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Comprehensive Assessment of Hull Geometry Influence of a Modernized Ship on Maneuvering Performance and Propulsion System Parameters

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ABSTRACT

The necessity to preserve economic efficiency of cruise ships operation stipulates fleet modernization in order to avoid expenses on ordering and construction of new ships. In this paper an approach based on hull length increase in the process of ship modernization is discussed. The method of evaluation of changes in maneuvering characteristics of ship after modernization is developed taking into account the operational parameters of propulsive electric power plants. The calculations are based on the analysis of transient modes of propulsive power plants operation during the corresponding maneuvers. The parameters influencing the characteristics of ship motion during turning circle are revealed; their significance is estimated, comparative analysis of the effect of ship hull length on maneuvering parameters before and after modernization is carried out. It was shown that in some cases the characteristics of the ship's controllability and operating parameters of the ship power plant after modernization remain within the permissible limits. The comparative results show that the increase in hull length leads to insignificant deterioration of the main maneuverability characteristics while the electric power plant indicators practically do not deteriorate, which confirms the expediency of such modernization.

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1 Introduction

At present, a steady trend of intensive development of passenger fleet and cruise transportation has been formed all over the world. In recent years, the number of passenger transportation exceeded twenty-two million passengers per year. According to expert environment forecasts, demand growth trend will remain in the foreseeable future. Growth in passenger traffic motivates ship-owners to construct new vessels. Such, quite reasonable, decision inevitably leads to a steep increase in shipbuilding companies' workload. However, most of shipyards are already occupied and have orders for years to come. Besides, the high cost of passenger ships construction and long construction duration (one and half years on average) hinder the rapid satisfaction of demand for passenger ships construction.

Among alternative ways of development for cruise companies is the modernization of their fleet, contributing to the reduction of the level of moral and physical ageing of ships. Modernization is one of the promising directions for increasing the competitiveness of shipping companies, including those engaged in marine cruise business.

Various factors contribute to the importance of maintaining the economic efficiency of cruise ship operation, including the optimization of fuel consumption and operating costs, the desire to improve the quality of passenger service and modern environmental standards and requirements. As one of the strategies to achieve these goals, modernization of cruise ships by changing the geometric parameters of the hull, namely increasing the overall length, is proposed. This significantly improves passenger capacity of the ship, which will lead to increased fuel efficiency and reduced emissions per passenger. By aligning modernization with economic goals, cruise ship operators can maintain their competitiveness while addressing environmental and operational concerns.

Modernization or reconstruction of ships by changing geometrical parameters of their hulls is a long-standing and quite justified practice that is successfully applied in shipping, because, taking into account the high cost of construction of new ships, it is nothing but an effective tool for increasing the competitiveness of a shipping company in current conditions and without significant capital investments.

As statistical data show, the average life cycle of passenger ships is more than thirty years and after this period one of the typical directions of modernization is to increase the length of the ship by manufacturing and installing an additional cylindrical insert in the hull. The cost of such modernization can be only 10% to 30% of the initial cost of ordering, designing and construction of a given project [5, 7, 8] and passenger capacity increases by 15%...20%.

However, it is quite natural that with the increase in the length of the hull of the ship inevitably arise questions about changes in its strength characteristics, hydro and aerodynamic properties and certainly changes in its controllability. This could be complex issue, especially for ships with long superstructures, as the passenger ships, as the superstructure is contributing to the longitudinal strength. In addition, there could be technological challenges in cutting and welding hulls of passenger ships. The issues of theoretical substantiation of ship characteristics and practical feasibility of this kind of modernization are devoted to the following works (Bačkalov et al., 2014; Samian, Yahya & Shah, 2021). This paper is focused on the study of the influence of the dependence of changes in the hull geometry after modernization on its controllability and operating parameters of the power plant.

One of the main qualities determining the seaworthiness of a ship is its maneuverability, which is characterized by turnability and steadiness on her course. Turnability, in its turn, is determined by the ability of the vessel to change course when moving along a curvilinear trajectory. The maneuverability characteristic, which allows to judge the controllability, is the turning movement. The main indicators of the quality of turning ability can be determined by the so-called turning curve.

Fundamental works [24, 33] in the field of ship control and maneuverability are devoted to the issues of maneuverability. The computational estimation methods are based on the results of solving the system of differential equations of ship motion and propeller engine operation. However, as shown in [37 – 39], in addition to the geometrical parameters of the ship hull, the quality of her motion (or, more precisely, the degree of its reduction) and the propeller rotation frequency influence the performance of the ship's turning circle indicators.

A wide range of scientific works is devoted to the problems of ship design in conjunction with the issues of monitoring the performance of propulsion systems in the process of developing modernization strategies and the issues of improving the maneuverability and controllability of ships. Thus, [41] investigated ship maneuverability while passing the moored ships in confined waterways, providing new benchmark cases for numerical analysis in ocean engineering. Hang et al. [11] explored the matching of waste heat recovery units and ship propulsion systems, focusing on efficient energy usage and propulsion system integration. The scientific work [6] analyzing the strategic rivalry and evolution of maritime power between India and China, examining the nexus of naval modernization in the context of geopolitical dynamics. Shibaev et al. [30] developed a strategy for modernizing passenger ships by optimizing fund allocation, contributing to decision-making processes for passenger ship upgrades. Dauti and Trifkovic [9] conducted behavior tests of a new propulsion form after ship reconstruction, evaluating the performance enhancements resulting from the ship's post-reconstruction changes. The study on a watertight door control system using Profinet IO, offering insights into ship control technology advancements and their implementation presented in [28].

