GAS TURBINES IN SHIP PROPULSION: 
DESIGN CONSTRAINTS IN RELATION TO SHIP TYPES

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ABSTRACT

In recent years merchant marine propulsion has been dominated by the diesel engine (primarily the slow speed type) with fuel costs being the principal factor in favour of their selection. Fuel costs, however, constitute but one of the major constraints entering the design and operation of the marine power plant.

Following a systems approach, the design problem of the marine power plant (within the framework of the overall ship design and seaborne transport systems) is considered, with the view to properly identify and classify the complete set of machinery constraints and their interactions, in relation to different ship applications.

On this basis, the gas turbine is compared with its internal combustion rival by considering the most significant constraints, but with due reference to other factors (of a lesser importance), where appropriate. It is shown that, in this way, the predominance of one type of prime mover over the other, in different applications can be easily explained.

Finally, consideration is given to future developments in terms of high-speed marine transportation demands, possible legislation requirements for environmental protection and potential advances in prime movers themselves. It is concluded that the gas turbine could well assume a more prominent role in marine propulsion, in the near or distant future.

INTRODUCTION

With the exception of naval (nuclear and conventional) and some other special applications (e.g. LNG carriers), marine propulsion is being dominated by the internal combustion engine. In the merchant ship sector, according to the Motor Ship (1991), there has only been one steam-driven ship built, for the whole of 1990. 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). The gas turbine on the other hand, with its applications of the aero-derived type, has had notable success in the naval sector, with some navies having made major policy decisions for all-gas turbine propulsion (Pidgeon, 1982).

Fuels costs have, by far, had the most significant influence towards the diesel preference whereas, for the gas turbine, specific weight and volume have been the major factors in its favor. Possible ship developments, environmental considerations as well as developments in prime movers themselves, in the near future, might well lead to a need for a move fundamental re-consideration of the marine power plant design problem.

MARINE SYSTEMS

The author has followed the systems approach in considering the design of complete marine propulsion systems, purely from the fuel-efficiency point of view (Bakountouzis, 1991a; Bakountouzis, 1992). In this paper, the design problem of the marine power plant is considered at a more basic level with the view to systematically classify the major constraints entering the design problem and thus provide a clear and comprehensive basis for the comparison of alternative prime movers.

NOMENCLATURE

BMEP - Brake Mean Effective Pressure  
CODAG - Combined Diesel And Gas  
CODOG - Combined Diesel Or Gas  
HSD - High Speed Diesel  
LNG - Liquified Natural Gas  
MER - Marine Engineering Review  
MSD - Medium Speed Diesel  
NPV - Net Present Value  
RFR - Required Freight Rate  
SCR - Selective Catalytic Reduction  
SSD - Slow Speed Diesel  
SWATH - Small Waterplane Area Twin Hulls

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Following a systems approach, the prime mover system may be considered as part of the ship system, with the ship itself being part of a transportation system (or international relations system). The concept is presented graphically in Figure 1 and could be considered suitable for both merchant and naval ship applications (with the “transport” frames being eliminated in the latter case).

THE SHIP SYSTEM

The design problem can always be viewed as one of economics simply by taking into account a number of constraints including technical and environmental ones (Bakountouzis, 1991a). Figure 2 attempts to depict the idea of defining a constrained problem and shows the major interactions for the prime mover system. The design problem is, of course, that of finding the optimum for a particular system, whilst taking into account any interactions with other systems (Machol, 1965). (It should be pointed out here, that viewing the design problem as one of economics is equally applicable to naval applications. This despite the apparent disparity in performance requirements between the two applications; the economics are, simply, of a different order (Kane, 1971)). Although this paper is concerned with prime mover systems, the design of the hull of the ship will be used as an example to show, with reference to Figure 2, the effect of interactions and some of the constraints in action.

