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Mathematical model for maneuverability of a riverine support patrol vessel with a pump-jet propulsion system

J.E. Carreño [a,*], J.D. Mora [a], F.L. Pérez [b,*]

[a] COTECMAR, Mamonal Industrial Zone km 9, Cartagena, Colombia
[b] Naval Architecture School of Madrid, Universidad Politécnica de Madrid, Avenida Arco de la Victoria SN, 28040 Madrid, Spain

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ABSTRACT

A study on the maneuverability of a riverine support patrol vessel is made to derive a mathematical model and simulate maneuvers with this ship. The vessel is mainly characterized by both its wide-beam and the unconventional propulsion system, that is, a pump-jet type azimuthal propulsion. By processing experimental data and the ship characteristics with diverse formulae to find the proper hydrodynamic coefficients and propulsion forces, a system of three differential equations is completed and tuned to carry out simulations of the turning test. The simulation is able to accept variable speed, jet angle and water depth as input parameters and its output consists of time series of the state variables and a plot of the simulated path and heading of the ship during the maneuver. Thanks to the data of full-scale trials previously performed with the studied vessel, a process of validation was made, which shows a good fit between simulated and full-scale experimental results, especially on the turning diameter.

1. Introduction

The research on mathematical models for ship maneuverability in the relevant publications has shown a broad variety of formulations which include the effects of the hull resistance, propulsion system thrust, rudder resistance and even other external actions, such as wind and current forces (Bertram, 2000). The reliability on certain method can only be claimed after a successful validation process has been completed ITTC (2002), but carrying out this task may turn into an inconvenience when no useable validation data are available. According to the recommendations by the international committees and academic researchers, full-scale trial results of well-known ships are a proper source of validation data, but only if the mathematical model used deals with the same type of ships and if its operating ranges enclose the specific vessel whose maneuverability parameters have been measured. This is the reason why some models derived to simulate alternative ship designs could lack the appropriate information for its validation.

In this paper, a set of full-scale trials with a Riverine Support Patrol Vessel (RSPV), constructed by COTECMAR (Science and Technology Corporation for the Development of the Colombian Naval, Marine and Riverine Industries), were performed in order to measure the standard parameters of the turning circle test and assess the manoeuvrability characteristics of the RSPV (Carreño et al., 2011). This vessel has two main remarkable design features which are a non-conventional propulsion system and a large beam-draft ratio (wide-beam vessel), among other particulars described below. Consequently, this collected information is useful for the validation of a maneuverability formulation specifically derived to model the maneuverability of a ship with those characteristics.

The wide-beam vessels have shown a particular maneuverability behavior when varying the water depth of the maneuver from deep to shallow water, which is opposite to the usual trend of conventional vessels. In the former case, the main maneuver parameters of the turning circle decrease as the depth decreases, that is, improves its maneuverability properties, while in the latter case the maneuverability parameters worsen (i.e. a reduction in turning performance increasing the tactical diameter) when changing from deep to shallow water. Such behavior seen on wide-beam vessels has been named NS (likely initials for non-standard) effect, which was first studied and computationally reproduced by Yoshimura and Sakurai (1988), who worked with a beam-draft ratio of 5.36 in comparison with a conventional ship with ratio 3.60. That effect was later observed again on ship model experiments by Yasukawa and Kobayashi (1995).

This behavior is different with the widely available literature for vessels with conventional proportions and equipped with propellers and rudders. Kikima et al. (2006) presents results of turn simulations in shallow waters for four different vessels and

* Corresponding author. Tel.: +57 5 6535035.
E-mail addresses: jorgec@cotecmar.com (J.E. Carreño), francisco.perez.arribas@upm.es (F.L. Pérez).

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in all cases the turning and tactical diameters increase as depth diminishes. Delefortrie and Vantorre (2007) studied the effect of the under keel clearance in container ships and validates the increment in the vessel's turning diameter as the under keel clearance diminishes. ITTC (2002) presented the effect of depth on standard maneuvers, describing an increment up to 75% of the tactical diameter in vessels navigating with an under keel clearance of 20%.

There are few results of full-scale maneuvers in shallow waters; this added to the specifics of the propulsion system and to the hull geometry making the presented experiments of relevance for the scientific community.

