Sizing Power Generation and Fuel Capacity of the All-Electric Warship

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Abstract – Current sizing algorithms for warship power generation and fuel tank capacity were developed over forty five years ago when ship service loads were a small fraction of the overall power demand. Electric load growth, particularly with the introduction of high power mission systems will soon result in ship service maximum margined loads being nearly the same as the maximum propulsion load. In many operating conditions, ship service power demands exceed propulsion demands. This paper proposes new sizing methods for all-electric warships that are tied to operational effectiveness. These sizing methods are based on mobility mission tactical situations such as high speed transit, economical speed transit, and on station time. Additionally, the methods are sensitive to drag reduction efforts, temperature, and the ability to maintain speed in higher sea states. The goal is to optimize shipboard power and propulsion system life cycle cost while meeting operational requirements.

Index Terms – Load Forecasting, Marine vehicle power systems, Marine vehicle propulsion.

I. INTRODUCTION

The integrated nature of the all electric warship employing an Integrated Power System (IPS) where propulsion and ship service loads are powered by common prime movers offer ship designers increased design flexibility as well as new design considerations [1] [2]. This paper specifically addresses the requirements and procedures for determining the maximum power generation capacity, and the size of the fuel tank. The existing design criteria are based on segregated propulsion and electrical power generation. For a mechanical drive ship, propulsion power is derived from a "sustained speed" requirement that is independent of the ship's operating conditions. Electrical power generation capacity is determined from the worst case operating condition and is independent of any ship speed or mobility requirements.

For naval warships, the ship seldom, if ever, is required to operate at the maximum speed under the maximum ship service power load operating condition. An IPS ship can take advantage of this to reduce cost by optimizing the installed power capability to achieve the combined maximum ship service power load and propulsion load. This capability is becoming more and more valuable as the electrical power demand of advanced radars and electric weapons is anticipated to grow in the coming decades to 50% or more of the power needed for propulsion to achieve the specified sustained speed.

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Furthermore, the definition of sustained speed simply as a percentage of maximum propulsion power does not allow the design process to optimize ship performance for various wind and wave conditions it will likely encounter in operation. By evaluating ship designs and hull forms in varying sea states, sustained speed and associated installed propulsion power can be more effectively traded-off with other ship design requirements and constraints.

To integrate mobility and mission system requirements, and to properly incorporate the impact of high sea-states into mobility and power system design, this paper proposes specifying operational requirements in the form of

a. Operational Conditions that reflect mobility and other mission system requirements under a given set of environmental conditions to include sea-state.
b. Operational Profiles that specify the amount of time spent in each Operational Condition.
c. Service Life Allowance to account for electrical load growth over the life of the ship.

With the growing electrical load demand of future combat systems, the method for sizing the fuel tanks also must evolve. Traditionally, fuel tankage is sized based on specifying an endurance range and an endurance speed. Neither of these values is explicitly tied to a concept for how the ship is intended to operate. This paper proposes that the ship carry enough fuel to satisfy three different constraints based on three different modes of operation: Surge to Theater, Economical Transit, and Operational Presence.

II. SIZING POWER GENERATION

Historically, propulsion power and electrical generation capacity for mechanical drive ships have been calculated using different algorithms. The rated propulsion power is based on the concept of "Sustained Speed" which is defined as that speed a ship is predicted to attain at full load displacement in smooth water with a clean bottom and typically 80% of the installed shaft horsepower. As a measure of that speed a ship should be able to attain over its service life, the sustained speed requirement is intended to account for the effects of weather, sea state, heading relative to wind and sea directions, and variations in bottom and propeller fouling. [3] Resistance generally increases due to fouling about 1% for every month after the hull and propulsor are cleaned. Because cleaning can not completely restore the smoothness of the ship's hull, a 1%

'hull efficiency' loss is generally assumed after each cleaning. [4]

Electric plant capacity is based on the maximum margined electrical load with service life allowance. Not counting one of the generator sets with the highest rating, the remaining generators must have sufficient capacity to provide power to the maximum margined electric load with service life allowance. If generators are intended to be paralleled to achieve the maximum capacity, they can not be loaded more than 95% (formerly 90%) to account for the inability for paralleled generators to perfectly share load. [5]

Once a ship enters service, it will normally generate and consume considerably less power than the maximum margined load. For most modern ships with all-electric heating, cold weather operations are the limiting case for electrical power demand. Fig. 1 shows the typical dependency of load on temperature [6].

