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CONTROL REDUNDANCY AS A QUANTITATIVE MEASURE OF MANEUVERABILITY

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The purpose of the article is to determine the criterion of control redundancy and calculate its value for various types of vessels and navigation modes. A brief review was carried out and it was concluded that redundancy controls are mostly used only as a backup to improve reliability, but not as a means of optimizing control. The dependence of the vessel's maneuvering capabilities on the value of this criterion and its importance in the classification is shown. A formula for calculating control redundancy is proposed, and control redundancy values are calculated for vessels with different control schemes.
***Keywords**: sea transport, automatic control, redundant control, optimal control, active control means, control scheme.*

Introduction. Sea transport for various purposes and operating conditions is classified according to the following main characteristics [1]:

- the way of movement (self-propelled and non-self-propelled);
- the method of movement (above water, on the surface of water or under water);
- the condition of the body (with a rigid, elastic, inflatable body);
- the main body material (steel, light metal alloys, plastic, wooden, reinforced concrete, elastic materials (nylon) and composite);
- the area of navigation (sea, raids and coastal navigation, inland and mixed navigation);
- the nature of the main power plant, which sets the vessel in motion (steamboats, motor ships; electric turbo-diesel motor ships, gas ducts);
- the type of propulsion (screw, wing propeller, water-jet, paddle wheels, sailing; oars, etc.);
- for special purposes (civilian ships and ships of the Navy).

The above list does not contain one of the important paragraph. It is control redundancy, which is being discussed in this article.

Vessel's control redundancy is currently only considered in terms of reliability. So, in the document [2], section 8, part XV «Automation» for dynamic positioning systems, it is said that redundancy of a dynamic positioning system is a duplication or multiple reservation of its elements, where a complex consisting of an electric power supply system and propulsive mechanisms with their individual control systems, is operated under the control of a computer system in such a way, that the failure of individual control systems of individual propulsive mechanisms or electronic cops of the electric power supply system does not affect the task of holding the vessel above the positioning point. Depending on the degree of reservation, one of the signs DYNPOS – 1, DYNPOS – 2 or DYNPOS – 3 is added to the main symbol of the vessel class. At the same time, DYNPOS – 1 defines the System with minimal redundancy, when the loss of the position of the vessel above the positioning point can occur in case of a single failure. DYNPOS – 2 provides that the System must have a redundancy that ensures the vessel is kept above the positioning point in case of a single failure in any active element of the system (failure in any passive element is excluded due to the availability of appropriate protection). DYNPOS – 3 provides that the System must have a redundancy that ensures the vessel is kept above the positioning point in case of a single failure of elements in the following variants:

− failure of any active and passive elements located in different watertight compartments;

− failure of active and passive elements located in any of watertight compartments as a result of flooding or fire;

− failure of active and passive elements located in any of fire zones as a result of fire or explosion.

At the same time, it has also been shown in [3–4] that the use of control redundancy makes it possible to increase the maneuverability of the vessel and also to optimize the vessel's movement in energy consumption under external influences. This can only be achieved if automatic control systems are used. The control of the vessel with the help of a command on the bridge is mainly carried out intuitively, without accurate mathematical calculation. The behavior of a person in a team when working on a bridge is considered in more detail, for example, in articles [5-11], and some psychological aspects of behavior in articles [12, 13]. In articles [14–21] various active control systems (ACS) have been used on vessels to increase their maneuverability. However, in these and other works, maneuvering capabilities have been evaluated qualitatively. The famous scientist D.I. Mendeleev in his work «Fundamentals of Metrology» mentioned that science begins where measurements are begun. Therefore, the introduction of numerical evaluation criterion and assessment of the maneuverability of vessels by this criterion is an urgent scientific and technical task.

The purpose of the article is to determine the criterion of control redundancy and calculate its value for various types of vessels and navigation modes.

