Marine power plants: design methodology and trends

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ABSTRACT

A systems design methodology for the marine power plant, within the overall ship system design, is expounded in the present paper. The design problem is delineated through considerations of constrained problem definition, and the important factors entering the design of the marine power plant are presented, with due account given to the complexity of their interactions. Finally, potential trends of present-day, alternative prime movers are considered in the context of specific applications and/or considerations of immediate or near future relevance.

INTRODUCTION

In recent years marine propulsion has come to be dominated by the diesel engine, primarily the one of the slow speed type. Exceptions can only be found in rather special applications, such as liquefied natural gas carriers, the only type of vessel presently fitted with the steam turbine plant. The gas turbine on the other hand, with its applications of the aero-derivative type, has had notable success in the naval sector, with some navies having made major policy decisions for all-gas turbine propulsion [1].

With attention being restricted to the merchant ship area, statistics show that, for the whole of 1990, there had only been one steam-driven ship built [2]. All other ships built (817 - in number) were fitted with diesel engines (with the slow-speed, direct-drive type representing more than 75% of the total installed power). Fuel efficiency has had, by far, the most significant influence towards the diesel preference, whereas specific weight and volume (power density) has been the deciding factor in favour of the gas turbine.

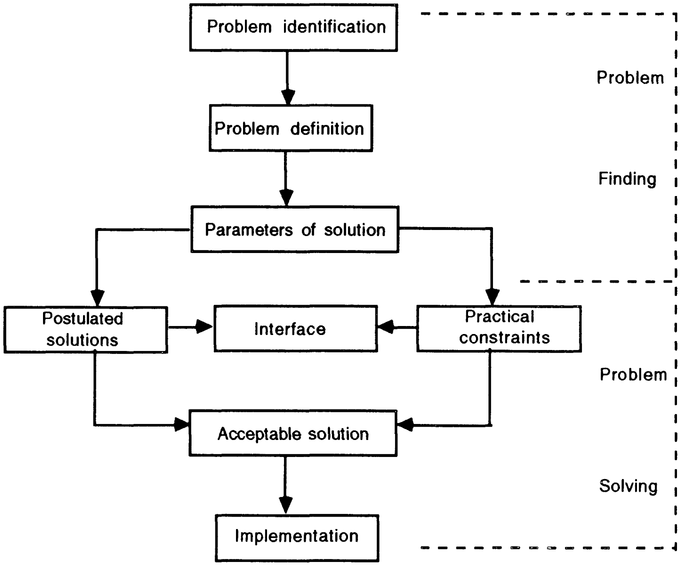

Fig. 1. The Design Process

Table 1. The Significance (Value) of Design Steps

Step	Value	Phase	Simplified
Identification	.50	Recognition & understanding of a basic need	.80 Problem finding
Definition	.20		
Parameters	.10		
Postulation	.08	Creation of a system to satisfy that need	.20 Problem solving
Evaluation	.06		
Solution	.04		
Implementation	.02		

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MARINE POWER PLANT DESIGN METHODOLOGY

Two of the most important factors, bearing on the design of marine power plant, have been referred to above. However, fuel costs and power density, although significant, are just two of the principal machinery constraints entering the design and/or operation of the marine power plant and, when the whole spectrum of machinery constraints is considered, in the context of specific ship applications, additional considerations are required. In the first instance, however, the position of the marine power plant within the overall ship system design should be clarified.

General Design Considerations

Most authorities agree that man's technological endeavours are made up of two distinct phases: problem finding and problem solving. Problem finding involves the identification and definition of a particular problem, as well as stating the parameters of its solutions; whereas, in problem solving, a number of plausible solutions are postulated and evaluated leading, in the end, to the most acceptable solution (that needs to be implemented). Or, in engineering terms, the design process starts with the identification of the problem and ends with the implementation of its solution. Figure 1 shows the design process, in a block diagram form, and Table 1 the significance to be accorded to each of the design steps.