For a given cargo-transportation capacity, at a specified speed, a fine hull form would, as a rule, be the optimum one from the fuel-efficiency point of view. However, a fine form would, invariably, require an increase in length coupled with a decrease in breadth, or depth, or both (dimensional constraints—effect on prime mover) and, perhaps more complex (from the case of construction point of view) afterbody and forebody shapes. Length, however, is the most expensive dimension of the ship and difficulty in construction (including machinery arrangement) adds to the initial cost of the ship (economic constraints). Furthermore, reducing the breadth of the ship could lead to stability problems (spatial constraint—need for the prime mover to be placed low) and depth reduction could present strength problems for the hull girder (technical constraints). Occasionally, but not always, a technical constraint may be overcome by various means and thus become another economic constraint. For example, strength problems due to depth reductions of the hull girder could be overcome by increasing the thickness of the shell plating and, in a similar way, spatial constraints on prime mover overcome by moving it forward. In both cases an economic penalty is incurred due to the increased first (acquisition) cost and the reduced cargo carrying capacity. (The possibility of a new technical constraint appearing, as another is being solved, should be pointed-out here; both modifications suggested above could have a direct impact on vibratory behaviour of the hull girder—effect on natural frequencies and location of excitation source.)

THE PRIME MOVER SYSTEM

From the previous discussion (and figures) it should be clear
Fig. 3. The Ship Design Spiral [Buxton, 1976]

that the marine power plant system forms part of the overall ship system; with its design being itself part of the overall ship design. The design of the marine power plant starts at the "preliminary ship design" phase where powering and other requirements are established and re-established following the "design spiral" as depicted in Figure 3 (Buxton, 1976). Machinery design is, therefore, an "offshoot" from the ship design spiral.

Machinery Constraints
The factors entering the design of the marine power plant have been enumerated in a number of publications (Yamashita, 1973; Woodward, 1975; Thompson, 1985) and economic comparisons of alternatives performed (Femenia, 1973; Lewis, Femenia, et al.; 1977, Thorp and Armstrong 1982). The author, however, is not aware of any publications presenting the complete picture of the marine power plant design problem in a comprehensive and functional way. Figure 4, developed by the author, attempts to do that (with arrows indicating "inputs" and dots indicating "splitting of outputs"). It may be seen from Figure 4 that the major machinery constraints entering the design of marine power plant can be classified as: environmental and operational/economic with a number of factors (constraints) contributing towards "flexibility of operation". With reference to Figure 4 the following should be noted:

a. The environment affects the prime mover (e.g. effect of ambient conditions—sea and air temperatures, barometric pressure, humidity); with the prime mover itself also 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.).
b. Economic criteria such as NPV and RFR can be used to...
evaluate any prospective prime mover. It should be appreciated, however, that it may not be easy to attach an economic figure to every one of the factors shown in Figure 4. Reliability (Woodward, 1975), vibrations, etc. or, in naval applications, military effectiveness and other similar issues are such factors.

c. Not all the "boxes" in Figure 4 are of equal significance and the thicker lines are used to indicate the most important ones, which need to be considered in a more simplified evaluation. It should be born in mind, however, that the functional relationships among the various constraints can not be under-estimated. For example, ambient conditions (probably coupled with motions) can lead to high temperature corrosion (sulfidation), when sulfur is present in the fuel and inadequate attention 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, as discussed later in the paper).

d. Since there is always a strong "coupling" between the prime mover and the ship type, no comparison of alternative prime movers can be made outside the framework of particular ship applications; hence, the need for the next section.

Ship Applications
For the purpose of the discussion in this paper, the following classification for ship applications is necessary.

I. Merchant (cargo) ship applications, which can further be classified as:
   (i) Displacement carriers (e.g. Ore-carrier—weight sensitive)
   (ii) Capacity (Volume) carriers (e.g. Containership, Ro/ Ro ship—space sensitive)
   (iii) High speed, high value cargo transportation (e.g. Techno-superliner—under development, in Japan)

II. Passenger ship applications; with further classification:
   (i) Conventional passenger ship (e.g. Cruiser)
   (ii) High speed applications, with either:
       a. Hydrodynamic support (e.g. Hydrofoil)
       b. Special type of hull (e.g. Catamaran, SWATH, etc.)