Main research material. As a criterion for redundancy in ship's control, the difference between the number of available controls and the number of degrees of freedom to be controlled is accepted. This criterion can be used to assess the maneuverability of the vessel as well as the ability to adapt control. The degree of control redundancy is determined by the following formula IU = NU – NS, where NU is the number of controls, NS is the number of sepia of freedom to be controlled. The vessel has three degrees of freedom – longitudinal, lateral movement and yaw angle. The number of controls depends on the number of control devices on this ship (aft steering, bow and stern thrusters, azipods, engines, etc.). At the transition and in maneuvering mode, a different number of control devices is used. So, in the maneuvering mode, bow and stern thrusters can be additionally used, the engines operating at different speeds in order to create additional control moments and increase maneuverability. Therefore, the degree of redundancy for control in maneuvering mode is always higher than at the transition.

The table 1 shows the IU redundancy data obtained for some types of vessels of the Navi Trainer 5000 simulator [22, 23]. The first IU value is calculated for the transition mode, and the second IU value is calculated for the maneuvering mode.

Results of research. The most common control scheme, which covers about 85% of all vessels, is represented by the vessels Bulk carrier 6 (Dis.44081t) and Crude Oil Tanker 4 (group 1 in table 1). The characteristics of Bulk carrier 6 (Dis.44081t) are given in table 2.

Table 1 – IU redundancy data obtained for some types of vessels

Gr.	*Type of vessel*	*Type of engine*	*Propulsion type*	*Bow thruster*	*Stern thruster*	*IU*
1.	Bulk carrier 6 (Dis.44081t)	low speed diesel (1x8002кВт)	FPP	not present	not present	-1=2-3 -1=2-3
	Crude Oil Tanker 4	low speed diesel (1x13560кВт)	FPP	not present	not present	-1=2-3 -1=2-3
2.	Car Carrier 2 (Dis.19587t)	low speed diesel (1x11695кВт)	FPP	present	not present	-1=2-3 0=3-3
	MSC container ship 1 (Dis.32025t)	low speed diesel (1x15890кВт)	FPP	present	not present	-1=2-3 0=3-3
3.	Shuttle tanker 1 (Dis.160529t)	low speed diesel (1x17400кВт)	CPP	present	not present	-1=2-3 0=3-3
4.	Container ship 22 (Dis. 191000t)	low speed diesel (1x71785кВт)	FPP	present	present	-1=2-3 1=4-3
5.	River-sea ship 3 “Sormovsky»	low speed diesel (2x640кВт)	FPP	present	present	-1=2-3 1=4-3
6.	Ro-Ro passeger farry 13	medium speed diesel (2x4000кВт)	FPP	present	not present	0=3-3 1=4-3
7.	OSV 9 (Dis.5291t)	medium speed diesel (2x6166кВт)	CPP	present	present	0=3-3 2=5-3
8.	Passenger cruise ship 10.	electric motor (2x17600 кВт) Azipode	FPP	present	present	1=5-3 3=6-3
9.	Semisubmersible 1 Semisubmersible 1AH, Semisubmersible 1AH Common, Semisubmersible 1AH Navis, Semisubmersible 1AH Common DP, Semisubmersible 1AH Navis DP.	high speed diesel (4x4100кВт) Steering column	FPP	not present	not present	5=8-3 5=8-3

Table 2 – Characteristics of the Bulk carrier 6 (Dis.44081t)

Bulk carrier 6 (Dis.44081t)		
Engine’s type	low-speed diesel (1x8002) kwt	
Propulsion type	FPP	
Bow thruster	not present	
Stern thruster	not present	
Displacement, t	44081,1	
Maximum speed, kn.	16,4	
Length, m	225	
Width, m	32,3	
Bow/Stern draft, m	7,4/8	

These vessels are equipped with one engine, Fixed Pitch Propeller (FPP) and one stern steering. Since the FPP is not controllable, the number of controls in this scheme is NU = 2 (engine revolutions + stern steering), the number of degrees of freedom to be controlled is 3. The degree of redundancy is IU = 2 – 3 = - 1. Since there are no other control devices on these vessels, this degree of control redundancy will be in transition and in maneuvering mode. Since the stern steering in this control scheme is used both to work out lateral displacements and to work out angular deviations, it is impossible to ensure the vessel moves along a route with a zero drift angle, which means that there will be additional resistance from the drift angle and additional fuel consumption, i.e. this scheme control is not optimal in terms of energy consumption.