Marine Systems Design

Systems ideas are most appropriate in marine design work. As with any design problem, a need that needs to be satisfied must be identified in the first instance, and the author has elsewhere elaborated on the design of marine propulsion systems, purely from the fuel-efficiency point of view [3]. In this paper, the design problem of the marine power plant is considered at a more fundamental level with the view to systematically identify and classify the major constraints entering the design problem and thus "set the scene" for a clear and comprehensive basis for the comparison of alternatives.

However, at the outset of the design problem definition (and following a true systems approach - up to the supramost level of design) the author wishes to point out that the power plant system should be considered in terms of the ship system (at different levels of emphasis and/or development); with the ship itself being viewed, ultimately, as part of the transportation system (or international relations system). The concept is depicted in Figure 2 and should be considered suitable for either merchant or naval applications (with the "transport" frames eliminated in the latter case).

It should follow from Figure 2 that, at the power plant system level, a truly successful design can only be affected given some knowledge of the "outer frames". Ignoring naval applications (who could have predicted the

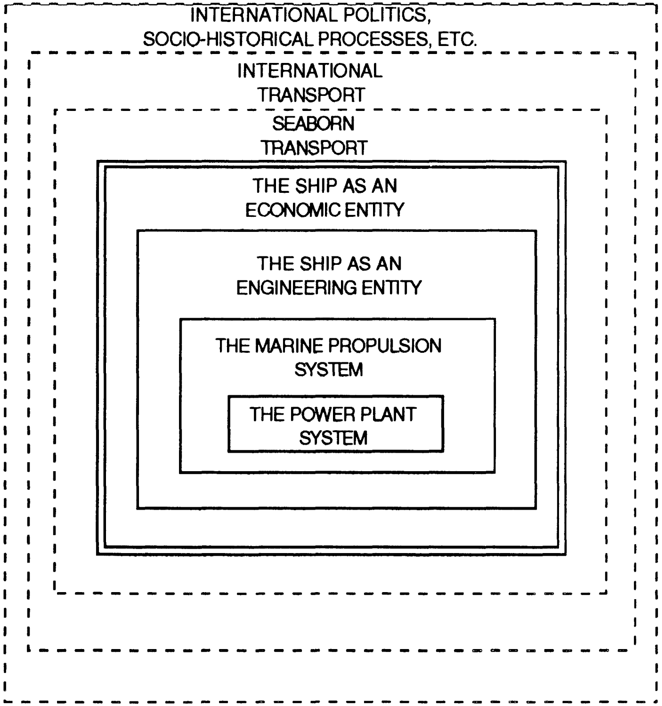

Fig. 2. The Power Plant System in a Wider Scene

Table 2. Forecast of Merchant Ships Demand [4]

Year	World Traffic Million Longtons		Tonnage Requirements Million G.R.T.	
	Tanker	Dry Cargo	Tanker	Dry Cargo
1966	100%	100%	100%	100%
1973	166%	128%	162%	113%
1983	359%	198%	326%	149%
2003	648%	476%	512%	258%
	Demand and Technolgical Forecast for Ocean-bore Shipping, LITTON Systems Inc., 1970			
1966	100%	100%	100%	100%
1973	204%	153%	195%	143%
1983	161%	193%	170%	164%
	Effective Figures Achieved from Different Sources (Estimation)			