The model development for energy efficiency management of ships throughout their lifecycle, offering insights into effective energy management strategies offered in [13]. Xie et al. [35] conducted a numerical simulation study on ship-ship interference in formation navigation through brash ice channels, contributing to the understanding of ship navigation in challenging environments. Issues of increasing the overall strength and energy efficiency in the design of ships were studied in [14, 15, 33]. Yulianto et al. [40] presented a preliminary study on ship maneuvering prediction of container ships, providing insights into predictive modeling techniques for ship navigation. The numerical simulation of a vessel's maneuvering performance in regular waves, contributing to the understanding of vessel behavior in wave conditions performed in [25]. Lee et al. [17] developed an enhanced two-time-scale model for simulating ship maneuvering in ocean waves, advancing the accuracy of ship maneuverability simulations. Introduction of integrated simulation workflow for automated IMO maneuverability verification for ship design using computational fluid dynamics, streamlining the design verification process proposed in [21]. When using mathematical models of ship motion, it is important to determine the values of parameters for the models. There are a number of papers aimed at developing methods for identifying the parameters of mathematical models of ship motion [4, 10]. Putranto and Purwanto [26] analyzed rolling damage ship motion caused by wave loads on bulk carrier vessels, providing insights into the effects of wave-induced forces on ship structures. Liu et al. [18] predicted ship maneuverability based on virtual captive model tests, contributing to the development of virtual testing methods for ship maneuvering. Skejic and Berg [31] investigated hydrodynamic interaction effects between ships in restricted water depth waters, offering insights into ship behavior in confined waterways. Xie et al. [36] proposed a framework for numerically evaluating maneuvering vessels in waves, advancing methods for assessing ship maneuverability. Aryawan and Putranto [1] analyzed the hydrodynamics performance of aquaculture fishing vessels with varying deadrise angles and sponson, contributing to the understanding of vessel stability and performance. Putranto and Sulisetyono [27] performed lift-drag coefficient and form factor analyses of hydrofoil based on shape and angle of attack variations, providing insights into hydrofoil performance. Introduction of a method for prompt evasive maneuver selection to alter a ship's course or speed, contributing to ship navigational safety and anti-collision strategies presented in [3]. Melnyk and Onyshchenko [20] conducted a navigational safety assessment based on a Markov-model approach, providing insights into risk assessment methodologies for maritime operations. The studies [15, 16] focuses on equipment replacement considerations by accounting for factors like wear and tear and obsolescence, provide insights into optimizing equipment replacement terms and stability of economic indicators. Studies [22, 32] focus on advanced techniques for diagnosing and optimizing marine diesel engines, emphasize vibrodiagnostics for engine health monitoring and introduce vibroacoustic diagnostics for fuel injection and lubrication systems. The work [23] explores various technical and operational strategies aimed at mitigating greenhouse gas emissions and enhancing the environmental and energy efficiency of ships.

The reviewed literature presents a wide range of studies that contribute to the development of marine engineering and ship operation. However, the issues of ship modernization require the development of special justification and evaluation approaches that take into account a number of specific conditions and limitations. These approaches should consider the ship as an integral system, which consists of such mutually influencing elements as ship's hull, ship power plant, driving motors, propellers, rudders, etc. and take into account the mutual influence and constraints of these elements. That is why the development of special models that allows comprehensive assessing of ship parameters before and after modernization and estimating the influence of modernization parameters on the maneuvering characteristics of the ship is a practically important and challenging task.

2 Materials and methods

Modern cruise ships are electrical powered vessels therefore increasing the load on their propulsion drives increases the load on the entire ship's electrical power plant. Under difficult maneuvering conditions – when the rudder is turned to a large angle at high ship speed – these overloads may exceed the limits set for electrical power equipment. As a result, the protection system may be triggered and the maneuver may not be executed.

In accordance with the International Maritime Organization Convention, ship maneuverability standards include the turning circle maneuver, which is performed by turning the rudder by 35 degrees or the maximum allowable turning angle at test speed. Geometric and time-velocity metrics are used to quantify the turning circle. This metrics are as follows:

- advance – distance X_1 traveled by the midships in the forward direction to the position corresponding to a 90 degrees course change;
- tactical diameter – distance D_{CT} traveled by the midships from the start of the turn to the position corresponding to a 180 degrees course change.

For a complete evaluation of this maneuver, to the listed indicators should be added, as is customary in the theory of ship maneuverability:

- turning diameter – distance D_C between the positions of the ship's diametral plane on two consecutive courses differing by 180 degrees at steady motion;
- transfer – distance Y_1 from the initial course line along the normal to the ship's center of gravity, by the moment of course change by 90 degrees;
- yaw rate – Ω_Z;
- Δv_C – decrease of the ship's speed when entering the steady-turning radius;
- maneuver time T_C.

Qualitative performance of the maneuver (ensuring the required numerical values of the listed indicators) is primarily determined by the capabilities of the ship's electric power plant (EPP), overloading capabilities of its components. As the vessel enters the turn, the loads on the propulsion system change. On this basis, it is necessary to add to the indicators of the ship turning motion also the indicators characterizing the operation of the EPP itself, changes in the process of maneuvering:

- angular velocity of propulsion motors (PM) and propellers $\Delta\omega_M$;
- rotation torque ΔM_M and current ΔI_M propulsion motors;
- capacity of heat engines of generator units – ΔP_D.

