

Preliminary Assessment of Nuclear Propulsion Load Variation under Wave-Induced Partial Propeller Emergence

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1. Introduction

Nuclear-powered ships require coordination among the reactor, power conversion system, and electrical propulsion system under varying propulsion loads. Waves and ship motions alter the propeller inflow and loading, introducing time-dependent disturbances into the propulsion system [1,2]. These disturbances should be considered when assessing the load-following and control requirements of nuclear marine power systems [3].

One of the hydrodynamic mechanisms responsible for such propulsion-load variations is the partial emergence of the propeller caused by wave-induced ship motions. Previous research has investigated the influence of proximity to the free surface on propeller performance [4] and the effects of immersion depth and regular waves on propeller loading [5]. Heave and pitch motions further alter the propeller operating condition in waves [6]. When these motions cause part of the propeller to emerge above the free surface, the submerged propeller area decreases temporarily, and the thrust, torque, and absorbed shaft power drop abruptly within a fraction of the wave encounter period.

The objective of this preliminary study is to establish a numerical framework for evaluating the influence of wave-induced partial propeller emergence on nuclear marine propulsion loads and to quantify the resulting load variation over several wave encounter cycles. The virtual disk method is used to represent the hydrodynamic action of the propeller and determine the time histories of thrust and torque in waves. The resulting torque is converted into absorbed shaft power, electrical power demand, and equivalent thermal power demand, and the peak-to-peak variation and maximum ramp rate of the propulsion load are evaluated at full scale. This framework provides time-resolved propulsion-load inputs for subsequent assessment of the load-following capability and power margin of the nuclear propulsion system.

2. Methods and Results

2.1 Propeller Modeling Using the Virtual Disk Method

The Virtual Disk (VD) method represents the hydrodynamic action of a rotating propeller by applying distributed forces within a disk-shaped region. As

illustrated in Fig. 1, the disk is located at the propeller position and has the same outer diameter and shaft-axis orientation as the modeled propeller. It represents the region swept by the rotating blades rather than a physical solid plate. Axial and tangential force components are applied to the fluid to represent the thrust and torque exerted by the propeller, respectively.

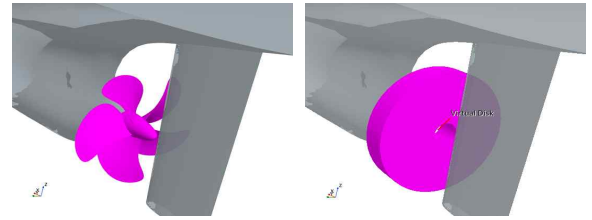


Fig. 1. Comparison of the propeller geometry (left) and its virtual-disk representation (right) at the ship stern.

In the present study, the Minsaas correction was applied to the VD model of the KP505 propeller to account for the effects of partial emergence.

Table 1. Specifications of the model propeller (KP505)

	Full Scale	Model Scale
Diameter [m]	7.9	0.25
Number of blades	5	
Scale Ratio	31.6	
Hub Ratio	0.180	
Section type	NACA66	

The open-water characteristics of the propeller provide the thrust and torque coefficients

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D^4}, \quad K_Q = \frac{Q}{\rho \cdot n^2 \cdot D^5}$$

as functions of the advance ratio

$$J = \frac{V_A}{n \cdot D}$$

where T and Q are the thrust and torque, ρ is the seawater density, n is the rotational speed in revolutions per second, D is the propeller diameter, and V_A is the advance velocity.

In the present study, these coefficients are corrected as a function of the instantaneous submergence ratio

$$I = h/D$$

where h is the shaft-center submergence depth and D is the propeller diameter

At the shallowest submergence encountered in this

study, the correction reduces the thrust and torque to about 42% and 48% of their deeply submerged values. The corrected loads are used to specify the forces applied within the VD, allowing the model to account for changes in propeller loading as the submergence condition changes.

The VD model is coupled with the Volume of Fluid (VOF) method to describe the air-water distribution and identify the exposed portion of the disk. The corrected VD model is applied in a wave-ship motion simulation performed in STAR-CCM+ to obtain the time histories of the propeller emergence ratio, thrust, and torque. The simulation condition and the definition of the emergence ratio are presented in Section 2.2.

2.2 Simulation Condition and Propeller Emergence in Waves

The propeller emergence ratio is defined using the air-exposed area of the VD as follows:

$$E(t) = \frac{A_{air}(t)}{A_{VD}} \times 100$$

where $A_{air}(t)$ is the air-exposed area of the VD at time t , evaluated from the air volume fraction within the disk region, and A_{VD} is the full circular reference area defined by the propeller diameter; the propeller tip is above the free surface when $I < 0.5$.

The Tasneef Rules assess the hourly occurrence of events in which the upper quarter of the propeller diameter emerges above the sea surface [8]. For a circular disk intersected by a horizontal free surface, this emergence depth corresponds geometrically to approximately 19.6% of the total disk area. This value defines an emergence event for seakeeping assessment, rather than an average operational emergence ratio, and it is used below as a reference for interpreting the computed emergence ratio.