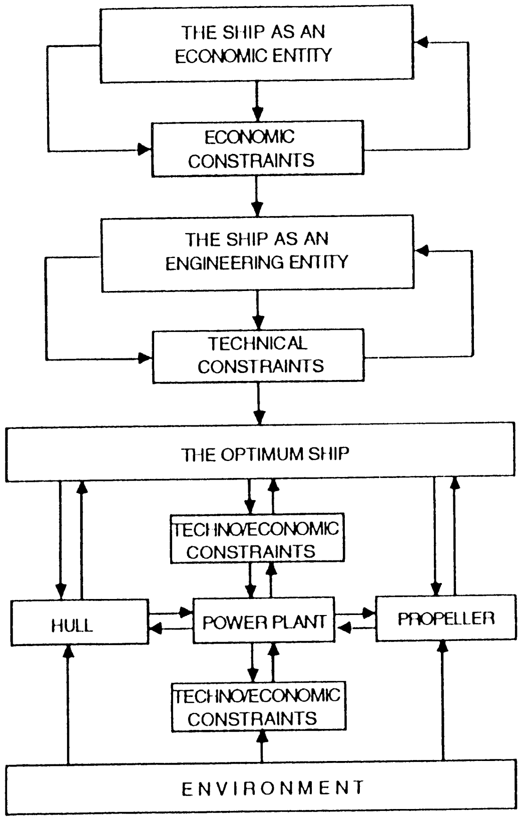

Fig. 3. Definition of Constrained Problem

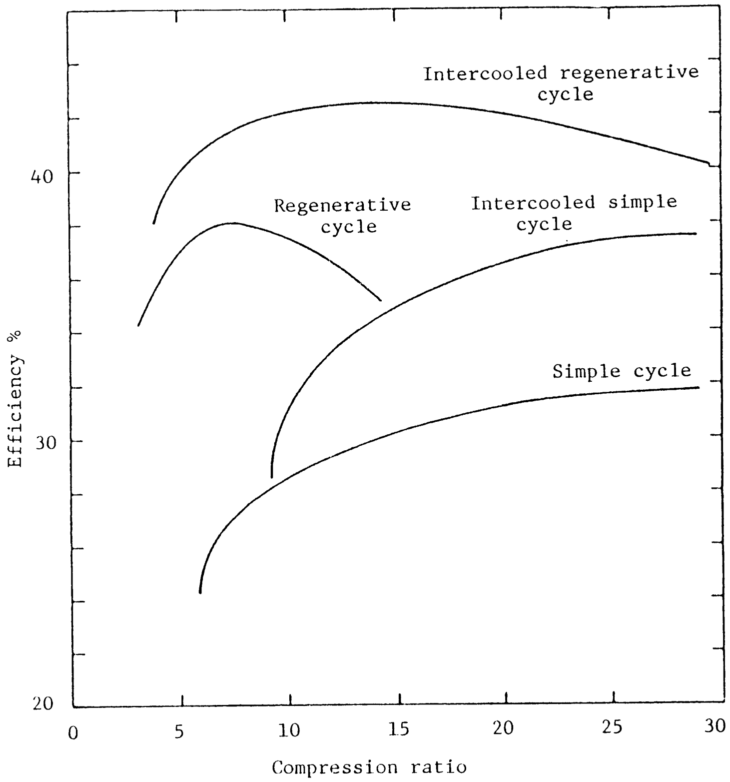

Fig. 5. Marine Gas Turbine Efficiency [10]

end of the cold war), this means that some form of economic forecasting becomes essential. (Reasons being: the relatively long time to built a ship, and its expected long life of operation.) Economic forecasting can often go wrong, and Table 2 shows such an example [4]; the predicted/actual figures shown for the years 1973 and 1983 are quite revealing. (In the meantime ULCC's had appeared - Suez Canal closed, steam turbine revival - and also containerships with speed in excess of 30 knots - steam and gas turbine revival; re-engineering, or scrapping, had to follow.)

Problem Definition - Constrained Systems

According to Table 1, problem finding is shown to be four times as important as problem solving. As it is often the case that recognizing (identifying) the need has to rely, often to a large extent, on forecasting, it should then be understood that, strictly speaking, a truly successful design might not be attainable in practice. The discussion so far has really been used to highlight the complexity of the overall design problem and, usually, engineers would be at great difficulties in dealing with the "outer frames", in Fig. 2.

Despite of all these, it should be possible, in the end, to arrive at a less complex problem, working on the basis of certain assumptions and/or constraints. The author has shown elsewhere [3] that the marine power plant design problem can always be viewed as one of economics, simply by taking into account a number of constraints including technical and environmental ones - availability of funds, prevailing level of technology in engineering materials, laws of nature and, increasingly nowadays, environmental protection requirements. Figure 3 attempts to depict the idea of defining a constrained problem, for the marine power plant (with the most important interactions with the other major elements of the propulsion system also shown).