These indicators of SSES operation have certain limitations on the permissible range of changes in their values. Therefore, they must be controlled during maneuvering. Proceeding from this, when analyzing the ship turning circle maneuver parameters, the object of research should be a single ship propulsion complex. It includes ship's hull, rudders, propellers, propeller electric motors, electric power converters, generating units with heat engines and synchronous generators. If ships with a unified shipboard

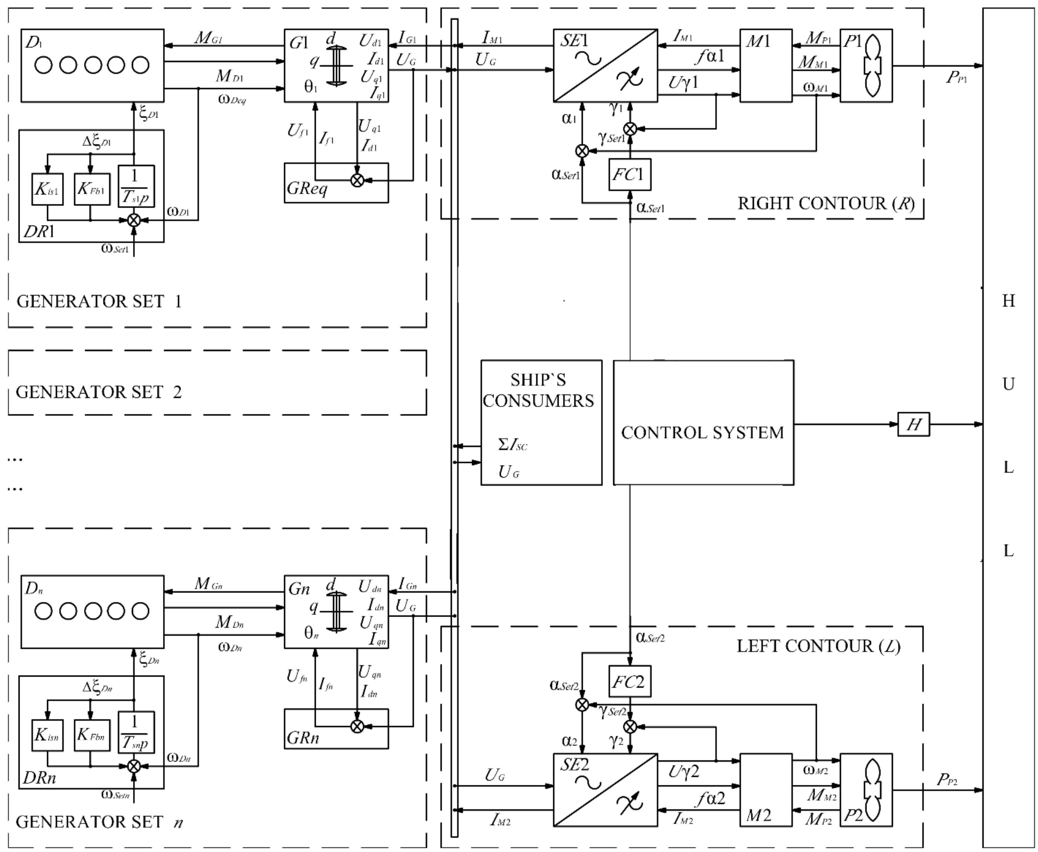

Figure 1 Structural diagram of the electric propulsion system

Source: [34]

electrical power system are considered, then the listed parts should be supplemented with general household electrical consumers. When maneuvering a ship, all these components operate in transient modes and have a mutual influence on each other.

To estimate the main indicators of the ship turning circle motion, we can use the structural scheme (Fig. 1) of the propulsion system proposed in [34].

The complex includes the following components:

- an electrical generating system, comprising several GENERATOR SETS generating units with heat engine speed controllers and active and reactive power distribution systems;
- two power circuits RIGHT CONTOR (*R*) and LEFT CONTOR (*L*), each of which has a frequency converter *SE,* a driving motor *M* and a propeller *P* (frequency-controlled induction motors are considered as rowing motors, but the generalized mathematical apparatus proposed in [6] covers all types of electric motors used in electric propulsion systems).
- SHIP'S CONSUMERS, CONTROL SYSTEM, rudders (*H*) and ship's hull (HULL).

A mathematical model of transient operating modes is developed on the basis of the structural diagram. To give generality to the results of the analysis, the concept of dynamically equivalent complex was used when compiling the model. The system of equations was converted to relative units. In the process of such transformations, the criteria of dynamic similarity of propulsive complexes were revealed. These are generalized dimensionless parameters of the system "propulsion power plant – propellers – rudders – ship hull". This approach considers the comprehensive parameters of all complex components, determining real-time values of relative mode and maneuvering quality indicators. Unlike conventional methods, this approach offers extensive generalization of results, ensuring uniformity in maneuvering quality indicators for electric powered ships with equivalent dimensionless parameters. This method optimally addresses tasks and facilitates the design of electric powered ships with desired maneuvering characteristics.

3 Results and discussion

Simulation modeling of the process of electric powered ship entering the turning circle maneuver was implemented as a Java platform based software with visual graphs and 3D animation. The developed software allowed us to trace the dynamics of the following key indicators:

Table 1 Main parameters of electric powered ships under consideration

Parameters	Initial ship	Upgraded ship	Parameter	Initial ship	Upgraded ship
Lightweight, t	29698	32757	Total thrust of propellers, kN	1602	1602
Length according to design waterline, m	251.2	276.2	Breadth on design waterline, m	32	32
Propeller moment of inertia, kg×m^2	7132	7132	PM torque, kN×m	146.1	146.1
Draft average, m	6.6	6.2	Squat ratio	0.136	0.137
Cruise speed, m/s	11.3	11.3	Screw diameter, m	4.95	4.95
Moment of inertia of the ship relative to the Z-axis, kg×m^2	1.56×10^{11}	2.08×10^{11}	Propeller speed, rpm	120	120
Fullness factor of midship section	0.98	0.98	Propulsive power of one PM, kW	9180	9180
Reduced area of the submerged part of the DP, m^2	1615	1668	The moment of inertia reduced to the shaft of the HEM, kg×m^2	7404	7404
Coefficient of added masses of water along the X axis	0.013	0.01	Coefficient of added masses of water along the Y axis	0.386	0.365
Coefficient of added masses of water around the Z axis	0.332	0.32	Power plant power, kW	30600	30600
Rudder area, m^2	28	28			