Group 2 of table 1 is represented by the Car Carrier 2 (Dis. 19587t) and the MSC container ship 1 (Dis. 32025t). The characteristics of MSC container ship 1 (Dis. 32025t) are given in table 3. The vessels are equipped with one engine, FPP, stern steering and bow thruster. In maneuvering mode, all available control devices can be used, i.e., the number of controls NU = 3 (engine revolutions + stern steering + bow thruster), and the degree of redundancy in control is IU = 3 – 3 = 0. At the transition, the bow thruster is not used, therefore the number of controls is NU = 2 (engine revolutions + stern steering), and the degree of redundancy in control is IU = 2 – 3 = -1. Vessels with this control circuit at the transition are similar to the vessels of group 1, i.e. the control circuit is not optimal in terms of energy consumption.

Table 3 – The characteristics of MSC container ship 1 (Dis. 32025t)

MSC container ship 1 (Dis. 32025t)		
Engine»s type	low-speed diesel (1x15890) kwt	
Propulsion type	FPP	
Bow thruster	present	
Stern thruster	not present	
Displacement, t	32025	
Maximum speed, kn.	19,4	
Length, m	203,6	
Width, m	25,4	
Bow/Stern draft, m	9,6/10	

In maneuverable mode, the control system of such vessels can provide movement along a route with a zero drift angle, witch meens less energy consumption.

Group 3 of the table 1 is represented by Shuttle tanker 1 (Dis.160529t). The characteristics of the vessel are given in table 4.

Table 4 – The characteristics of the Shuttle tanker 1 (Dis.160529t)

Shuttle tanker 1 (Dis.160529t)		
Engine’s type	low-speed diesel (1x17400) kwt	
Propulsion type	CPP	
Bow thruster	present	
Stern thruster	not present	
Displacement, t	160529	
Maximum speed, kn.	17	
Length, m	277,4	
Width, m	46	
Bow/Stern draft, m	15,9/15,9	

The vessel is equipped with one engine, Controlled Pitch Propeller (CPP), stern steering and bow thruster. CPP allows to change the screw force without changing the engine revolutions, but change of screw pitch and engine revolutions lead to a change in screw force and parameters of longitudinal movement and cannot be considered as two independent controls. In the maneuvering mode, all available controls can be used, i.e. the number of controls NU = 3 (engine revolutions and CPP + stern steering + bow thruster), and the degree of redundancy is IU = 3 – 3 = 0. At the transition, the bow thruster is not used, therefore, the number of controls is NU = 2 and the degree of redundancy is IU = -1.

Group 4 of table 1 is represented by Container ship 22 (Dis. 191000t). The characteristics of the vessel are given in table 5. The vessel is equipped with one engine, FPP, stern steering, bow and stern thrusters. In the maneuvering mode, all available control devices can be used, i.e. the number of controls NU = 4 (engine revolutions + stern steering + bow thruster + stern thruster), and the degree of control redundancy is IU = 4 – 3 = 1, i.e. in maneuvering mode such control schemes can provide optimal control with a zero drift angle. At the transition, bow and stern thrusters are not used, therefore, the number of controls is NU = 2 (engine revolutions + stern steering), and the degree of redundancy is IU = 2 – 3 = -1, i.e. the control scheme is similar to the vessels of group 1.

Table 5 – The characteristics of the Container ship 22 (Dis. 191000t)

Container ship 22 (Dis. 191000t)		
Engine's type	low-speed diesel (1x71785) kwt	
Propulsion type	FPP	
Bow thruster	present	
Stern thruster	present	
Displacement, t	191000	
Maximum speed, kn.	25,5	
Length, m	393	
Width, m	56	
Bow/Stern draft, m	13,7/13,7	

Group 5 of the table 1 is represented by the vessel River-sea «Sormovsky». The characteristics of the vessel are given in table 6.

