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Performance Analysis of a Hardware in the Loop based Emulation of a Naval Propulsion System associated with Supercapacitor Energy Storage

Nabil Benyahia · Jean-Frederic Charpentier · Franck Scuiller · Florent Becker

Abstract Electric autonomy, environment respect, compactness, lifespan and low maintenance costs, are real technological challenges to be taken up on the future ship propulsion system. In this paper, an experimental study of a Hardware In the Loop (HIL) based Emulation of a Naval Propulsion System associated with Supercapacitor Energy Storage System is proposed. For these purpose two electrical machines are associated in the same shaft (DC machine and PMS machine) to reproduce the behavior of the association of the electrical motor and the propeller of a ship at laboratory scale. The whole system is constituted by three subsystems. The first one is represented by a PM synchronous machine associated with a controled VSI which plays the role of the electrical propulsion motor following a realistic mission profile. The second one is constituted by a DC machine associated with a DC/DC converter which is controled in order to reproduce the hydrodynamic behavior of the propeller and the ship, and the third one is constituted by a buck-boost DC/DC converter and an ultracapacitor bank, the ultracapacitor gives to the emulated mechanical shaft the ability to reinject kinetic power into the grid in case of transients. This experimental tool can be associated to innovative hybrid energy system to test and validate hybrid system configuration and can be exploited for many kinds of propellers. In addition, it gives the designer a feedback to optimise ship design. The effectiveness of the proposed HIL

platform in terms of DC grid stability and 4 hydrodynamic operation of propeller is verified by experimental results.

1 Introduction

The maritime industry is currently forced to adapt on the ship technology choice in order to reach atmospheric and environmental pollution restrictions, which are increasingly restrictive in terms of carbon emissions. The development of the futur electric or hybrid ship must necessarily be validated before by low-power experiments prototypes [1,2]. These tools have recently been proposed and well-proven especially from the automotive industries [3,4]. These prototypes aim to reproduce the behavior of a part or several parts of the propulsion system [5,6]. Scaling study can complete these tools for real ships. These experimental tools are complementary with numerical models and will provide designers of ship an insight into expected performance of the whole system in term of ship dynamic, grid stability, motor speed regulation, propeller geometry and fuel consumption. Architectures of electric naval propulsion were brought forward by multiple researchers. In [7], a low power DC machine is used to emulate the propeller and ship dynamics in first hydrodynamic quadrant, where, a 5-leg Voltage Inverter Source (VSI) has been used to ensure power supply and speed control of the propulsion 5 phases motor. Therefore, the fault-tolerant control strategies under different operating conditions and a specific naval navigation profile have been presented, however, the study uses a common DC bus for the DC machine and the AC machine, which does not allow the upstream part of the grid to be studied correctly. In [8], a propeller emulator is proposed by using a DC machine operating as a generator to reproduce the dynamic characteristic of the ship. In this

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work, the DC generator is coupled to the induction machine and feed an electric load through a chopper, nevertheless, the study is focused to first-quadrant operations and the realised HIL is very low power, however scaling errors of the experimental set-up made for a real electric vessel can be occur.

An evaluation of the potential of energy recovery in a low tonnage full electric ship has been presented in [9], in this paper, the propeller is working as a turbine during regenerative braking operations, therefore, the MPPT strategy is considered to increase the recovered energy, the main drawback of this study is that, the obtained results are limited to the numerical simulation. The developed HIL open water tests combine software and hardware components to reproduce real behaviour of the shipboard propulsion system in the towing tank has been proposed in [10]. The authors have demonstrated that HIL can be used to precisely emulate ship propulsion dynamics in the ship model basin.