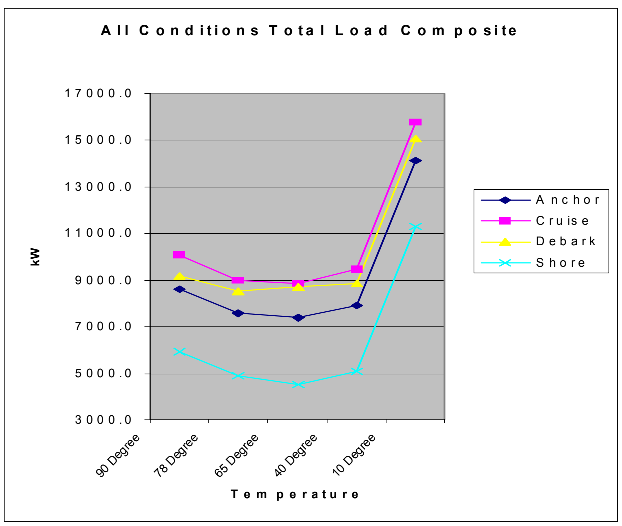

Fig. 1: Predicted LHD 8 ship service loads without service life allowance

Furthermore, the amount of propulsion power required by displacement ship is roughly proportional to the cube of the speed (Fig. 2). This means that a ship designed for 30 knots will only experience a 1 knot (3.3%) drop in speed for a 9.7% reduction in propulsion power and a 2 knot drop (6.7%) in speed for an 18.7% reduction in propulsion power.

Another point to consider is that a naval warship typically operates infrequently at its maximum speed. Fig. 3 shows that a modern destroyer only operates about 2% of the time above 25 knots. Most of the time is spent operating at less than 15 knots.

Integrating propulsion power and ship service power using an Integrated Power System (IPS) architecture offers the ship designer considerable flexibility, but simply applying rules for segregated propulsion and electric power plants results in excess generation capacity at increased cost. Furthermore, future combat systems, high power radars, and electric weapons may result in ship service loads for a cruiser sized ship on the order of 30 MW compared to a propulsion requirement for roughly 60 MW. Should the ship be designed to provide the full 30 MW of ship service power while using the full 60 MW of propulsion power? Would it be tolerable to install 70 MW of power and accept a lower maximum speed (About a 4 knot drop) on very cold days when the combat systems are being used? If that is not acceptable, would it be tolerable to deliver a ship with a very conservative service life allowance and accept a potential loss in maximum speed on cold days when the service life allowance is expended? Is there an Operational Condition that demands that a ship be capable of achieving its maximum speed while operating all of its combat systems at their maximum power? Does a warship have to do everything at once, or can the power be apportioned to those systems that are most critical to the success of the mission?

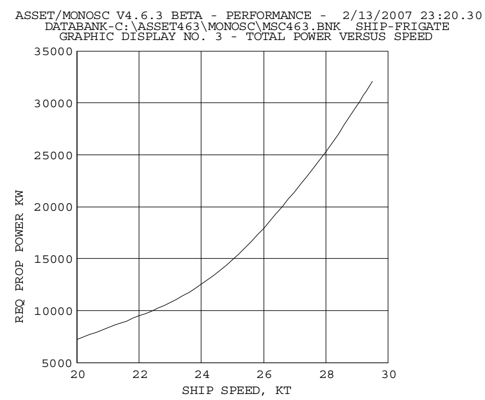

Fig. 2. Typical Speed vs. Propulsion Power Curve for a frigate sized warship.

