of redundancy is defined as a ratio of the number of standby components to the number of basic components described by this relationship:

$$\kappa = \frac{R(X,t)}{P(X,t)} \quad (17)$$

All the numbers in models presented have amplitudes belonging to the first quarter of the coordinate system, that is:

$$\{\varphi = \arg F(X,t)\} \in <0, 90°> \quad (18)$$

A number of relationships can be presented for the proposed model. It has been assumed that there exists at least one component in the system:

$$P(X,t) > 0 \Rightarrow F(X,t) \neq 0 \quad (19)$$

When there is no redundancy in a system, that is:

$$r(X, t) = [\Im_{kr}(X) - p(X, t)] = 0 \quad (20)$$

the following relationships can be written:

$$z(X,t) = p(X,t) \Rightarrow \overline{z(X,t)} = \overline{p(X,t)} \quad (21)$$

after taking (19) into account:

Table 1. Equipment requirements for specified DP classes.

DP class - IMO		N/A		Class 1		Class 2		Class 3	
DP class - DNV		DNV-T		DNV-AUTS DNV-AUT		DNV-AUTR		DNV-AUTRO	
DP class - LRS		DP (CM)		DP (AM)		DP (AA)		DP (AAA)	
DP class - ABS		DPS-0		DPS-1		DPS-2		DPS-3	
System	Subsystem								
	X	P(X)	$\Im_{kr}(X)$	P(X)	$\Im_{kr}(X)$	P(X)	$\Im_{kr}(X)$	P(X)	$\Im_{kr}(X)$
E_{S1} [B]	E_{S1-1}	0	0	1	1	1	2	1	3[A]
	E_{S1-2}	1	1	1	1	1	2	1	3[A]
	E_{S1-3}	1	1	1	1	1	1	1	1
	E_{S1-4}	-	-	-	-	-	-	-	-
E_{S2} [B]	E_{S2-1}	1	1	1	1	1	2	1	2[A]
	E_{S2-2}	1	1	1	1	1	2	1	2[A]
	E_{S2-3}	1	1	1	1	1	2	1	2
	E_{S2-4}	0	0	0	0	1	1	2	2
	E_{S2-5}	-	-	-	-	-	-	-	-
E_{S3} [B]	E_{S3-1}	1	2	1	2	1	2	1	2
	E_{S3-2}	1	2	1	2	1	2	1	2
	E_{S3-3}	1	2	1	2	2	4	2	4
	E_{S3-4}	1 [C]	1[C]	1[C]	1[C]	1	2	1	2
	E_{S3-5}	-	-	-	-	-	-	-	-
E_{S4} [B]	E_{S4-1}	0	0	1	1	1	2	1	3[A]
	E_{S4-2}	0	0	1	1	1	2	1	3[A]
	E_{S4-3}	1	1	1	1	1	1	1	1
	E_{S4-4}	-	-	-	-	-	-	-	-
E_{S5} [B]	E_{S5-1}	1	1	1	1[D]	1	2[E]	1	3[A]
	E_{S5-2}	0	0[F]	1	1[D]	1	2[G]	1	2[H]
	E_{S5-3}	0	0[I]	1	1[J]	1	3	1	3[A]
	E_{S5-4}	0	0[I]	1	1[K]	1	2	1	2[A]
	E_{S5-5}	-	-	-	-	-	-	-	-
E_{S6}	E_{S6}	-	-	-	-	-	-	-	-

A) one system is located in a separate room; B) hypothetical systems are given as basic components in places where the number of operating elements refers to a single system (*e.g.* power plant or propeller); actually, most systems are in continuous operation (hot spare); C) common solution, although there are cases where instead of azimuth thrusters tunnel thrusters only are used; D) one component is required by *IMO* and *DNV*, whereas *Lloyds* and *ABS* require two; E) two components are required by *IMO* and *DNV*, whereas *Lloyds* and *ABS* require three; F) one component is required by *Lloyds* and *ABS*, whereas *DNV* has no requirement in this respect; G) two components are required by *ABS*, *DNV* and *Lloyds*, whereas *IMO* requires three; H) two, one of which at another location, whereas IMO recommends three with one in another location; I) one is required by *Lloyds* and *ABS*; J) two components are required by *ABS*, *DNV* and *Lloyds*, while one is required by *IMO*; K) one component is required by *DNV* and *ABS*, two by *Lloyds*, no requirements by *IMO*.