This work aims to develop a new method to realize a Hardware In the Loop based a naval propulsion platform able to reproduce hydrodynamical and electrical behavior of the propeller and the ship. The objective is to get a completed platform that can emulate a ship propulsion behaviour in various operating conditions. This platform is constituted of three sub-systems: the first one is represented by a PM synchronous machine associated with a controlled VSI which plays the role of the electrical propulsion motor following a realistic mission profile, the second one is constituted by a DC machine associated with a DC/DC converter which is controlled in order to reproduce the hydrodynamic behavior of the propeller and the ship, and the third one is constituted by a buck-boost DC/DC converter and an ultracapacitor which are controlled to achieve a constant voltage source able to absorb or supply power during the 4 quadrant operations of the DC machine. The advantage of this topology enables studying the interaction between the sub-systems and insight an idea of the stability of DC grid during the ship speed transients for instance.

We consider that the proposed work increments the published studies concerning the following criteria. First, the four quadrant open water diagrams are integrated in the propeller model dynamic by using the cinematic angle of attack (advanced angle) in the developed HIL. Second, the use of a supercapacitor associated with a buck-boost DC/DC converter and the propeller emulator allows to operate in all the possible operation modes of the propulsion system. These modes include regenerating braking and propulsive mode in the two rotation directions. For propulsion modes, the SCs are able to store energy and the DC machine is controlled as a brake (generator). In generative mode, the SCs store energy while the DC machine is used as a motor to follow the hydrodynamic characteristics of the propeller and hull system.

2 System description and modeling

The basic components of the developed HIL based naval propulsion platform are shown in Fig. 1. A Permanent Magnet Synchronous Machine (PMSM) is used for the ship propulsion, it is supplied by a DC/AC inverter. The DC machine is controlled through a four quadrants DC/DC converter and is controlled to reproduce the torque related to the propeller in the shaft considering the propeller behaviour in all the possible hydrodynamic operating conditions. The Supercapacitor is used to store or provide power to stabilize the DC voltage grid from DC machine via a DC/DC bidirectional converter.

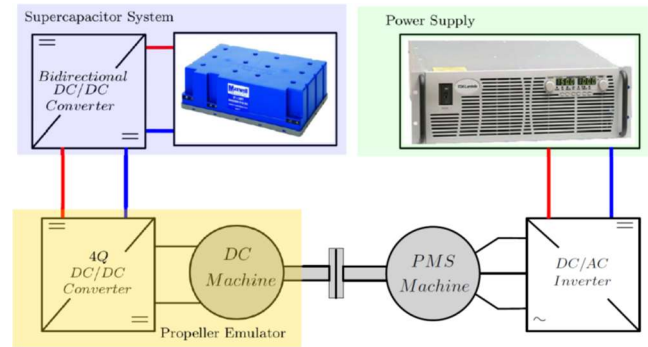


Fig. 1 Basic scheme of naval propulsion platform system.

2.1. Propeller modeling

In order to analyse the performance of the propeller operation in the four hydrodynamic quadrants, the used propeller model is based on C_T and C_Q curves. Where, C_T and C_Q are non-dimensional numbers which characterize the propeller hydrodynamic behavior for a given propeller geometry. These numbers are determined by experimental tests in traction basin or numerical CFD simulations [11] as functions of the advance angle β (6). These numbers are directly linked to the thrust T and torque Q related to the propeller by equations (1), (2), (4) and (5).

$$C_T = \frac{T}{\left(\frac{1}{2} \rho V_r^2\right) D^2 \frac{\pi}{4}} \quad (1)$$

$$C_Q = \frac{Q}{\left(\frac{1}{2} \rho V_r^2\right) D^3 \frac{\pi}{4}} \quad (2)$$

Where V_r is the relative advance velocity at 70 % of the external radius of the propeller and is defined as:

$$V_r = \sqrt{(V_a)^2 + (0.7\pi nD)^2} \quad (3)$$

Consequently, the equation (1) and (2) can be written explicitly as:

$$C_T = \frac{T}{((V_a)^2 + (0.7\pi nD)^2)\rho D^2 \frac{\pi}{8}} \quad (4)$$

$$C_Q = \frac{Q}{((V_a)^2 + (0.7\pi nD)^2)\rho D^3 \frac{\pi}{8}} \quad (5)$$

The advance angle beta is defined by equation (6).

$$\beta = \tan^{-1}\left(\frac{V_a}{0.7\pi nD}\right) \quad (6)$$

This C_T and C_Q coefficient can be interpolated by Fourier series. Fig. 2 shows the C_T and C_Q curves versus beta angle for the Wageningen B4-70 screw propeller series [11]. These curves allow to model the propeller in all the possible modes. It can be noticed that C_T and C_Q can reach positive and negative value depending of the angle beta. The sign of the C_Q is directly linked to the direction of the mechanical power related to the propeller (propulsion or regenerative braking).