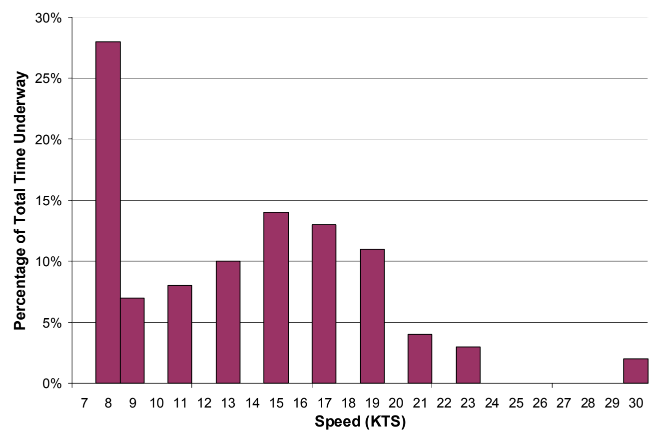

Fig. 3: Operating Speed Profile for DDG 51 [7]

One impact of specifying a ship's speed requirement in terms of the sustained speed is that there is no incentive to improve the ship's mobility performance in higher sea states. Fig. 4 shows that the maximum speed a ship can attain as a function of wave height and sea direction. Fig. 5 correlates wave height with sea-state. Note that sea-state does not capture the spectral content of ocean waves; a sea-state 6 in the North Atlantic is not the same as a sea-state 6 in the Yellow Sea in terms of the wavelengths of the ocean waves a ship will encounter. Fig. 6 shows that in addition to the reductions in speed due to increased drag in higher sea states, a ship's operator will voluntarily reduce the speed of a ship due to slamming and deck wetness. By fixing the sustained speed to the calm water condition, the ship designer has no incentive to improve the hull design for better mobility performance over the sea conditions the ship is expected to see in the open ocean as shown in Fig. 7 and Fig. 8.

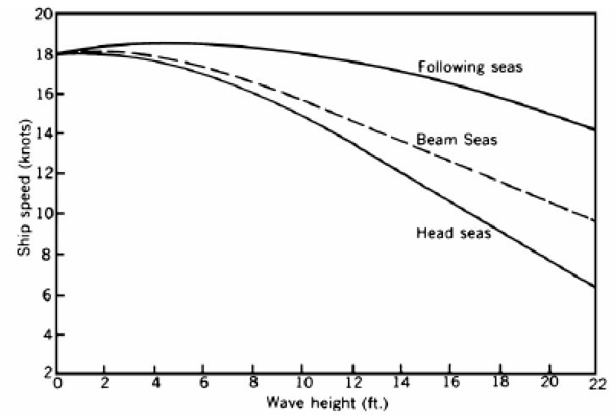

Fig. 4. Impact of Waves on Ship Speed [8]