Source: Authors

- parameters of ship motion in the associated non-inertial *XYZ* coordinate system: velocity components v_X and v_Y and turn angular velocity Ω_Z around the *Z* axis;
- vessel motion parameters in the inertial coordinate system $X_1Y_1Z_1$: speed components v_{X1}, v_{Y1}, heading angle ϕ_C, heading angle ψ_C and traveled distance along X_1 and Y_1 axes;
- angular speed of rotation ω_M, voltage U_M, current I_M, torque M_M of drive motors;
- thrust P_P and drag moment M_P of the propellers;
- voltage U_G and current I_G of generating units;
- angular velocity of rotation ω_D, torque M_D and power P_D of heat engines of generating units.

Relative time in simulation was calculated as

$$T = \frac{v_0}{L} t \tag{1}$$

where v_0 is the ship's speed in the basic steady-state mode of operation, *L* – ship's length, *t* – current time.

As a practical experiment, an electrically powered passenger vessel m/v LIRICA (reference vessel as initial one) is considered, the main parameters needed for further calculations of which are given in Table 1. The upgraded ship, after modernization, is an electric powered ship with the same electric power plant, but with the hull lengthened by 25 meters, her parameters are given in the same table.

As an example, Fig. 2 shows the simulation results of two consecutive maneuvers: acceleration of the electric powered ship to a steady-state value of relative speed

$v = \frac{v_t}{v_0} = 1$ (v_t – current speed),

and the entering of the ship into turning circle maneuver due to rudder rotation β_R. A ship with two power circuits and two rudders is considered in the modeling.

For detailed information about the mathematical model and other model elements one can refer to [36]. Further we adjust the model proposed in [36] and focus on the aspects that are of key importance for determining the ship parameters before and after modernization and estimating the influence of modernization parameters on the maneuvering characteristics of the ship. The analysis of the modeling results shows the following: at intensive acceleration and entering the maneuver, the loads on both the propulsion motors and the generating units increase. They can exceed the permissible values. The settings of the automatic control system limit the rate of change of the control signals of both the propulsion unit and the rudder drive.

Fig. 3 shows the trajectory of the vessel during this combined maneuver.

Visualization of the maneuver allows to analyze the trajectory of the movement and evaluate all the indicators characterizing this maneuver. On Fig. 3 pivot points markers contain information about the duration of the completed leg in relative (*T*) and absolute (*t*) time, distance traveled by the vessel in relative (in vessel lengths) and absolute (in meters) units, etc. The pivot points for this maneuver are:

- the beginning of maneuver (set the rudder to starboard);

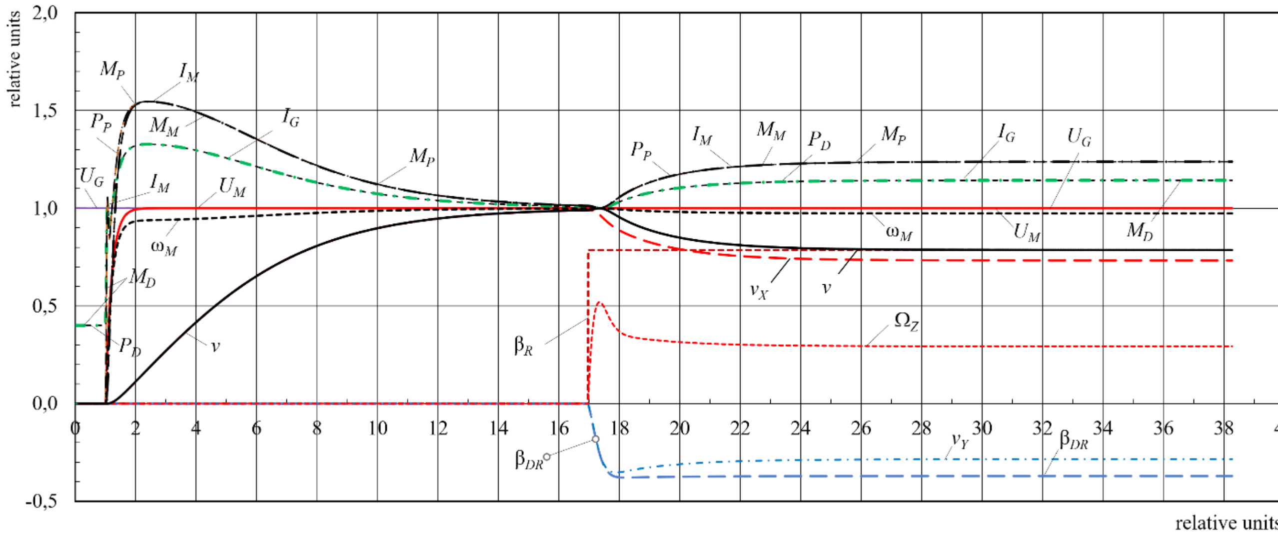

Figure 2 The key indicators dynamics when performing "acceleration – enter to turning circle" maneuver

