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STRUCTURAL REDUNDANCY IN AN OFFSHORE VESSEL DYNAMIC POSITIONING SYSTEM

Key words

Technical system, dynamic positioning, redundancy, spare components, offshore vessel, marine system, reliability estimation, complex number plane.

Summary

A decomposition of dynamic positioning system structures and a description of redundancy in this system using a complex plane have been outlined. System state transition models based on a complex plane have been shortly described and a graph of the system transition has been shown. Application of the redundancy model proposed by the authors for reliability estimation of dynamic positioning system has been presented.

Introduction

Among many kinds of offshore facialities there is a group of ships operating as construction support vessels in offshore crude oil and natural gas production. These vessels are fitted with dynamic positioning (*DP*) systems used to automatically maintain the ship's defined position and heading. In order to ensure a given level of safety and reliability, most of the *DP* subsystems are subject to redundancy [1, 2]. The dynamic positioning system is characterized by all types of redundancy (*DP* system can be said to be a system with mixed 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.

Real physical systems (i.e. technical systems) are characterized by the existence of a situation in which the incompatibility of a feature of a certain system with required features are fail-safe. In such situations, the fault of the component's group does not lead to system failure (system is in full up state or is in partial up state). Systems with such features are called systems with surplus reliability structure. These systems can realize expected (predictable) tasks in certain definite conditions with given damages or the non-performance of required conditions. A system with a non-surplus coherent structure is a system where a fault of any of system component leads to a complete system in a down state. This takes place for systems with a serial reliability structure. Such a structure is in fact an approximation of the real system reliability structure, and it has the theoretical character for the reliability estimation of the whole system, taking into consideration the most pessimistic reliability model. In real systems, we always have surplus structure. The most important redundancy types are shown in Fig. 1.

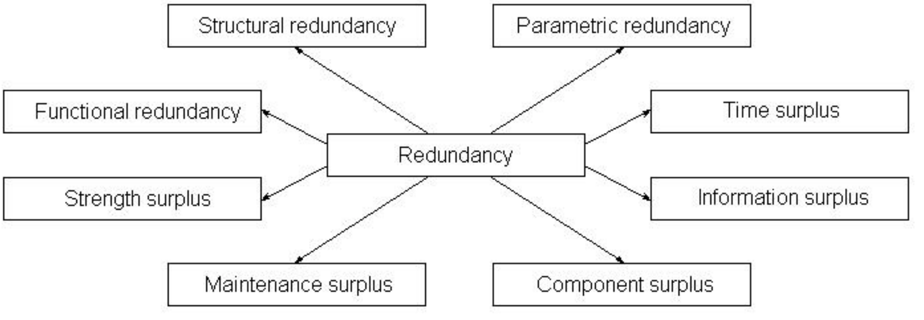

Fig. 1. Redundancy types in the technical systems

The authors of this paper are mostly analyzing structural redundancy with the proposed application of a complex number plane for redundancy modeling [4, 6]. Below, this application is described and an example application for *DP* subsystems' reliability estimation is presented.

1. Proposed redundancy model outline

A system with structural redundancy consist of basic components which are performing system functions and stand-by components which are taking over the basic components functions in case of a basic component fault.

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. Different methods of redundancy in systems with structural redundancy are shown in Fig. 2.

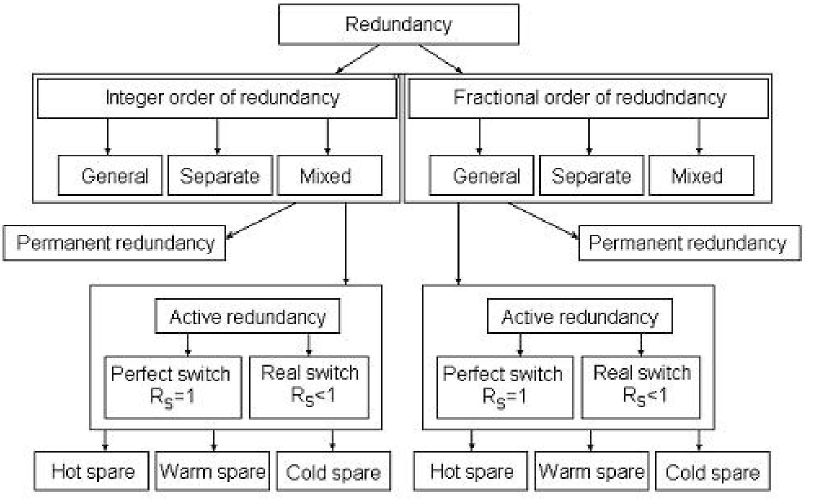

Fig. 2. Methods of structural redundancy

Redundancy of components allows keeping the system fault tolerant. Class 3, (the highest redundancy level) according to the International Maritime Organization *IMO*, is the system in which a 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 a flooded watertight engine room compartment. Single faults also include a single inadvertent act by any person on board the *DP* vessel [7]. Such a system is shown in Fig. 3.