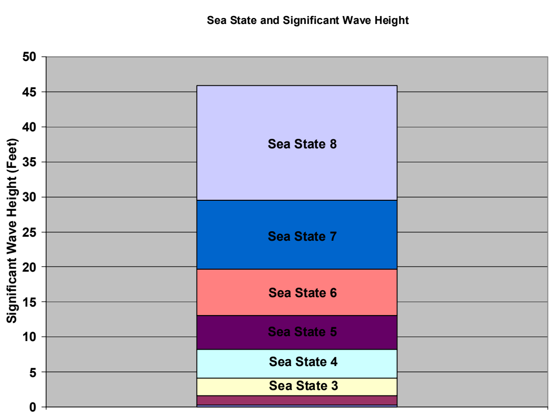

Fig 5: Sea State and Significant Wave Height

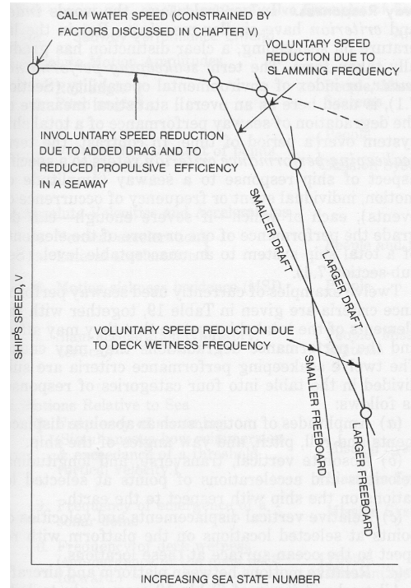

Fig. 6 Conditions limiting Ship Speed due to increasing Sea State [9]

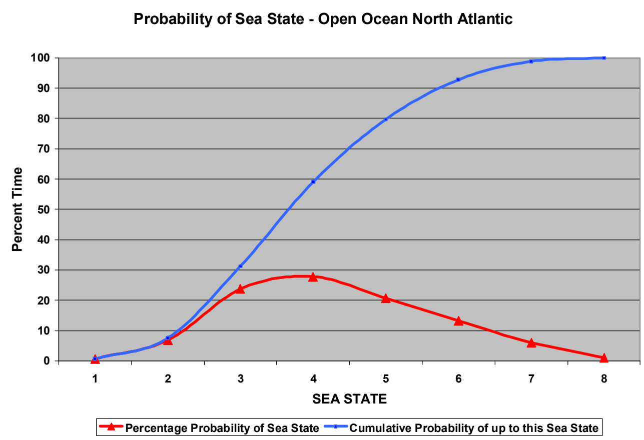

Fig. 7. Probability of Sea State – Open Ocean North Atlantic. Data for graph from [9]

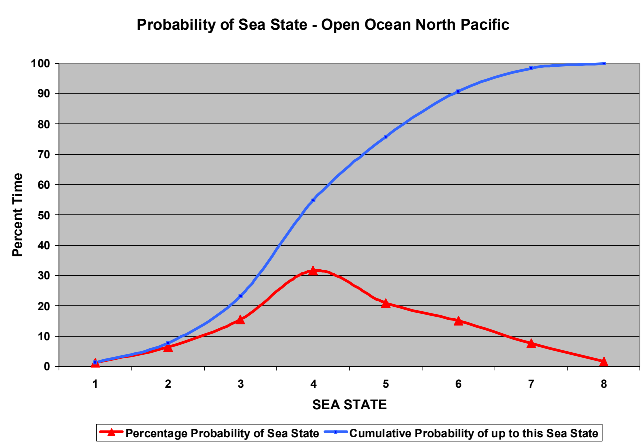

Fig. 8. Probability of Sea State – Open Ocean North Pacific. Data for graph from [9]

To take advantage of the flexibility of IPS, and to tie the propulsion requirement to environmental conditions the operator will face, the author proposes specifying requirements for electric warships in the following manner:

a. Operational Conditions should be defined in terms of the level of performance of the different mission systems, including mobility. For combat systems and other mission systems, the levels of performance should be translatable into electric load requirements, Quality of Service (QOS) Mean Time Between Service Interruption (MTBSI), and acceptable performance degradation in higher sea-states. For mobility, a speed profile (including the maximum speed required) at a given operationally significant sea-state should be specified. The author suggests that the upper limit of Sea State 4 be used in these calculations to represent the sea conditions the ship will likely encounter at least half the time as shown in Fig 7 and Fig 8. In calculating the ship's resistance, margins appropriate for the stage of design and estimates for hull fouling should be incorporated in addition to added resistance due to the increased sea-state and wind as well as reduced propulsion efficiency due to un-steady conditions. Resistance calculations should use the worst case heading. Hull fouling has a significant impact on ship drag and should be modeled based on the ant-fouling features incorporated into the ship design and on the planned hull cleaning strategy. For mobility, a minimum tactically useful speed should also be defined to support Quality of Service calculations [10].

b. An Operational Profile specifying the percentage of time over ship's service life the ship is expected to operate in each operational condition for 3 air temperatures (10°F, 59°F, and 100°F) should be defined. Specifying the air temperature is important because it has a significant impact on electrical power consumption and should therefore be considered in system optimization. The Operational Profile should be based on and traceable to official Defense Planning Scenarios.

c. A Service Life Allowance for the ship service electrical loads should be defined.