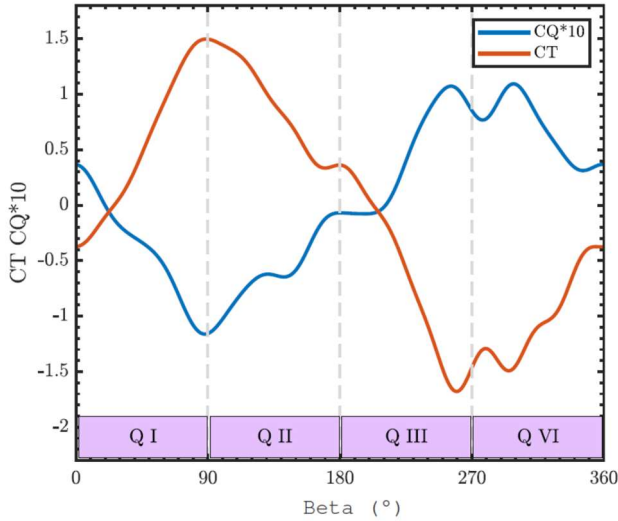


Fig. 2 Open water test results with B4-70 screw series in four quadrants [11].

The Fourier series of C_T and C_Q can be described as:

$$C_T = \frac{1}{N} \sum_{k=0}^{\infty} [A_T(k) \cos(k\beta) + B_T(k) \sin(k\beta)] \quad (7)$$

$$C_Q = \frac{1}{N} \sum_{k=0}^{\infty} [A_Q(k) \cos(k\beta) + B_Q(k) \sin(k\beta)] \quad (8)$$

The equation of motion which represents the ship manoeuvring dynamics in one degree of freedom is defined as:

$$\frac{dV_{ship}}{dt} = \frac{T - R_T}{M_{ship}} \quad (9)$$

Where, V_{ship} is the ship speed, M_{ship} is the ship masse and R_T is the total force acting in the opposite direction of motion, it is also called the total hull resistance and can be expressed by (10) and is a function of many factors including ship speed, hull form and sea state. Total hull resistance increases as ship speed increases, the simplified function is shown in Fig.3. In this case a basic curve with a theoretical calm sea state is considered.

$$R_T = R_V + R_W + R_{AA} \quad (11)$$

Where, R_V is the viscous (friction) resistance, R_W is the wave making resistance and R_{AA} is the air resistance caused by ship moving through calm air.

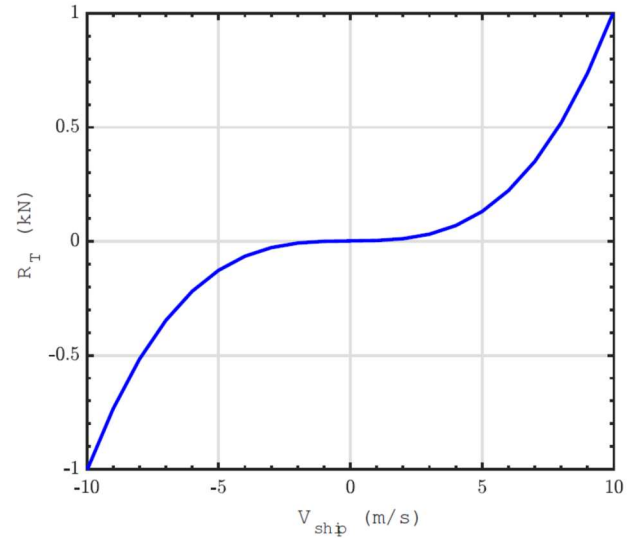


Fig. 3 Hull resistance curve.