Table 6 – The characteristics of River-sea «Sormovsky»

River-sea "Sormovsky»		
Engine»s type	low-speed diesel (2x640) kwt	
Propulsion type	FPP	
Bow thruster	present	
Stern thruster	not present	
Displacement, t	4514	
Maximum speed, kn.	10,3	
Length, m	119,2	
Width, m	13,4	
Bow/Stern draft, m	3,4/3,6	

The vessel is equipped with two engines, FPP, stern steering and bow thruster. In maneuvering mode, all available control devices can be used, i.e. the number of controls is NU = 4 (engine revolutions 1 + engine revolutions 2 + stern steering + bow thruster), and the degree of redundancy in control is IU = 4 – 3 = 1. At the transition, both engines operate at the same revolutions, and the bow thruster is not used, so the number of controls is NU = 2 (engine revolutions + stern steering), and the degree of redundancy IU = 2 – 3 = -1.

Group 6 of table 1 is represented by the Ro-Ro passenger ferry. The characteristics of the vessel are given in table 7.

The vessel is equipped with two engines, CPP, a stern steering and a bow thruster. In maneuvering mode, all available control devices can be used, i.e. the number of controls NU = 4 (engine revolutions 1 and CPP + engine revolutions 2 and CPP + stern steering + bow thruster), and the degree of control redundancy is IU = 4 – 3 = 1. At the transition, both engines operate at the same revolutions, and the bow thruster is not used, so the number of controls is NU = 3 (engine revolutions and CPP + stern steering), and the degree of redundancy is IU = 3 – 3 = 0.

Table 7 – The characteristics of Ro-Ro passenger farry

Ro-Ro passenger farry		
Engine's type	medium speed diesel (2x4000) kwt	
Propulsion type	CPP	
Bow thruster	present	
Stern thruster	not present	
Displacement, t	7796,8	
Maximum speed, kn.	20,5	
Length, m	125	
Width, m	23,4	
Bow/Stern draft, m	5,3/5,3	

Group 7 of the table 1 is presented by OSV 9 (Dis.5291t). The characteristics of the vessel are given in table 8.

Table 8 – The characteristics of OSV 9 (Dis.5291t)

OSV 9 (Dis.5291t)		
Engine's type	medium speed diesel (2x6166) kwt	
Propulsion type	CPP	
Bow thruster	present	
Stern thruster	present	
Displacement, t	5291	
Maximum speed, kn.	16,2	
Length, m	80,4	
Width, m	18	
Bow/Stern draft, m	6,6/6,6	

The vessel is equipped with two engines, CPP, stern steering, bow and stern thrusters. In maneuvering mode, all available control devices can be used, i.e. the number of controls NU = 5 (engine revolutions 1 and CPP + engine revolutions 2 and CPP + stern steering + bow thruster + + stern thruster), and the degree of control redundancy is IU = 5 – 3 = 2. At the transition, both engines operate at the same revolutions, the bow and stern thrusters are not used, therefore the number of controls is NU = 3 (engine revolutions and CPP + stern steering), and the degree of control redundancy is IU = 3 – 3 = 0.

Group 8 of table 1 is represented by Passenger cruise ship 10. The characteristics of the vessel are given in table 9.

Table 9 – The characteristics of Passenger cruise ship 10

Passenger cruise ship 10	
Engine's type	electric motor (2x17600) kwt
Propulsion type	Azipod, FPP
Bow thruster	present
Stern thruster	present
Displacement, t	44000
Maximum speed, kn.	24
Length, m	294
Width, m	37,9
Bow/Stern draft, m	8/8

The vessel is equipped with two azipods with FPP, bow and stern thrusters. In maneuvering mode, all available control devices can be used, i.e., the number of controls is NU = 6 (2 azipode deflection angles + 2 engine revolutions + bow thruster + stern thruster), and the degree of control redundancy is IU = 6 – 3 = 3. The bow thrusters are not used at the transition, therefore the number of controls is NU = 4 (2 azipode deflection angles + 2 engine revolutions), and the degree of control redundancy is IU = 4 – 3 = 1.