In calculating the electrical load requirements for each of the operational conditions, either a systems load and power analysis similar to that defined in [11] or a stochastic approach similar to that described in [12] should be employed.

In determining the powering requirements for different sea-states, resistance and sea-keeping prediction tools such as model testing, SEAWAY, NavCad, Ship Wave Analysis (SWAN), Large Amplitude Motions Program (LAMP), Visual Ship Motion Program (VisualSMP), and FREDYN should be employed to estimate the ship resistance and to ensure slamming or deck wetness will not lead to voluntary speed reduction. A suitable margin should be incorporated into the resistance estimates to account for potential inaccuracies in the resistance prediction tools.

Additionally, a method must be developed to translate data measured in full power and economy ship trials as described in [13] to the requirements described above. The goal would be for the full power and economy ship trial to validate a model of the ship's resistance that could in turn be used to ensure the ship's requirements were met.

III. SIZING FUEL CAPACITY

Traditionally, the capacity of the fuel tanks of a naval warship is specified by an endurance speed and an endurance range [14]. Historically, this definition was sufficient because the ship service load did not contribute significantly to the total energy consumption of the ship. Specifying the endurance speed at about 18 to 20 knots and endurance range in the mid thousands of nautical miles was sufficient for defining acceptable operational capability for most operational situations.

Recently, the Naval Sea Systems Command led a study on Alternate Propulsion Methods for Surface Combatants and Amphibious Warfare Ships [15]. This study demonstrated considerable variance in performance of different power system options if endurance is measured in different, operationally significant ways. Based on the work of this study, the following metrics are recommended for determining the fuel load of a naval warship:

a. Surge to Theater: This method specifies the maximum number of refueling allowed to transit a given distance (typically 4,000 to 10,000 nm) at maximum design speed at a given sea state, with only self defense capability. Refueling is assumed to occur when 50% of the fuel capacity is consumed. The ship must arrive in theater with tanks at least 50% full. Goal is to minimize dependence on replenishment ships to arrive at a theater of operations as fast as possible. A Surge to Theater Operational Condition should be defined to specify environmental conditions (sea-state and temeperature) as well as enable a prediction of electrical load and Quality of Service requirements.

b. Economical Transit: This method is similar to the traditional Endurance Speed and Endurance Range. The ship must be able to reach the endurance range when traveling at a speed at least equal to the endurance speed. For this analysis all of the fuel capacity, minus tail pipe allowances are allowed to be consumed. An Economical Transit Operational Condition should be defined and used to calculate fuel requirements.

c. Operational Presence: Operational Presence is the minimum time that a ship should be capable of conducting one or more missions (such as theater ballistic missile defense) using a given speed-time profile and mission system capability, such that a maximum of 1/3 of the fuel capacity is consumed. An Operational Presence Operational Condition should be defined and used to calculate fuel requirements.

Each of these three constraints should be independently met. As electrical load for mission systems increase, the operational presence constraint becomes more important. Similarly, with the size of the fleet below historic norms, the importance of being able to quickly transit to a theater of operations becomes more important. From a power system design viewpoint, fuel efficiency at high speed and large fuel tanks become desirable.

Table I demonstrates how growth in ship service load lead to different criteria becoming the constraint for fuel tankage. In the low mission system (SHIP A) electrical load case, Surge to Theater is the limiting case. In the high mission system (SHIP B) electrical load case, Operational Presence is limiting. Note that this table is illustrative. With the larger fuel tankage requirement of Ship B, it would likely be a larger ship that would require additional Propulsion Power to achieve a given speed, further driving the fuel tankage up. Additionally, the table assumes a constant specific fuel consumption so that the energy used is directly proportional to the amount of fuel consumed. Actual ship designs would likely show some variance from this table, but the driving constraint would not likely change.