The used ship global model synopsis is shown in Fig. 4. It can be seen that a gearbox can be inserted in the model to adapt the propeller speed to the motor one, where n_M is the motor speed in (r/s) and T_M is the motion torque.

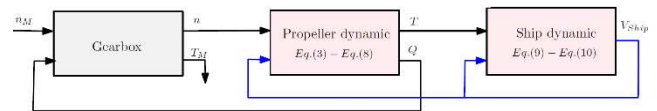


Fig. 4 Mechanical shaft model.

3 Experimental results

The whole system control scheme showed in Fig.5 is implemented on a dSPACE DS1202 MicroLabBox platform. The PMSM drive is controlled by FOC control. The FOC system consists of two control loops: A speed controller in an outer loop and a current controller in an inner loop. The PMS motor is driven by a three-leg voltage-source inverter. The DC machine is mechanically associated

to the PMS motor and can be operate in the four quadrants. The resulting voltage and current are positive or negative according respectively to the PMSM speed direction and the torque imposed by the propeller (DC current reference).

The propeller emulator (DC machine and drive) control is based on current control of the DC machine through four quadrants chopper, the DC machine reference current I_{dcm}^* can be obtained by multiplying the propeller torque Q related to hydrodynamic model (5) by gearbox factor $k_{Gearbox}$ and DC machine torque constant k_{dcm} .

$$I_{dcm}^* = k_{Gearbox} k_{dcm} Q \quad (12)$$

In charging mode, the current I_{scmax} is negative. Maximum current that can be injected into the ultra-capacitor is limited by the capacitor terminal voltage.

$$I_{scmax} = \frac{V_{scMax} - V_{sc}}{ESR_{DC}} \quad (14)$$

The ultra-capacitor control is implemented through two control loops: one outer voltage control loop that controls the DC bus voltage V_{bus2} and inner current loops in order to control the current I_{sc} flowing through the ultra-capacitor inductor L_{sc} .