The wave-ship motion simulation was performed at model scale for a ship advancing in regular head waves that represent high sea conditions with wave heights of about 6-9m [11], such as may be encountered in the Pacific Ocean.

Figure 2 compares the water volume fraction on the VD at a fully submerged instant and at maximum emergence. Over the analyzed interval, the propeller tip was exposed for 46% of the time, while the maximum and time-mean emergence ratios were approximately 25% and 4%, respectively. Emergence recurred with successive wave encounters. The maximum emergence ratio is therefore a case-specific instantaneous value, rather than a representative operating average.

The shaded bands in Figs. 3 and 4 indicate the intervals during which the propeller tip was exposed above the free surface. During most emergence events, the emergence ratio $E(t)$ exceeded the 19.6% reference threshold. These marked intervals provide a temporal reference for comparing propeller emergence with the corresponding variations in thrust, torque, and

power.

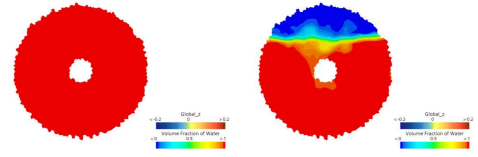


Fig. 2. Water volume fraction distribution on the Virtual Disk: fully submerged (left) and 25% propeller emergence conditions (right)

2.3 Propeller Performance under Partial Emergence

Figure 3 shows the full-scale thrust and torque histories during repeated propeller emergence and resubmergence. Over the analyzed interval, the thrust ranged from 0.68 to 1.94 MN and torque from 1.10 to 2.61 MN·m, corresponding to maximum-to-minimum reductions of approximately 65% and 58%, respectively. The load minima occurred near maximum emergence, followed by recovery as the propeller became resubmerged. These repeated load reductions and recoveries define hydrodynamic disturbance histories for assessing propulsion availability and the safety of the nuclear marine power system.

Table 2. Comparison of full-scale propeller performance between the fully submerged and 25% exposed conditions

	Fully submerged	25% exposed
K_T	0.170	0.060
$10K_Q$	0.290	0.122
Thrust T	1.94 MN	0.68 MN
Torque Q	2.61 MN·m	1.10 MN·m

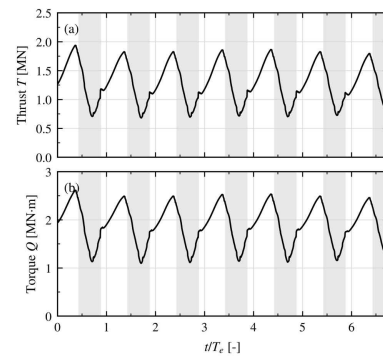


Fig. 3. Time histories of the full-scale propeller (a) thrust and (b) torque in head waves

From a nuclear-ship safety perspective, thrust loss may reduce the available propulsion and maneuvering capability, while rapid torque reduction and recovery impose unloading and reloading disturbances on the power system. If these disturbances are transmitted through the electrical and power-conversion systems without adequate compensation, they may create a temporary imbalance between reactor heat generation and heat removal. Depending on the reactor design and

control response, this imbalance could cause transients in coolant temperature, system pressure, and reactor power, potentially requiring power reduction or protective shutdown [3,12]. The safety assessment must therefore determine whether the control and protection systems maintain the plant within applicable limits or achieve safe shutdown with continued core cooling [13]. Accordingly, the torque histories are converted into power-demand transients in Section 2.4 to provide inputs for subsequent coupled safety analyses.

2.4 Propulsion Load Coupling with the Nuclear Power System

To characterize the propulsion-load disturbances relevant to nuclear marine safety assessment, the propeller torque histories are converted into power-demand histories. At a constant propeller rotational speed, the instantaneous absorbed shaft power is calculated as

$$P_{shaft}(t) = 2\pi n Q(t)$$

where n is the propeller rotational speed in revolutions per second and $Q(t)$ is the propeller torque

Using constant conversion efficiencies, the corresponding electrical and equivalent thermal power demands are calculated as

$$P_{elec}(t) = \frac{P_{shaft}(t)}{\eta_{motor}\eta_{drive}}$$

where η_{motor} and η_{drive} denote the motor and drive-system efficiencies, respectively

$$P_{th,eq}(t) = \frac{P_{shaft}(t)}{\eta_{motor}\eta_{drive}\eta_{PCS}}$$

where η_{PCS} is the efficiency of the power conversion system

Rapid load changes in nuclear marine propulsion systems require control strategies with appropriate response characteristics [3]. To characterize the load variation, the peak-to-peak power variation and maximum power ramp rate are defined as

$$\Delta P = P_{max} - P_{min}$$

$$R_P = \max \left| \frac{dP(t)}{dt} \right|$$

where $P(t)$ denotes the shaft power, electrical power demand, or equivalent thermal power demand being evaluated. P_{max} and P_{min} are the maximum and minimum values over the analyzed interval, and t is expressed in full-scale time. The reported maximum absolute ramp rate is evaluated using a 1 s window in full-scale time.