Source: Authors

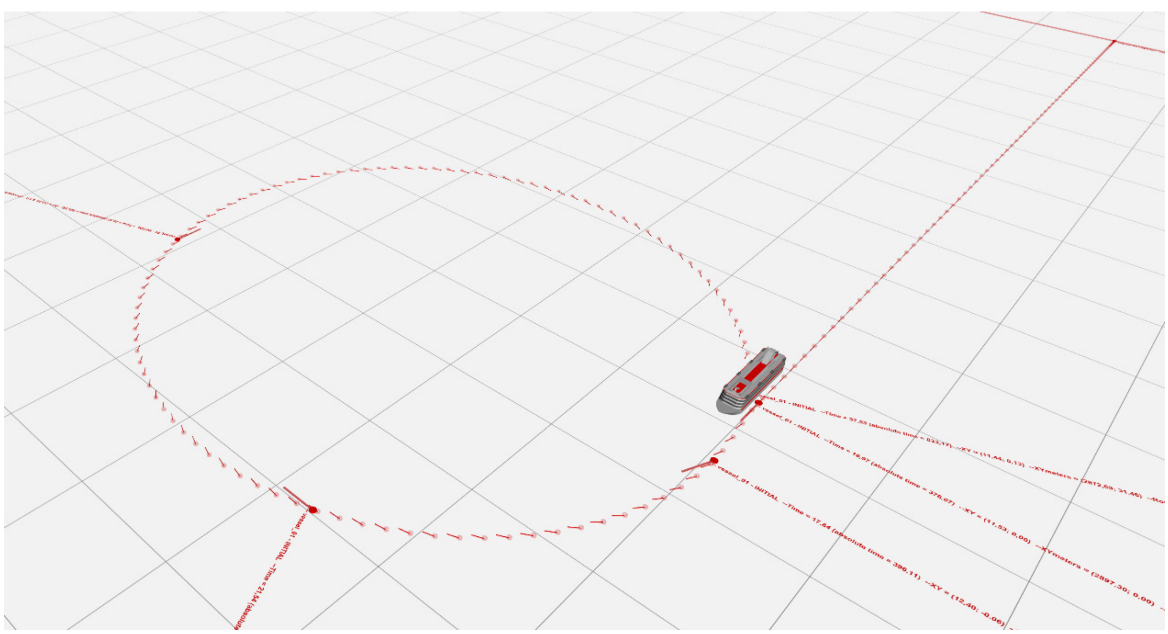

Figure 3 Developed software screenshot with vessel trajectory when entering the turning circle maneuver with pivot points markers

Source: Authors

- the point of maximum displacement of the ship's center of gravity from the original course line in the opposite direction to the direction of turn;
- trajectory point corresponding to the change of the ship's course by 90 degrees;
- trajectory point corresponding to a change in the ship's course by 180 degrees from the beginning of the turn;
- a trajectory point corresponding to a change in the ship's centerline position on two consecutive courses differing by 180 degrees at steady motion.

The study [34] have shown that the key indicators of such maneuvers are significantly influenced by:

- initial speed of the vessel v_{str} before entering the maneuver;
- rudder angle β_R;
- propeller location;
- generalized dimensionless parameters of the propulsion complex.

Table 2 Impact of initial speed on turning circle parameters

Turning motion indicator	Relative speed of the vessel v_{str}			
	0.3	**0.6**	**0.8**	**1**
X_1, L (m)	3.66 (918)	3.68 (924)	3.71 (931)	3.73 (936)
Y_1, L (m)	1.93 (485)	1.92 (482)	1.91 (480)	1.90 (480)
D_{CT}, L (m)	5.78 (1453)	5.77 (1451)	5.77 (1451)	5.77 (1451)
D_C, L (m)	5.65 (1419)	5.65 (1419)	5.65 (1419)	5.65 (1419)
Δv_C, (%)	+ 170	+ 35	+ 1,25	– 11
Ω_Z (rad/s^2)	0.233	0.312	0.405	0.495
T_C (s)	27.9 (619)	29.04 (644)	30.77 (684)	39.49 (877)

Source: Authors

Table 3 Effect of rudder angle on turning circle maneuver indicators

Maneuver indicators	Rudder angle β_R, degree			
	25	**30**	**35**	**40**
X_1, L (m)	5.24 (1316)	4.36 (1094)	3.73 (936)	3.27 (820)
Y_1, L (m)	3.06 (770)	2.38 (599)	1.91 (480)	1.57 (395)
D_{CT}, L (m)	8.53 (2142)	6.91 (1736)	5.78 (1451)	4.95 (1243)
D_C, L (m)	8.39 (2107)	6.78 (1702)	5.65 (1419)	4.82 (1212)
Δv_C, (%)	0.88	0.84	0.81	0.78
Ω_Z (rad/c^2)	0.357	0.426	0.495	0.561
T_C (s)	47.7 (1059)	42.86 (951)	39.49 (877)	37.03 (822)

Source: Authors

The effects of ship speed v_{str} and rudder flip angle β_R on the maneuver parameters are explainable. To quantify them, additional studies were carried out. Their results are given below.

Table 2 shows the effect of the initial speed v_{str} at a rudder angle of 35 degrees on the turning motion performance.

The turning circle maneuver indicators in Table 1 were evaluated in the following units: advance X_1, transfer Y_1, tactical diameter D_{CT}, steady turning diameter D_C in ship lengths L and in meters; relative velocity change Δv_C in percent; maximum value of angular velocity of rotation Ω_Z – in relative units; maneuver duration T_C in relative units and in seconds.

Analysis of the results in Table 1 shows the following. The initial velocity v_{str} practically does not affect the vessel trajectory parameters. Only Δv_C changes significantly. At that, when starting the maneuver from the initial course, the ship's speed, as expected, decreases. If the vessel enters the maneuver after reaching low or average speed, it continues to grow further in accordance with the initial position of the rudder. As the vessel enters the steady-state phase of maneuver, the vessel's speed v_C gradually reaches the same value. This is the speed determined by the position of the control stick and the rudder angle set. This explains the fact that not all other indicators of turning circle motion (except for duration) practically change.