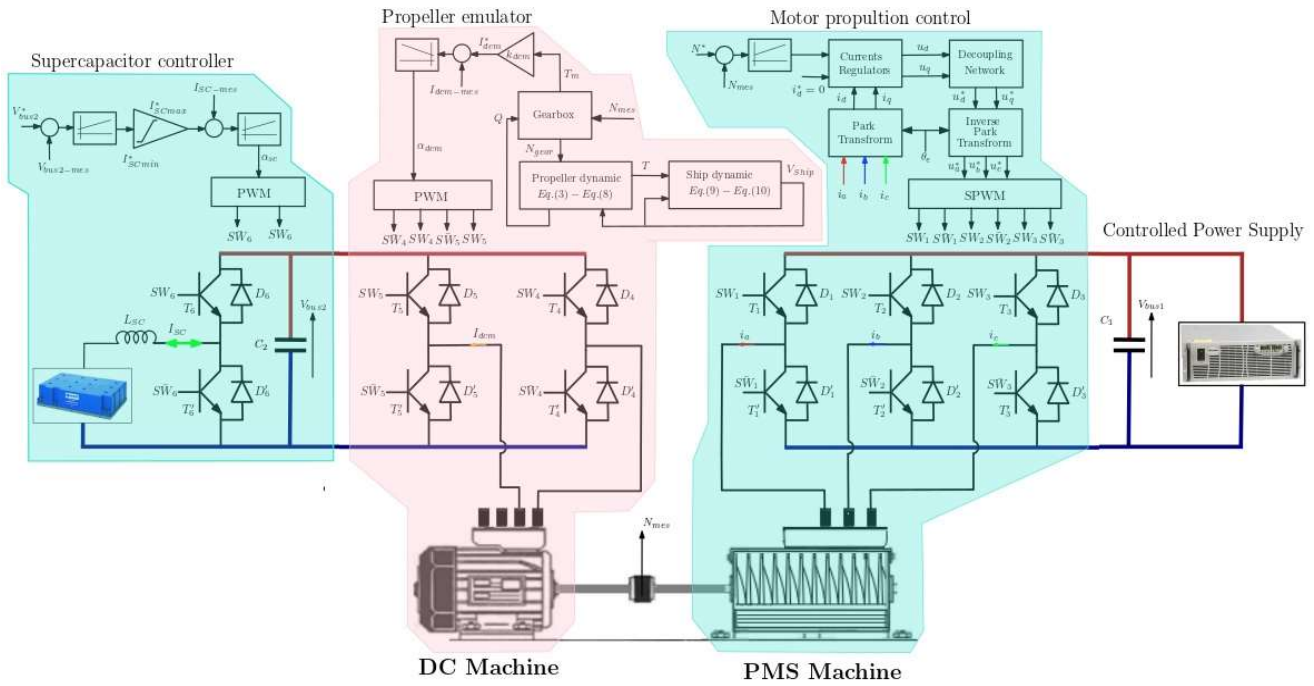


Fig. 5 Global system scheme.

By using PI regulator, it is possible to obtain accurate current control over a wide range in clockwise as well as anticlockwise directions. The DC bus voltage V_{bus2} is controlled as constant through the buck-boost DC/DC converter associated with the supercapacitors, the objective is to achieve with the buck-boost converter and the supercapacitors a constant voltage source able to absorb or supply power (power balance) during all the possible operation modes of the DC machine used as propeller emulator.

In discharging mode, the maximum current delivered I_{scmax} to the DC bus depends on the capacitor voltage V_{sc} , maximum voltage, and the equivalent serial resistance ESR_{DC} ,

$$I_{scmax} = \frac{V_{sc}^2}{4ESR_{DC}V_{scMax}} \quad (13)$$

In order to prove the good behavior of the proposed propeller emulator under different ship operating conditions, the propulsion motor speed is controlled periodically in ahead and then in astern as shown in Fig. 6.

It can be noticed that the measured speed tracks exactly the reference speed for different variation and the ship speed follows the motor speed but with a delay which is due to the ship inertia. when the boat starts to move in ahead or in astern, the propeller accelerates slightly about 85 rad/s, this phenomenon can be explained by the angle beta variation, but recovered quickly.

Fig.7 shows the steady state of PMSM quadrature current component, DC machine current and supercapacitor current I_{sc} . This illustrates also the comparison of the measurement and reference currents DC machine armature, it shows that the measurement current is close to the reference current. These results prove the good accuracy of the propeller emulator control with high dynamic response.

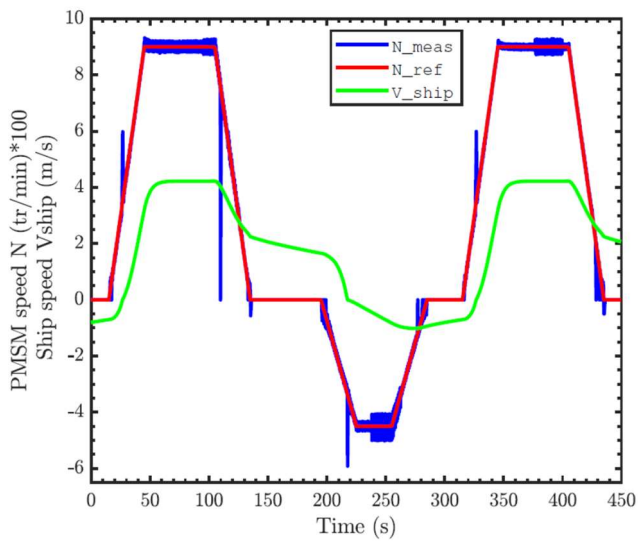


Fig. 6 Propeller and ship speed.