This paper is focused on the development of a mathematical formulation which may model the maneuverability of the RSPV, by incorporating the pump-jet propulsion model that enables a thrust of 360° increasing maneuverability in shallow water and the specific geometric and hydrodynamic data of the vessel, in order to finally simulate the turning circle under variable input conditions and validate the model by means of the corresponding full-scale experimental tests. Firstly a description of the studied vessel is presented, followed by a stepwise explanation of the mathematical model derivation, which allows carrying on with a simulation and validation stage, which, after the result analysis, leads to the final conclusions.

2. Study case: vessel description

The main particulars of the *RSPV* are listed in Table 1. Its hull corresponds to a riverine ship with small deadrise and with a high beam-draft ratio, designed to navigate on very shallow water. A photograph of the ship while being operated is shown in Fig. 1. In Fig. 2 a close-up of the propellers location is presented. These last photographs were taken from the ship scale model that was built for the self-propulsion test in a towing tank. As it is shown, the propulsion pumps are located by the ship's sternpost and there are no exposed surfaces.

The ship hull does not have any appendages besides a central skeg which separates the water flow towards each propulsion pump, as well as two flow separation plates that direct the outgoing flow from the pumps, contributing to minimizing the thrust losses.

The propulsion system is composed of a pair of *pump-jet* type centrifugal pumps, ref. SPJ 82RD, made by *Schottel*, powered by two MTU-series 60 diesel engines, which produce 450BHP at 1800RPM, and are coupled through a reduction and reverser gear along with a cardan shaft. The pump jet can be directed in any of 360° either individually or in tandem by means of a joy-stick control at the command bridge or locally at the engine control room.

Fig. 1. Picture of RSPV during sea trials.

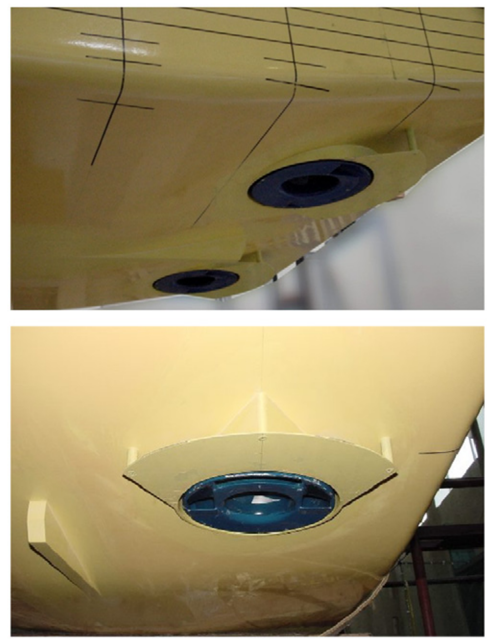

Fig. 2. Detail of ship model ready for self-propulsion test. (*Source*: CTO Report).

Table 1
Main particulars of *RSPV*.
(*Source*: COTECMAR).

Main particulars of riverine supply patrol vessel "*RSPV*"			
Length overall	L_{OA}	40.3	m
Length between perpendiculars	L_{BP}	37.9	m
Beam	B	9.5	m
Design Draft	T	1.0	m
Beam-Draft ratio	B/T	9.5	
Displacement	Δ	303	tons
Radius of gyration	R_{zz}	8.53[a]	m
Block Coefficient	C_B	0.78	
Prismatic Coefficient	C_P	0.87	
Longitudinal Center of Gravity	LCG	17.31	m
Design speed @ deep water	V_{MAX}	9.5	knots
Main Diesel Engines	2 × MTU Series 60, 450BHP@1800RPM		
Propulsion device	2 × Schottel Pump Jet, model SPJ 82RD		
Shipyard	COTECMAR		
Owner	COLOMBIAN NAVY		

[a] Estimate, equals to 22.5% of L_{BP} Lloyd (1998).

3. Derivation of the mathematical model

3.1. Reference system

The reference system to be used in order to develop the equations of the state variables in time domain for the studied vessel is shown in Fig. 3, which takes into account two translational directions and one rotational direction (PMM: Planar Motion Model).

3.2. Derivation of the mathematical model

The dynamic model is represented by a system of three ordinary differential equations, in order to find the value of the three degrees of freedom in the time domain. The notation used from here on is strongly based on the one proposed by Fossen (2011). The general model basically consists of a balance between