A general structure of dynamic positioning systems consists of [4]:

$$S=\{E_{S1}, E_{S2}, E_{S3}, E_{S4}, E_{S5}, E_{S6}\} \tag{1}$$

where:

E_{S1} – automatic system of dynamic positioning supervision (4 main components),
E_{S2} – ship's electric power plant (5 main components),
E_{S3} – ship's propulsion system (5 main components),
E_{S4} – emergency electric power supply (4 main components),
E_{S5} – reference sensors system (5 main components),
E_{S6} – the other components of DP system.

The subsystems' structures have been described in [2, 4, 6].

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:

$$z(X,t) = (p(X, t), r(X, t)) \tag{2}$$

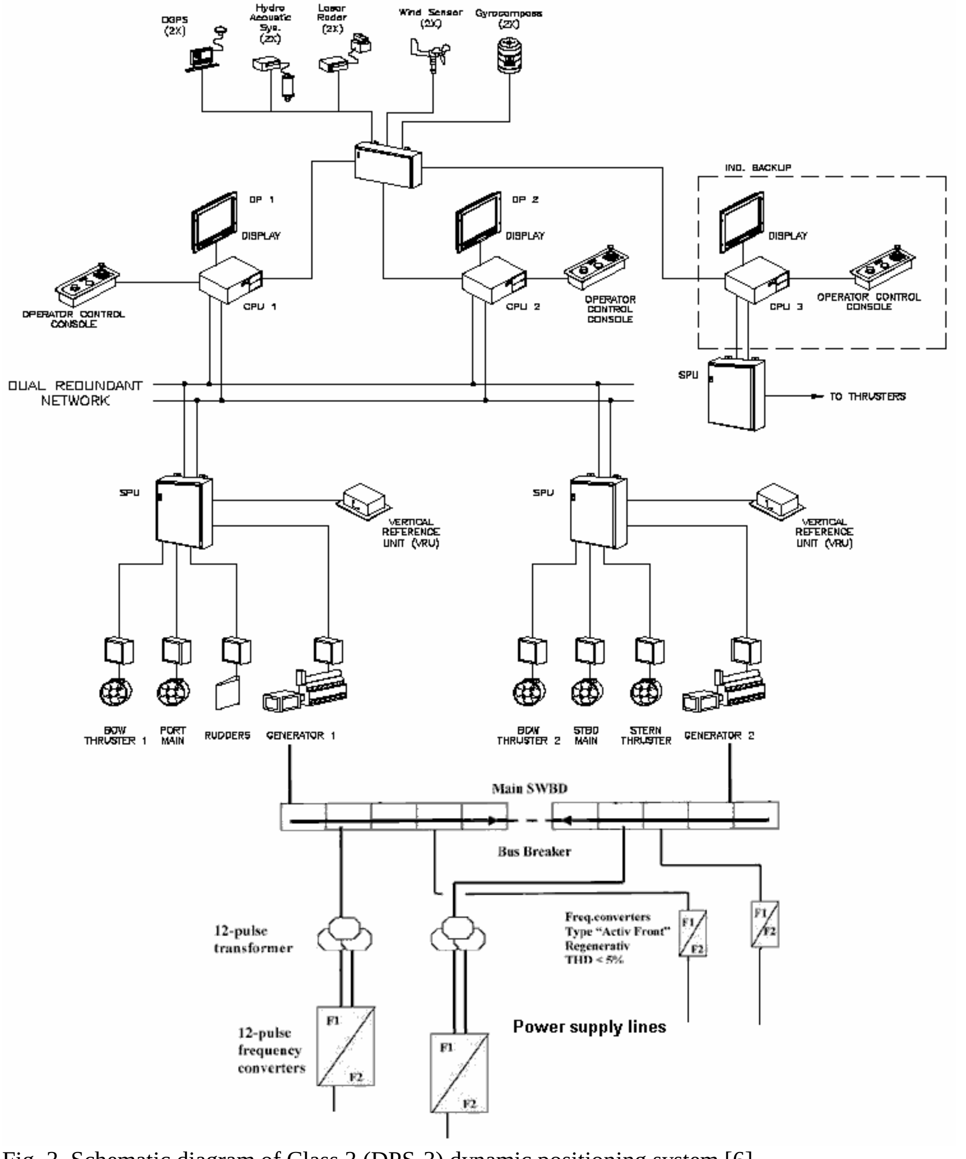

Fig. 3. Schematic diagram of Class 3 (DPS-3) dynamic positioning system [6]

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

$$\Im(X, t) = p(X, t) + r(X, t) = \Im(X,0) - \Im_{REST}(X, t) \tag{3}$$

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

$$\Im(X,0) = \underset{t=0}{card}(X) = p(X,0) + r(X,0) \tag{4}$$

where: $\Im_{REST}$ – the number of components of the system X that have failed until the time t.