The Minsaas correction was applied because the uncorrected open-water characteristics do not account for the thrust and torque losses associated with partial propeller emergence [8,9]. The corrected loads were then used to evaluate the resulting propulsion-power variations.

Table 3 summarizes the effect of the Minsaas

correction on the full-scale shaft-power demand under the analyzed wave condition. Applying the correction reduces the minimum and time-mean shaft powers from 18.65 to 11.65 MW and from 23.88 to 20.19 MW, respectively, while the maximum changes only slightly, from 28.29 to 27.75 MW. The peak-to-peak power variation increases from 9.64 to 16.10 MW (+67%), and the maximum ramp rate, evaluated over a 1 s window at full scale, increases from 3.16 to 7.06 MW/s (+123%). These increases indicate that accounting for partial emergence produces larger and more rapid propulsion-load fluctuations, highlighting the importance of including emergence-induced disturbances in the transient safety assessment of nuclear marine power systems.

Table 3. Effect of propeller emergence on the full-scale shaft power demand

	Fully submerged	25% exposed	Change
Maximum	28.29 MW	27.75 MW	-1.9 %
Minimum	18.65 MW	11.65 MW	-37.5 %
Time-mean	23.88 MW	20.19 MW	-15.5 %
Power swing ΔP	9.64 MW	16.10 MW	+67 %
Fastest power change, per second	3.16 MW/s	7.06 MW/s	+123 %

Figure 4 shows the time histories of shaft power, electrical power demand, and equivalent thermal power demand with and without the Minsaas correction. The corrected histories exhibit repeated power reductions during propeller emergence and subsequent recovery as the propeller becomes resubmerged, illustrating the temporal development of the load fluctuations summarized in Table 3. With the correction, the electrical and equivalent thermal power demands range from 12.4 to 29.5 MW and from 31 to 74 MW, respectively. The equivalent thermal power is an efficiency-based representation of the propulsion load and does not represent the actual reactor transient response. Such analyses are required to determine whether the resulting reactor power, coolant-temperature, and system-pressure transients remain within applicable limits and whether adequate safety margins are maintained.

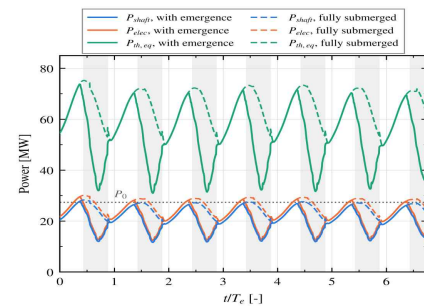


Fig. 4. Time histories of shaft power, electrical power demand, and equivalent thermal power demand with 25% propeller emergence and fully submerged conditions

The predicted propulsion-load disturbances occur over seconds and recur with successive wave encounters. The resulting power-demand histories, characterized by their amplitudes and ramp rates, provide inputs for subsequent transient safety analyses of nuclear marine power systems. Coupled simulations of the reactor, power-conversion system, and electrical system are required to determine whether the associated reactor-power, coolant-temperature, and system-pressure transients remain within applicable limits. These analyses should also assess how coordinated control, electrical buffering, and adjustments to propeller operation influence the transient response and the available safety margins [14].

3. Conclusions

A numerical framework was developed to investigate the influence of wave-induced partial propeller emergence on the propulsion-load conditions of a nuclear-powered ship. The STAR-CCM+ wave-ship motion simulation in regular head waves representing high sea conditions (wave heights of about 6–9 m) showed that the propeller tip emerges during 46% of the time and that the emergence ratio reaches approximately 25%, exceeding the 19.6% reference threshold in most of the emergence events.

At full scale, the thrust and torque exhibited maximum-to-minimum reductions of approximately 65% and 58%, respectively, over the analyzed interval. With the Minsaas correction, the shaft power ranged from 11.65 to 27.75 MW, with a peak-to-peak variation of 16.10 MW and a maximum absolute ramp rate of 7.06 MW/s evaluated over a 1 s window. The peak-to-peak variation and maximum ramp rate were 67% and 123% greater, respectively, than those obtained without the correction, demonstrating the importance of accounting for partial emergence when characterizing rapid propulsion-load disturbances.

The shaft, electrical, and equivalent thermal power histories provide load inputs for subsequent transient safety assessments of nuclear marine power systems. The equivalent thermal power is an efficiency-based estimate of the propulsion load. Future work will extend the analysis to irregular waves and a wider range of wave heights and headings, and will use coupled reactor, power-conversion-system, and electrical-system simulations to determine whether the resulting reactor-power, coolant-temperature, and system-pressure transients remain within applicable limits. The effectiveness of coordinated control, electrical buffering, and adjustments to propeller operation in maintaining safety margins will also be assessed.

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