Group 9 of table 1 is represented by the platforms Semisubmersible 1, Semisubmersible 1AH, Semisubmersible 1AH Common, Semisubmersible 1AH Navis, Semisubmersible 1AH Common DP, Semisubmersible 1AH Navis DP. The characteristics of the Semisubmersible 1 platform are given in table 10.

Table 10 – The characteristics of Semisubmersible 1 platform

Semisubmersible 1 platform	
Engine's type	high-speed diesel (4x4100) kwt
Propulsion type	steering column, FPP
Bow thruster	not present
Stern thruster	not present
Displacement, t	35700
Maximum speed, km	10
Length, m	129,8
Width, m	79,6
Bow/Stern draft, m	10/10

Platforms are equipped with four azipods with FPP.

In maneuvering mode, all available control devices can be used, i.e. the number of controls is NU = 8 (4 deflection angles of steering column + 4 screw force), and the degree of control redundancy is IU = 8 – 3 = 5. The transition uses the same controls as in maneuvering mode.

Conclusions. As can be seen from the obtained results, most of the vessels have the control redundancy IU = -1. This means that the control systems of such vessels cannot ensure the simultaneous development of all control parameters (lateral displacement and yaw angle). In this case, it is necessary to organize double-circuit control. First, the lateral deviation to be worked out, then the angular deviation. When moving along the route, vessels with such control scheme have a drift angle that causes additional resistance to movement and additional fuel consumption. The control of such vessels is not optimal in terms of energy consumption. Vessels with a control redundancy IU = 0 have sufficient control. The control systems of such vessels make it possible to keep the vessel on route with a zero drift angle, including when in the presence of external disturbances. Control redundancy IU > 0 means that control systems of such vessels make it possible not only to keep the vessel on route with a zero drift angle, including when in the presence of external disturbances, but also to optimize controls within the system itself.

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Зінченко С. М., Носов П. С., Попович І. С. НАДЛИШКОВІСТЬ ПО УПРАВЛІННЮ ЯК КІЛЬКІСНА МІРА МАНЕВРЕНОСТІ СУДНА

Метою статті є визначення критерію надлишковості по управлінню та розрахунок його значення для різних типів суден і режимів плавання. Проведено короткий огляд літератури, з якого зроблено висновок, що надлишковість по управлінню в основному використовується тільки як резервування для збільшення надійності, але не як засіб оптимізації управління. Показана залежність маневрових можливостей судна від значення поданого критерію та його важливість у класифікації. Запропоновано формулу розрахунку надлишковості по управлінню, а також розраховані значення надлишковості по управлінню для суден з різними схемами управління і режимами плавання.

***Ключові слова**: морський транспорт, автоматичне керування, надлишкове керування, оптимальне керування, засоби активного керування, схема керування.*

Зинченко С. Н., Носов П. С., Попович И. С. ИЗБЫТОЧНОСТЬ ПО УПРАВЛЕНИЮ КАК КОЛИЧЕСТВЕННАЯ МЕРА МАНЕВРЕННОСТИ СУДНА

Целью статьи является определение критерия избыточности по управлению и расчет его значения для различных типов судов и режимов плавания. Проведен краткий обзор литературы, из которого сделан вывод, что избыточность по управлению в основном используется только как резервирование для увеличения надежности, но не как средство оптимизации управления. Показана зависимость маневренных возможностей судна от значения данного критерия и его важность в классификации. Предложена формула расчета избыточности по управлению, а также рассчитаны значения избыточности по управлению для судов с разными схемами управления и режимами плавания.

***Ключевые слова**: морской транспорт, автоматическое управление, избыточное управление, оптимальное управление, средства активного управления, схема управления.*

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