The influence of the rudder angle is much more significant. Table 3 shows the results of calculations of ship entering the turning circle at full speed when the rudder angle is set to 25, 30, 35 and 40 degrees respectively. (The range of variation of the rudder angle is specially increased, compared to 35 degrees, for research purposes).

The effect of rudder angle corresponds to expectations. As β_R, increases, the main parameters of turning motion – advance X_1, transfer Y_1, tactical diameter D_{CT}, steady-state motion diameter D_C, steady-state vessel speed v_C, and maneuver duration T_C – decrease. Only the yaw rate increases.

Decrease in speed also affects (see Fig. 2) the performance of the electric power plant – the loads on the propulsion motors and on the generating units increase.

The influence of propeller location and the influence of dimensionless parameters of the system needs additional comments. Thus, the external and internal propellers to the turning motion center are differently streamlined by the water flow. This affects the local drift angle and leads to a change in propeller loading. Therefore, when quantifying the degree of change in current ΔI_M and torque ΔM_M on the propeller motor shaft, the location of this propeller should be considered.

Of the generalized dimensionless parameters of the system [34], the most significant influence on the turning motion parameters is exerted by the following parameters

Table 4 Generalized dimensionless parameters of the propulsion system

Parameters	Numerical value		Parameters	Numerical value	
	Initial ship	Upgraded ship		Initial ship	Upgraded ship
C_{12}	4.505	4.654	C_{65}	7.454	7.422
C_{21}	0.418	0.366	C_{RY}	8.150	8.150
C_{22}	47.760	44.540	N_X	0.104	0.1047
C_{23}	5.790	5.980	N_Ω	0.631	0.636
C_{61}	3.730	3.324	$C\lambda2$	1.168	1.351
C_{63}	4.385	4.813	$C\lambda21$	0.736	0.703
C_{64}	0.644	0.266	N_M	5.100	5.100
			C_{M16}	7.150	7.150

Source: Authors

$$N_X = \frac{L\sum K_{Pj}P_{ej0}}{(m+\lambda_{11})v_0^2};\; C_{65} = \frac{2\left[0{,}739+8{,}7\frac{H}{L}\right]C_{m0}^{\omega}\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}}; \quad (2)$$

$$C_{M16} = \frac{\beta_{M0}}{r'^2_M}\left[(b_M^2 + c_M^2\alpha_0^2) + (d_M^2 + e_M^2\alpha_0^2)\frac{r'^2_{2M}}{\beta_{M0}^2} + 2r_{1M}\alpha_0\frac{r'_{2M}}{\beta_{M0}}\right], \quad (3)$$

where: P_{ej} and K_{Pj} – useful thrust of each propeller and its share in the total flow, respectively; H and m – draft of the vessel and its mass; ρ – specific density of water; λ_{11} – added mass along the X axis; F_D – reduced area of the submerged part of the vessel's diametral plane; C_{m0}^{ω} – coefficient of damping moment of resistance; β_{M0} – absolute slip of PM rotor; α_0 – relative frequency of PM voltage; r_{1M}, r'_{2M} and r_{1M}, r'_{2M} and b_M, c_M, d_M, e_M – parameters and constant coefficients of frequency-controlled induction motor.

The results of the preliminary studies allowed us to proceed to the solution of the main task – to assess the influence of geometrical parameters of hull (electric powered ship) on the turning circle motion indicators.

The use of generalized dimensionless parameters makes it possible to evaluate and illustrate the influence of ship hull elongation on the main quality indicators of turning circle motion. In accordance with [34], these indicators, in addition to the listed N_X, C_{65} and C_{M16}, are significantly influenced by the numerical values of dimensionless parameters C_{12}, C_{21}, C_{22}, C_{23}, C_{61}, C_{63}, C_{64}, C_{RY}, N_Ω, $C_{\lambda2}$, $C_{\lambda21}$, N_M which are defined by the formulas

$$\begin{gathered} C_{\lambda2} = \frac{m+\lambda_{22}}{m+\lambda_{11}};\; C_{\lambda21} = \frac{2(\lambda_{22}-\lambda_{11})}{m+\lambda_{11}};\; C_{RY} = \frac{\mu_K\frac{\rho}{2}v_0^2S_C(1-\psi)^2}{\sum K_{Pj}P_{ej0}}; \\ C_{12} = \frac{0{,}07\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}};\; C_{21} = \frac{0{,}5C_Y^{\beta}\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}};\; C_{22} = \frac{c_2\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}};\; C_{23} = \frac{c_3\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}}; \\ C_{61} = \frac{2m_1\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}};\; C_{63} = \frac{2m_3\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}};\; C_{64} = \frac{2m_4\frac{\rho}{2}v_0^2F_D}{\sum K_{Pj}P_{ej0}}; \\ N_\Omega = \frac{L^3\sum K_{Pj}P_{ej0}}{2(J_Z+\lambda_{66})v_0^2};\; N_M = \frac{M_{M0}L}{J_M\omega_{M0}v_0}, \end{gathered} \quad (4)$$

where: λ_{22} – attached water masses along the Y axis; J_Z – moment of inertia of the ship in rotation about the Z axis; λ_{66} – attached water moment of inertia; μ_{rx} – rudder drag coefficient; μ_K – rudder side force coefficient; ψ – heading angle; S_C – reduced rudder area; c_4 – coefficient of longitudinal positional water drag force; C_Y^{β}, c_2, c_3 – hull force coefficients; m_1, m_2, m_3, m_4 – positional drag moment coefficients.

The numerical values of these generalized parameters for the initial and upgraded ships are presented in Table 4.