A comparison of the redundancy level in *DP* systems on ships belonging to any of the equipment class is possible through, for example, 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:

$$\Im_{real}(X) = \max_{t\to\infty} \underset{t}{card}(X) \tag{5}$$

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:

$$\Im_{real}(X) \geq \Im_{kr}(X) \tag{6}$$

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:

$$r(X, t) = \Im_{kr}(X) - p(X, t) \tag{7}$$

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

$$Z(X, t) = p(X, t) + i \cdot r(X, t) \tag{8}$$

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

After substituting for the relation (2), we obtain a formula connected with the standard measure $\Im_{kr}$ which has this form:

$$z(X,t) = p(X, t) + i \cdot [\Im_{kr}(X) - p(X, t)] \tag{9}$$

2. System state transitions

A series of transitions from the starting state to a system failure and a series of transitions from the initial down state to full up state of the system and all its redundant components have been described in [7]. In the presented complex model, all system transitions for failures and repairs can be presented in the form of a transition graph, which is shown in Fig. 4.

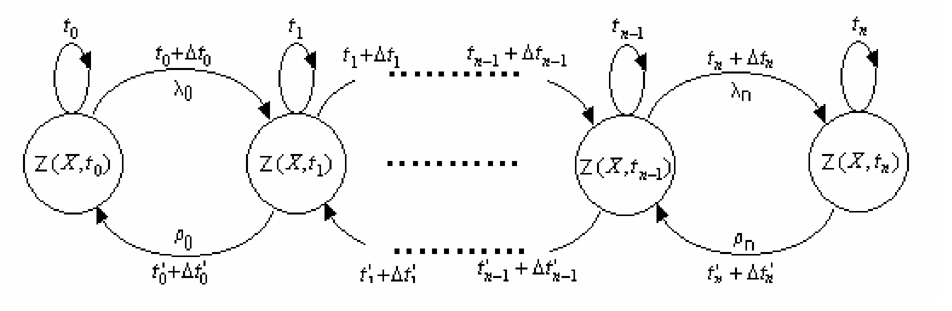

Fig 4. The system states transition graph

3. Using of redundancy models for the *DP* system reliability calculation

One condition for a dynamic positioning system to work properly is that one has to assure that all its subsystems work correctly. Therefore, the *DP* system structure corresponds to a series structure composed of particular subsystems. Using the decomposition described by the formula (1), we can write down the reliability $R(s,t)$ of a dynamic positioning system S at an instant of time t in this form:

$$R(S,t) = \prod_{k=1}^{6} R(E_{Sk},t) \tag{12}$$

where: $R(E_{Sk},t)$ – reliability of the subsystem E_{Sk} at the instant of time t.

The reliability of particular subsystems can be determined with the use of the proposed models of redundancy in a dynamic positioning system. In a general case, for the subsystem X with a threshold structure composed of identical components E_X, having taken into account the quantities presented with the use of the relationship (8), the system reliability at the instant of time t≥*0* can be expressed as follows:

$$R(X,t) = \sum_{k=p(X,t)}^{n=\Im(X,t)} \binom{n}{i} \cdot [R(E_X,t)]^k \cdot [1-R(E_X,t)]^{n-k} \tag{13}$$

For the threshold structure *k-z-n* composed of components E_1, E_2,…E_n with various reliability characteristics and the required number of components *k* ensuring the system is in up state, the system reliability can be presented in this general form:

$$R(X,t) = 1 - \sum_{k=r(X,t)+1}^{n=\Im(X,t)} \left\{ (-1)^{k+r(X,t)+1} \binom{k-1}{n-i} \sum_{\substack{\forall P(E_{Li}) \\ Li \in \{1 \dots n\}: \\ l1<\dots<\ln}} \prod_{j=1}^{k} [1-R(E_{Li},t)] \right\} \tag{14}$$

Examples of a reliability analysis for subsystems of a *DP* system can be found in professional literature, e.g. in reference [3, 5]; they will not be quoted here as they are rather lengthy.

Final Conclusions

This article presents the application of a new reliability model of redundancy of technical systems for reliability estimation of technical systems, in this case, referring particularly to systems of dynamic positioning that offshore vessels are fitted with. One of the differences in ship design between dynamically positioned offshore vessels and cargo transport vessels is that the former have a much higher level of redundancy, especially in subsystems directly or indirectly connected with maintaining the specified position and heading of the ship (*DP* system).

The tasks for which a ship is intended affect the scope of redundancy in particular subsystems providing the vessel's dynamic positioning (electric power and propulsion system, control and supervision system, thruster system, system of reference sensors, emergency power supply system etc.). The presented model can be useful for building complex technical systems' reliability calculation computer algorithm.

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Reviewer:
Krzysztof CZAPLEWSKI

Rezerwowanie strukturalne w systemie dynamicznego pozycjonowania jednostki oceanotechnicznej

Słowa kluczowe

System techniczny, pozycjonowanie dynamiczne, rezerwowanie, komponenty części zamiennych, jednostka oceanotechniczna, system okrętowy, szacowanie niezawodności, liczba płaszczyzn zespolonych

Streszczenie

W materiale zarysowano dekompozycję struktur systemu dynamicznego pozycjonowania oraz specyfikę rezerwowania w tym systemie wykorzystując płaszczyznę zespoloną. Krótko scharakteryzowano przejścia stanów systemu stosując płaszczyznę zespoloną oraz pokazano graf przejść stanów systemu. Przedstawiono zastosowanie modelu rezerwowania zaproponowanego przez autorów dla szacowania niezawodności systemu dynamicznego pozycjonowania.