TABLE I
Comparison of Two Notional Ship Concepts

	SHIP A		SHIP B	
Surge to Theater Speed	30	knots	30	knots
Surge to Theater Range	4,200	NM	4,200	NM
Surge to Theater Ship Service Load	4	MW	4	MW
Surge to Theater Propulsion Load	60	MW	60	MW
Surge to Theater Max Refuelings	2		2	
Surge to Theater Refueling %	50%		50%	
Surge to Theater Time	140	Hours	140	Hours
Surge to Theater Total Energy	8960	MW-Hours	8960	MW-Hours
Surge to Theater Tankage Requirement	5973	MW-Hours	5973	MW-Hours
Economical Transit Speed	20	knots	20	knots
Economical Transit Ranges	4,200	NM	4,200	NM
Economical Transit Ship Service Load	4	MW	4	MW
Economical Transit Propulsion Load	18	MW	18	MW
Economical Transit Time	210	Hours	210	Hours
Economical Transit Tankage Requirement	4573	MW-Hours	4573	MW-Hours
Operational Presence Speed	10	knots	10	knots
Operational Presence Time	7	days	7	days
Operational Presence Ship Service Load	6	MW	30	MW
Operational Presence Propulsion Load	2	MW	2	MW
Operational Presence Refueling %	67%		67%	
Operational Presence Total Energy	1381	MW-Hours	5413	MW-Hours
Operational Presence Tankage Requirement	4136	MW-Hours	16208	MW-Hours
Minimum Tankage Requirement	5973	MW-Hours	16208	MW-Hours
(assuming constant specific fuel consumption)				
Relative Size of Tankage	**1**		**2.7**	

IV. FUTURE WORK

To implement the recommendations in this paper, the author recommends accomplishing the following work

a. Produce and implement a guidance document for specifying ship requirements in the form identified in this paper.

b. Formalize the methodology in standards such as the Naval Vessel Rules and Design Data Sheets.

c. Develop improved ship resistance tools for predicting powering requirements in various sea-states. Validate these and other existing tools with experimental data and full-scale trial data.

d. Develop improved tools for predicting the efficiency of propulsors in various sea-states. Validate these tools with experimental data and full-scale trial data.

e. Develop improved electric load forecasting models. Calibrate these models with full-scale data.

f. Develop and formalize methods to correlate trials data in observed sea-states to ship mobility requirements under other sea-states.

g. Develop tools for predicting the rate of fouling and its impact on ship's resistance for a given operational profile, antifouling features and hull cleaning strategy. Validate these tools with experimental data and full-scale trial data.

h. Institutionalize the use of operational profiles and operational conditions as a basis for calculating life cycle cost.

V. CONCLUSION

To take advantage of the benefits of an Integrated Power System, the requirements of future electric warships should evolve to better map IPS capabilities to true mission needs. Integrating mobility and mission system requirements while properly incorporating the impact of high sea-states into mobility and power system design can be accomplished by specifying operational requirements in the form of

a. Operational Conditions that reflect mobility and other mission system requirements under a given set of environmental conditions to include sea-state.
b. Operational Profiles that specify the amount of time spent in each Operational Condition.
c. Service Life Allowance to account for electrical power growth over the life of the ship.

With the growing electrical load demand of future combat systems, the historical method for sizing the fuel tanks based on endurance speed and endurance range is no longer sufficient. A warship should carry enough fuel to satisfy three different constraints based on three different modes of operation: Surge to Theater, Economical Transit, and Operational Presence.

Implementing the proposed methods in this paper will require additional development of tools, standards and policy. Once implemented however, the warships of the future promise to be better matched to the operational requirements placed on them.

VI. ACKNOWLEDGEMENT

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