MARINE POWER PLANT CONSTRAINTS AND TRENDS

It should be clear, from Fig. 3, that the marine power plant system can only be defined as part of the optimum ship system. At the preliminary ship design phase, where powering and other requirements are established and re-established following the well-known "design spiral" [5], preliminary power plant design could thus be defined as being an "offshoot" from the ship design spiral.

Marine Power Plant Constraints

The various factors affecting the design of marine power plant have been enumerated in a number of publications [6,7,8]. However, the author is not aware of any publications presenting the complete picture of the marine power plant design problem, in a comprehensive and functional way. Figure

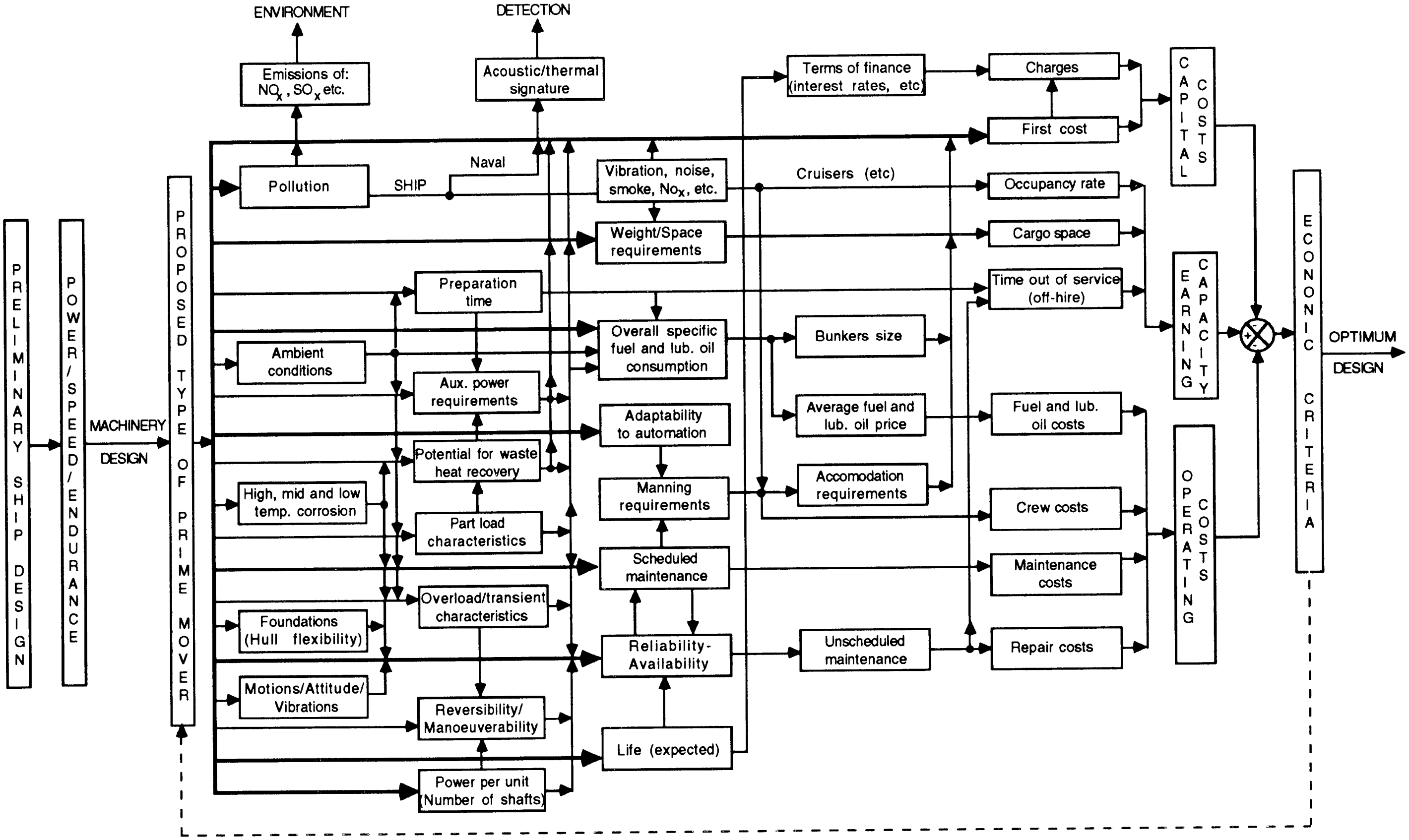

Fig. 4. Marine Power Plant System Design

4 attempts to do that in a block diagram form, including cause-and-effect relations of the various constraints [9]. The length limitations of this paper, prevent the author from expounding, in length, on all important implications of the various factors depicted in Fig. 4, so that only some of the most important aspects, relevant to the theme of this paper, will be dealt with here (with a more comprehensive exposition to be given during the seminar).

It may be seen that the machinery constraints shown in Fig. 4 can be considered under different groupings; e.g. "environmental" (first column) or "techno-economic" (remaining columns - with some factors (second column) contributing towards what might be called "flexibility of operation". It should be pointed out that it is often a two-way interaction. For example, the environment affects the plant (e.g. effect of ambient conditions - sea and air temperatures, barometric pressure, humidity); with the power plant itself affecting the environment (pollution). In a similar way, the ship (hull/propeller) affects the prime mover (motions - roll, pitch, heave; attitude - heel, trim; vibrations) with the prime mover itself affecting the ship also (vibrations, noise, smoke, etc.).

As suggested earlier, a full discussion on every machinery constraint can not be given here and, in fact, it must be made clear that Figure 4 is, by necessity, rather simplified - as the number of possible interactions among the different blocks can be endless. Considering, ambient conditions for example, there would be effects (shown in Figure 4) on:

(i) Specific fuel consumption (gas turbine affected most)
(ii) Preparation time (steam and slow speed diesel affected most)
(iii) Aux. power requirements (e.g. pump and heat exchanger sizes; steam and slow speed diesel affected most)
(iv) Potential for waste heat recovery (slow speed diesel very seriously affected)
(v) Part load characteristics (gas turbine most seriously affected)
(vi) Overload, etc. (again, gas turbine most seriously affected)

But, also, effects (not shown in Figure 4) on:

(vii) Pollution (NO_x production)

(viii) Corrosion (High temp. - effect of vanadium; Mid temp. - sulphuric acid effects on boiler)

Also coupling of various factors. For example, ambient conditions coupled with motions can lead to high temperature corrosion (sulfidation), when sulphur is present in the fuel and inadequate attention has been paid to the design of demisters. (This, and also the presence of vanadium, have effectively led to abandoning the use of heavy residual fuel in gas turbine applications; with very serious repercussions on the operating costs, however).

Potential Prime Movers

Reference has already been made above to the three principal, alternative prime movers (diesel, steam and gas turbines). Diesel could be further classified on the basis of speed of rotation (slow, medium and high) and gas turbine on the basis of cycle complexity (simple, intercooled, recuperated, etc.). Furthermore, combinations of prime movers should also be considered (CODAG, COGAS, etc.). Not all the factors appearing in Figure 4 are equally significant and the thicker lines are used to emphasize the most significant ones. Furthermore, it can also be seen in Figure 4 that ship speed (together with power and endurance) becomes an important input to marine power plant selection (Froude No. effects - ship block coefficient and afterbody sections). What this entails, in fact, is that the marine power plant design problem can be perceived, from the outset, in the context of specific ship applications.

Marine Power Plant Trends

Following from the last paragraph, the remaining part of this paper would be concerned with specific applications and considerations, of most relevance to its theme.