The influence of the ship hull length on the turning circle motion parameters was analyzed, in accordance with the standards of ship maneuverability, by turning the rudder 35 degrees to starboard after the ship reached a steady speed without yawing. Fig. 4 shows the trajectories of the initial and upgraded ships. At the initial moment of time, both vessels are located at the beginning of the coordinate system, but with an offset (for convenience of presentation and analysis of the results) along the transverse axis by one vessel length. At the moment of time $T = 0$, acceleration begins. When the speed $v = 1$ is reached, the rudder is turned to starboard, at the angle of 35 degrees. The maneuver ends when the vessels, having completed the maneuver, return to the original course. At the characteristic points of the trajectories of the initial and upgraded ship, similar to Fig. 3, the information on the duration (in relative T, and in absolute time t), the path traveled by the both ships (in ship lengths L, and in meters) is presented.

For convenience of comparison, Fig. 5 shows in absolute units the changes in time of the main parameters of the turning circle motion of each electric powered ship: the shifting of the center of gravity along the X_1 axis, along the Y_1 axis and the path S_1 traveled by the ship.

In the course of turning circle maneuver, the ship gets a dynamic heel. The value and side of the heel angle depend on the turning maneuver period of the ship. In the period of maneuver under the action of steering force, heel is directed to the side in which the rudder is set. In the evolutionary period, the ship is first straightened as a result of the righting moment of stability, and then acquires the maximum dynamic heel directing to the opposite side of the turning circle, as the centripetal force begins to act. After one or two oscillations, by the beginning of the period of steady motion the ship acquires a static heel directed in the opposite direction to the turning circle.