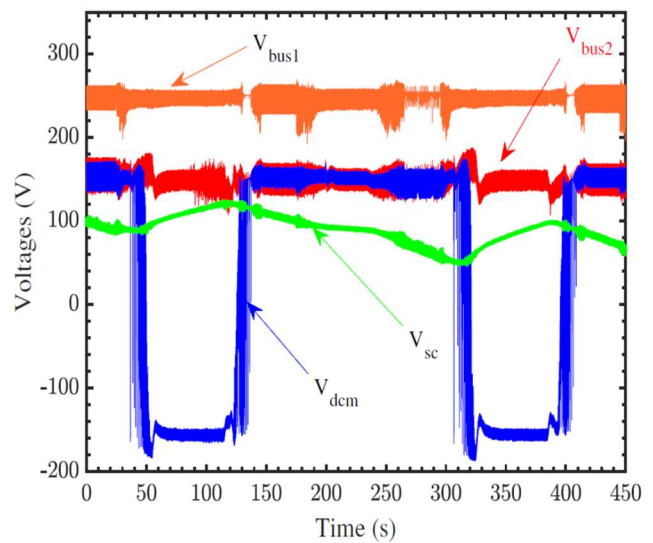


Fig. 8 DC bus, DC machine armature, and ultracapacitor voltages.

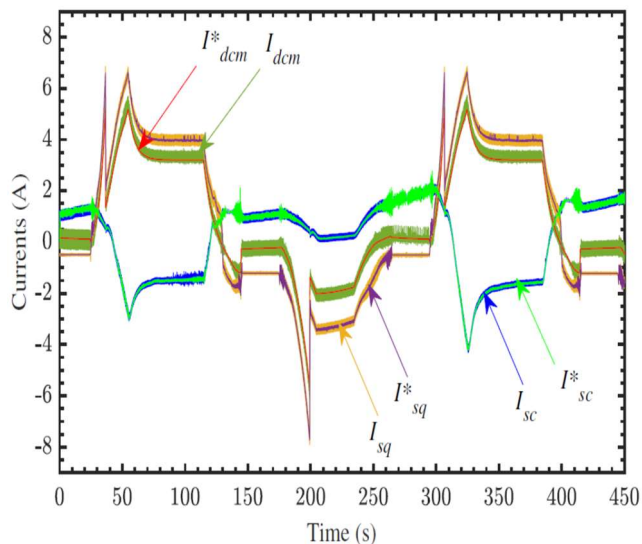


Fig. 7 DCM armature, PMSM quadratic and ultracapacitor Currents.

Fig. 7 illustrates that in discharge mode, the ultra-capacitor outputs an average current about of 2 A to stabilize DC bus voltage at 150V although the DC bus current abrupt change. The fluctuation of the DC bus voltage V_{bus2} depends on the ultracapacitor's SOC. In charge mode, the DC machine provides energy to DC bus with 4 A current. In order to stabilize DC bus voltage at 150 V, the surplus energy is transmitted to the ultracapacitor. The dynamic response results of the conventional double closed loops control strategy are shown in Fig.8. Fig.8 clearly shows that the voltage of the supercapacitor tends to decrease over time. To avoid the complete discharge of the supercapacitor, the reference of the DC bus voltage can be variable according to the level of the state of charge. Figs. 9 and 10 show the operation of the propeller in the four hydrodynamic quadrants,

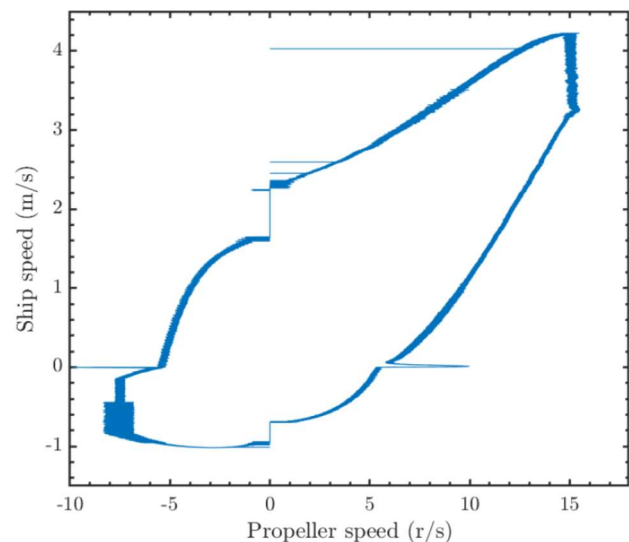


Fig. 9 Four hydrodynamic quadrant curve.