$$\varphi = \arg F(X,t) = 0 \qquad (22)$$

for two systems with the same order of redundancy we obtain:

$$\kappa_1 = \kappa_2 \Leftrightarrow \frac{r(X_1,u)}{p(X_1,u)} = \frac{r(X_2,v)}{p(X_2,v)} \Leftrightarrow \sin\varphi_1 = \sin\varphi_2 \qquad (23)$$

therefore:

$$\arg F(X_1,u) = \arg F(X_2,v) \qquad (24)$$

For a failure of any basic component in a system in which standby components are working it has been assumed that the system in a time interval $(t, t+\Delta t)$ does not change its operating state, that is:

$$p(X, t) = constans \tag{25}$$

and consists of at least one standby (redundant) component:

$$r(X, t) \geq 1 \tag{26}$$

Besides, it has been assumed that at one instant of time $\Delta t \rightarrow 0$, only one basic component can sustain a failure. Another assumption is that redundant components are operational and switch on for operation (take over the load in a negligibly short time). Then a failure of any of the basic components in the system X will cause a state transition:

$$z(X,t) \underset{\lambda}{\overset{t}{\longrightarrow}} z(X,t+\Delta t) \tag{27}$$

where: λ – system failure rate.

The new state of the system can then be described by this formula:

$$F(X,t+\Delta t) = F(X,t) - i \tag{29}$$

For a repair of any redundant component in the system during its up state it has been assumed that the system in a time interval $(t,\ t+\Delta t)$ does not change its operating state (25) and is in the up state; it has also been assumed that at one instant of time $\Delta t \rightarrow 0$ only one component can be repaired and that operational components of the system do not get damaged during the repair.

$$z(X,t) \underset{\rho}{\overset{t}{\longrightarrow}} z(X,t+\Delta t) \tag{30}$$

where: ρ – system repair rate.

The new system state can then be described by this formula:

$$F(X,t+\Delta t) = F(X,t) + i \tag{31}$$

For a failure of any basic component in the system when all the redundant components are damaged, it has been assumed that the system in a time interval $(t,\ t+\Delta t)$ does not change its operating state (25), and that all the redundant components are damaged:

$$r(X, t) = 0 \tag{32}$$

Besides, it has been assumed that at one instant of time $\Delta t \rightarrow 0$ only one basic component can sustain a failure. Then the failure will cause the transition of the system from up state into down state:

$$z(X,t) \underset{\lambda}{\overset{t=t_{kr}}{\longrightarrow}} z(X,t+\Delta t) \tag{33}$$

The new state of the system can be described by this formula:

$$F(X,t+\Delta t) = F(X,t) - 1 \tag{34}$$

For a repair of any component in the system during its down state, it has been assumed that the system in the time interval $(t,\ t+\Delta t)$ does not change its operating state (25). Besides, down state results from a failure of only one component critical for the system, *i.e.* the failure that caused a system damage (breakdown) was a result of the process (33). It has been assumed that at one instant of time $\Delta t \rightarrow 0$, only one component can be repaired and that operational components do not sustain a failure during the repair. The repair of a faulty critical component will cause a transition from down state to up state:

$$z(X,t) \underset{\rho}{\overset{t=t_{kr}}{\longrightarrow}} z(X,t+\Delta t) \tag{35}$$

The new state of the system can be described by the formula:

$$F(X,t+\Delta t) = F(X,t) + 1 \tag{36}$$

For the transition into down state of the system initially being at up state altogether with all redundant components it has been assumed that the system within the process of transition into down state does not change its operating state (25). Another assumption is that no repairs are performed in the system until it goes into down state. It has been assumed that at one instant of time $\Delta t \rightarrow 0$ only one basic component can be damaged and that redundant components, if still operational, switch on for work (take over the load in a negligibly short time). Then the failure of any of the basic components in the system X will cause a transition into the state (32). For a change of system from full up state to down state, with the described assumptions maintained, requires the occurrence of, subsequently, $(n+1)=(r(X,\ t) + 1)$ transitions of system states. Of these, $r(X,\ t)$ transitions are described by the relationship (28), which is connected with the fact that the system has run out of redundant components, whereas the component 1 is described by the transition (33) and is directly connected with system failure. A series of transitions from the starting state to a system failure can be described as:

$$\{\underbrace{[F(X,t_0) \underset{\lambda}{\overset{t_0}{\longrightarrow}} F(X,t_0+\Delta t), F(X,t_1) \underset{\lambda}{\overset{t_1}{\longrightarrow}} F(X,t_1+\Delta t), \ldots, F(X,t_{n-1}) \underset{\lambda}{\overset{t_{n-1}}{\longrightarrow}} F(X,t_{n-1}+\Delta t)],}_{\times R(X,t_0)} \\ F(X,t_n) \underset{\lambda}{\overset{t_n}{\longrightarrow}} F(X,t_n+\Delta t)\} \tag{37}$$