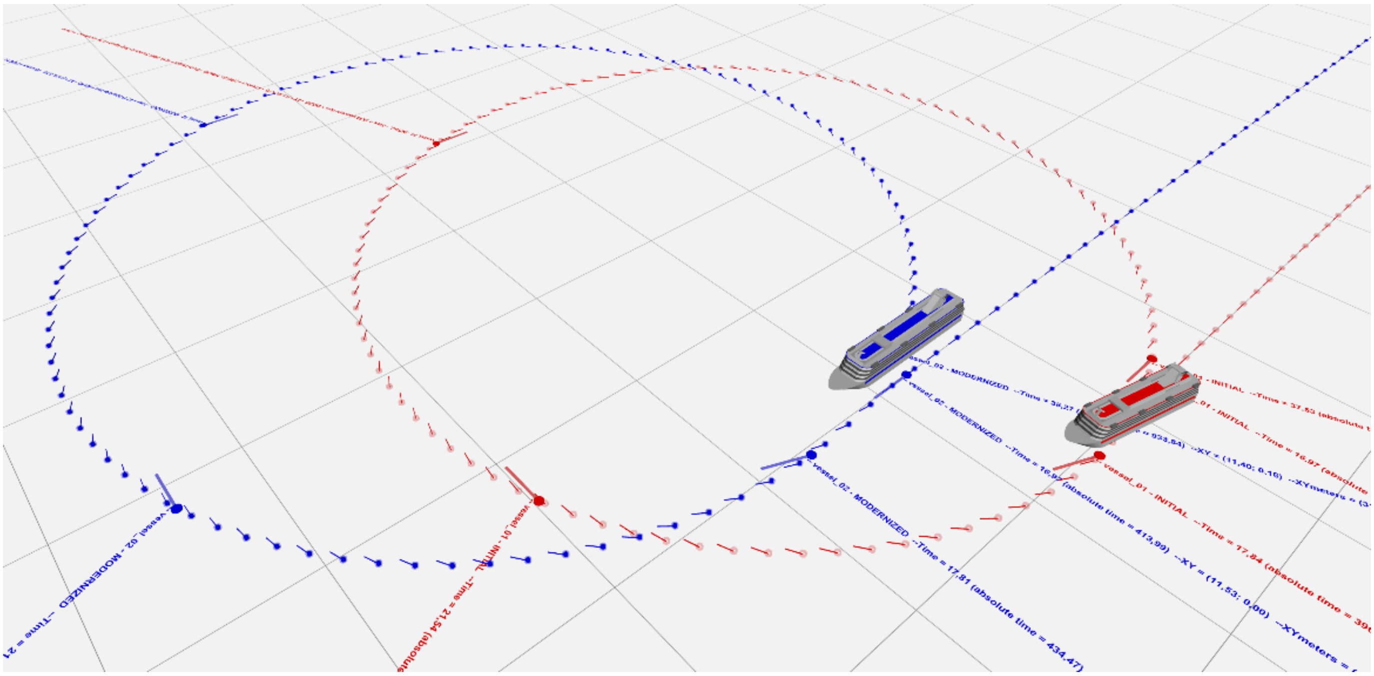

Figure 4 Trajectories of the initial and upgraded ships

Source: Authors

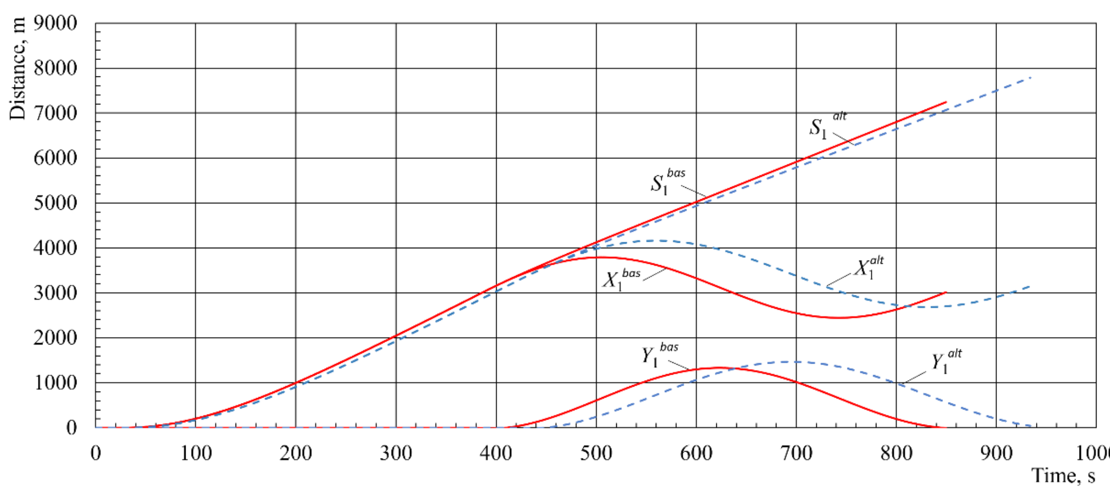

Figure 5 Time variations of turning motion parameters

Source: Authors

A rigorous solution in determining the angle of heel can be obtained by introducing into the mathematical model the equation of rotational motion of the ship around the *X*-axis. This will significantly complicate the calculation of the turning circle motion. At the same time, based on the goals set in the paper – to assess the influence of the ship's hull elongation on the turning motion parameters the task can be simplified. It makes sense to estimate only the change of the maximum angle of heel ϑ_{max}. Approximately this angle can be determined as

$$\vartheta_{max} = 1{,}4\left[v_0^2 \big/ h_0 L \right] \cdot \left(z_g - H \big/ 2 \right), \qquad (5)$$

where h_0 is the transverse metacentric height; z_g is the distance from the lower boundary of the midship section to the point of application of the centrifugal force of inertia of the ship's masses.

Relative change of the maximum angle of heel $\overline{\vartheta_{max}}$ is the ratio of the corresponding parameter of the upgraded ϑ_{max}^{alt} and initial ship ϑ_{max}^{bas}:

$$\overline{\vartheta_{max}} = \frac{\vartheta_{max}^{alt}}{\vartheta_{max}^{bas}} \cong 0{,}87. \qquad (6)$$

Table 5 The main parameters of maneuver for the initial and upgraded ships

	Turning circle maneuver parameters						
	X_1, м	Y_1, м	D_{CT}, м	D_C, м	$\Delta\Delta v_C$, %	Ω_Z,	T_C, sec
Initial ship	936	480	1451	1419	19	0,477	877
Upgraded ship	1020	526	1597	1553	22	0,495	981
Variation of indicators, %	+ 8,97	+ 9,58	+ 10	+ 9,4	+ 3	+ 3,8	+ 12

Source: Authors

Table 6 The influence of ship's hull length on the performance of the electrical power plant

	Turning circle stage	Performance indicators of a power plant					
		v	Ω_Z	ω_M	M_M	I_M	P_D
Initial ship	Inception	0.99	0	1.0	1.013	1.013	1.008
	Steady	0.785	0.38	0.97	1.238	1.238	1.142
	Deviation, %	–20.7	–	– 3	+22.2	+22.2	+13
Upgraded ship	Inception	0.99	0	1.013	1	1	1.001
	Steady	0.753	0.37	0.97	1.268	1.268	1.161
	Deviation, %	–24	–	– 4.2	+26.8	+26,8	+16

Source: Authors

Thus, the maximum angle of heel of the upgraded electric powered ship decreases by about 13 % when it enters the turning circle maneuver. This means that the considered negative phenomenon becomes smaller.

The results of the comparative analysis of the main parameters of maneuver for the initial and upgraded ships are given in Table 5.

Comparison of the calculation results shows the following: as expected, the turning circle parameters deteriorate with increasing vessel length. The maneuver parameters increase on average by 10%, the duration – by 12%. The ship speed at the steady-state stage of maneuver and the maximum value of the angular velocity of rotation around the vertical axis change insignificantly. As follows from Table 5, the deterioration of the indicators is insignificant (it directly depends on the degree of vessel hull elongation) and does not exceed the limits regulated by the Classification Society.

Decrease of the vessel speed with her entering the turning circle maneuver leads to increase of the propeller resistance moment, increase of loads on propeller electric motors and on generating units of the ship power plant. The simulation results (for the initial ship they are given earlier in Fig. 2), the deviations of the electric power plant indicators at steady mode during the maneuver are given in Table 6.

Table 6 shows that for the upgraded vessel, the reduction in speed after reaching steady-state turning radius increases from 20.7% (for the initial vessel) to 24%. The loads on the propulsion motors increase from 22.2% to 26.8% and the loads on the generating units increase from 13% to 16%. This indicates that the additional loads on the propulsion system are increasing but as with the indicators characterizing the ship's trajectory are small.

Thus, both vessels successfully performed the maneuver. All the main performance indicators of both the initial and upgraded electric powered ships and the performance indicators of the power plant are within the permissible limits.

4 Conclusion

The perspectives of modernization for passenger ships by increasing the hull length are studied in this paper, which is a promising strategy to improve the economic efficiency of the fleet by increasing the passenger capacity and economic performance. The dependence of changed dimensions of ships after modernization and the degree of influence on their maneuvering characteristics are studied. The obtained results and the level of their efficiency are estimated. However, altering the dimensions of ships can affect their structural and maneuvering features. Thus, evaluating potential outcomes, whether advantageous or not, is essential when deciding on such modernization.

Research findings reveal that increase in ship length corresponds to an average elevation in fundamental trajectory turning circle maneuver parameters. The duration of maneuvers increases with a relative decrease in steady-state speed during the maneuver along with a change in maximum angular rate of turn within small limits. However, in general, it should be noted that the lengthening of some vessels, taking into account the effect on the parameters during the maneuver and the efficiency of the propulsion system, generally comply with the regulatory limits set by the classification societies. Consequently, the feasibility of such design changes is basically in line with the modernization objectives and can be recommended as an acceptable option for upgrading some passenger ships.

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