Fig. 9 compares the forward speed and the shaft speed on the other hand, Fig. 10 illustrates the advance angle β . Fig. 11 shows the balance at steady state of thrust and total resistance. During ship acceleration and deceleration manoeuvres the thrust increases in response to the total resistance which depend on ship velocity. Otherwise, the difference between the thrust generated by the propeller and the ship's resistance is nul when the ship's velocity is constant.

4 Conclusion

This paper presents a solution to emulate the behaviour of a ship in a HIL approach. This solution allows to test electric ship propulsion chain configuration and control in a low scale laboratory experimental set-up. To be able to emulate

the propeller hydrodynamic behavior in a mission profile a real time-controlled DC machine is associated with a supercapacitor bench which is used as a controlled power source or a controlled power load depending on the operating mode of the ship. This propeller emulator allows to represent the behaviour of the ship and propeller in all the possible modes (propulsion, regenerative braking in the two rotation direction of the propeller). Experimental results underline the relevancy of the approach. Several possible improvements are identified. As an example, a supercapacitor's state of charge estimator can be associated with SC control and can be used to maintain the SOC of the SC bench around an optimal state of charge during long term tests.

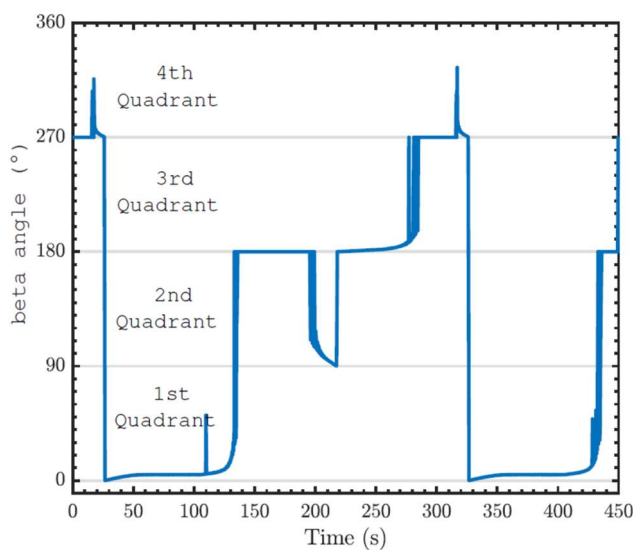


Fig. 10 Beta angle variation.

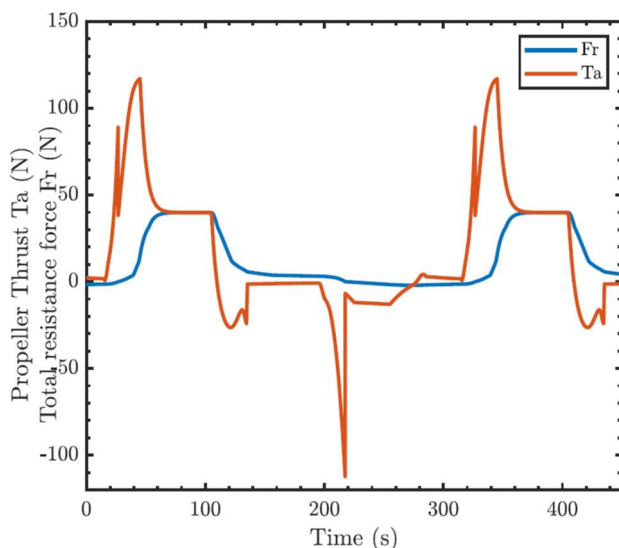


Fig. 11 Thrust and total resistance curves.

Table 1 System parameters

Parameter	Value
Armature DC machine voltage	200 V
Armature DC machine Current	9 A
DC machine torque constant	1,2
Gearbox factor ($K_{Gearbox}$)	4
Ship mass (M)	400 Kg
Propeller diameter (D)	0.5 m
Ultracapacitor's rated voltage	160 V
Ultracapacitor's capacitor	5 F

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