For the transition into the full up state of the system and of all redundant components from the down state of the system it has been assumed that during the entire process of transition into full up state of the system and its redundant components, the system does not change its operating state (26). Besides, the down state results from a failure of only one component critical for the system, i.e. the failure that caused the system breakdown resulted from the process (34). It has been assumed that at one instant of time $\Delta t \rightarrow 0$, only one component can be repaired and that operational components do not fail during the repair process. The repair of the faulty critical (first) component causes a transition of the system from down state to up state. It has been assumed that after restoration the system in subsequent instants of time $(t, t+\Delta t)$ is in up state; besides, it has been assumed that at one instant of time $\Delta t \rightarrow 0$, only one component can be repaired and that operational components do not fail during the repair process. The transition of the system from down state, with all the described assumptions being maintained, to the full up state of the system and all n redundant components requires that first one transition (34) takes place, connected with the restoration of system availability and $(r(X, t_n))$ transitions described by the relationship (31), connected with repairs of all the redundant components in the system. A series of transitions from the initial down state to full up state of the system and all its redundant components can be described as:

$$\{F(X,t_n)\xrightarrow[\rho]{t_n}F(X,t_n+\Delta t),\qquad (38)$$

$$\underbrace{[F(X,t_{n-1})\xrightarrow[\rho]{t_{n-1}}F(X,t_{n-1}+\Delta t),F(X,t_{n-2})\xrightarrow[\rho]{t_{n-2}}F(X,t_{n-2}+\Delta t),\dots,F(X,t_0)\xrightarrow[\rho]{t_0}F(X,t_0+\Delta t)]}_{=(n=\mathrm{im}F(X,t_n))},$$

Conclusions

This article presents a new reliability model of redundancy of technical systems, in this case referring particularly to systems of dynamic positioning that offshore vessels are fitted with. Vessels with dynamic positioning (such as dive support ships, cable-laying vessels, drilling vessels) have to perform tasks different from those of ships designed for cargo carriage (such as bulk carriers, container ships, ro-ro ships *etc.*). One of the differences in ship design between dynamically positioned offshore vessels and cargo transport vessels is that the former have much higher level of redundancy, especially in subsystems directly or indirectly connected with maintaining the specified position and heading of the ship (*DP* system) [12]. In order to maintain required standards of safety and reliability of operation, dynamically positioned vessels are characterized by high functional and structural component spare, where the system structure shows all kinds of redundancy (general, separate and mixed) with a varied order of redundancy depending on the system and operating state (integer or fractional order of redundancy). The tasks a ship is intended for affect the scope of redundancy in particular subsystems providing for vessel dynamic positioning (electric power and propulsion system, control and supervision system, thruster system, system of reference sensors, emergency power supply system etc.).

Models of redundancy using the complex plane have been developed for various design solutions of DP systems of vessels supporting the seabed exploration. These vessels, featuring equipment classes ranging from 0 to 3, are capable of performing advanced deep sea operations. As there are no commonly adopted unequivocal definitions of particular equipment classes of DP vessels (guidelines of IMO and classification societies), certain assumptions have been made to present the requirements of the particular classes in a form enabling their comparison.

The proposed notation in the form of integer pairs allows to carry out a number of transformations on the complex plane. These make it possible to check a series of relationships between subsystems in systems with redundancy. The relationships can be used for modeling and numerical analysis of complex technical systems with a variable functional and reliability structure. For instance, it is possible to sum up the measures $z(X,t)$ for the same components of a system, which can be interpreted as an extension of the system with a specified number of basic and redundant components (serial connection of two systems represented by appropriate measures). Deducting these measures, in turn, is interpreted as a comparison of the structure (difference in the required number of basic components) while redundancy (difference in the required number of redundant components) can be useful in the analysis of operating safety of a DP vessel.

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