COGAS applications The LNG carrier is the only type of slow-speed merchant ship application where serious competition to the diesel engine becomes possible; this is due to the overwhelming influence of fuel costs in such applications. On the basic premise that the true measure of efficiency should be defined in terms of \$/kWh (rather than gr/kWh) the gas turbine is not in a position to compete, on its own, with the diesel engine. This, despite of projected efficiencies in excess of 40% (Figure 5, [10]). Diesel engines can nowadays achieve efficiencies in excess of 50% and this, combined with the price differential between heavy residual and distillate oils, can readily lead to fuel costs of a gas-turbine ship being twice that of the equivalent diesel-engine ship.

The even lower efficiency of the steam plant (and despite its ability to burn the worst quality fuel) would still make it uncompetitive with the diesel engine. The LNG carrier (at present the only ship where steam plant can find applications) could become a potential candidate for combined gas and steam power plant (to achieve fuel efficiencies comparable with those of the diesel engine); as the gas turbine can readily operate on gas, whereas substantial modifications would be required in the case of the diesel engine. Furthermore, the gas turbine, having effectively all its waste heat rejected in the exhaust gases, at a rather high temperature, offers greater potential for waste heat recovery through a conventional steam cycle, leading to significant improvements in overall efficiencies. Studies suggest that efficiencies comparable to those of diesel engines are possible [11].

Fast Ship Applications Serious efforts are being made at present to increase speeds of operation for a variety of crafts; vessels carrying vehicles, passengers or high value cargoes (this latter in competition with aircraft transport, in certain routes). Speeds as high as 50 knots [12] are being quoted for hull forms varying from monohuls to SWATHs and catamarans. The high speed diesel and the gas turbine are the only alternative choices for such applications due to the paramount importance of the weight/space constraints. In such cases, the fuel efficiency gap, between the two alternative types of prime mover, is not that great - as compared with that for the slow speed diesel, for example. As far as power density is concerned, the most highly rated diesel engines, in such applications, can achieve specific weights of the order of 2.8 kg/kW (with smaller sizes achieving, lately, figures as low as 1.9 kg/kW [13]). In extremely weight-sensitive applications, the simple cycle gas turbine is unsurpassed in power density (with figures down to 0.1 kg/kW becoming possible).

Environmental considerations Perhaps the most significant development in years to come could be in relation to possible future regulations regarding exhaust emissions (such as SO_x and $NO_{x)}$. In relation to fuel costs, the major advantage of the diesel engine, over the gas turbine, is related to the use of low quality, higher sulphur content, heavy fuel oil (with prices, at some parts of the world, being only half of those for distillate oil); any future regulations restricting SO_x emissions would erode the fuel price differential advantage of the diesel engine. The other important pollutant of internal combustion engines, oxides of nitrogen, could also be subject to legislation in the future. Much of the improvement in fuel-efficiency of the diesel engine has resulted from the increased maximum pressure of the cycle (SSD ~ 135 bar, MSD ~ 180 bar). High cycle pressure, of course, imply high combustion temperatures which promotes the production of NO_x and, since formation and destruction mechanisms are rate-controlled [14], significant amounts of the NO_x produced at the high temperatures "freeze", appearing thus in the low-temperature exhaust gases. It appears that primary measures to control NO_x (control of combustion process) would require compromises in efficiency, unless other artificial methods (such as the use of emulsified fuels) are used. Secondary methods (exhaust gas after-treatment) using Selective Catalytic Reduction (SCR) appears to present problems, at present, due to capital costs and space constraints [15]. On the other hand, gas turbines have more controlled, continuous combustion at relatively lower temperatures which result in the creation of much lower amounts of NO_x and, furthermore, application of other artificial methods to control NO_x production (such as water injection) can also be accommodated much more easily in gas turbine applications.

CONCLUSIONS

The marine power plant design methodology has been detailed in this paper through considerations of constrained problem definition and following a systems approach. The complete spectrum of machinery constraints entering the power plant design problem has been presented in a diagrammatic form with the view to properly classify the important factors and show, by example, the strength of their interactions.

In the context of specific applications and considerations, recognized as important currently or in the near future, alternative marine power plants have been considered. It is concluded that changes to the present status of marine power plants are not improbable with the gas turbine in particular assuming a more prominent role in marine propulsion.

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