III. Naval applications

Gas Turbine versus Diesel
The following constraints (from Figure 4) should be considered as the most significant ones (not necessarily listed in order of importance):

1. Maximum power available per unit
2. Weight/space requirements (kg/kW, m³/kW, m/kW of length, breadth and height)
3. Adaptability to automation & Manning/Reliability/Maintenance & Repair costs
4. Capital costs and charges
5. Fuel and Lub. oil costs
Maximum Power per Unit. It can be safely assumed that, nowadays, there would be no upper limit for the gas turbine, in the great majority of marine applications. (Limit imposed by the power absorbed by the propeller, rather than the capacity of the prime mover itself.) Just over ten years ago, the maximum power available from a SSD was no more than 30 MW (Schmidt-Sorensen, 1982). At present, powers in excess of 50 MW are available from a single SSD (with similar figures obtained from twin MSDs) whereas, for the same power, 6 to 7 units would be needed of the most highly rated (twin stage turbocharging, BMEPs in excess of 30 bars) HSD (MER 1991a).

The push for higher powers with diesels started in the late sixties/early seventies, the days of optimism for expansion in seaborne trade. The two abrupt increases in oil prices, however, changed the economic scenario completely; with the immediate result of reduced operating speeds (as simple economic theory demands) and even more dramatic changes in the level of installed powers (as power varies with the cube of speed — "propeller demands") and even more dramatic changes in the level of installed powers (as power varies with the cube of speed — "propeller law"). What all the above now means is that there is no merchant ship (I(i)) & (I(ii)) built nowadays that cannot have its power requirements met either from a single SSD or a twin MSD. In other words, the power-per-unit constraint is not effective anymore, as far as diesel engines are concerned, for a very large number of applications.

Weight and Space Requirements. The SSD has to be excluded even from some ships under category I(ii). (Ro-Ro ship, for example, demanding continuity of decks; i.e. height constraint.) With the exception of a few passenger ship applications, SSD is excluded from all ship applications in categories II and III. (Naval applications, with heavy weaponry on deck, can have, in addition, stability problems; i.e., again, height constraint). The MSD can easily find application in Ro-Ro ships as well as passenger ships where electric transmission can solve problems discussed above and, also, eliminate structure-borne noise by means of elastic suspension of units. The most highly rated HSD have achieved specific weights of the order of 2.8 kg/kW (MER 1991a) and, when both weight and space constraints are considered (with gearing requirements also taken into account), can compete with aeroderivative gas turbine installations. The limitations of the previous section, however, restrict applications to lower power levels only, or to uses in combination with gas turbines (CODOG, CODAG, etc.), in naval applications. Ships under category II(iii) are other examples where the HSD is now in competition with the gas turbine, lower speeds/powers are considered. There are serious expectations, however, of breakthroughs in high speed transportation (ships under I(iii)). The Japanese are now experimenting with ships having speeds of up to 50 knots (Yamaguchi, 1991) where the gas turbine will be dominant due to its high power density. (The power density of the gas turbine, together with its excellent transient performance characteristics, and the almost zero preparation time requirements, have helped to secure its present position in naval applications.)

Adaptability to Automation & Manning/Reliability /Maintenance & Repair Costs. The gas turbine is at an advantage, particularly over the SSD, as far as ease of application of automation is concerned. This is due to its compactness and the limited number of auxiliary services needed (e.g. cooling water requirements). As far as reliability is concerned, this is an area which is very hard to quantify (Woodward, 1975). Data on reliability and availability of gas turbine installations are published (Reid, 1991) but they are mostly obtained from applications, such as naval, where modes of operation differ significantly from those where the diesel engine is being used and, as a result, direct comparisons are difficult to make. Under normal conditions, in well designed systems (proper design of demisters, etc.), and with operation on distillate oil, the gas turbine should have lower maintenance costs compared with diesel, for the same power level. However, the problems associated with the availability of suitable personnel for gas turbine operation and maintenance should not be underestimated. The diesel engine (requiring mostly skills of a mechanic, for its operating personnel) has, effectively, no manning problems, and a good service infrastructure is already in place.

Gas turbines on the other hand, perceived as "high tech" (and requiring, therefore, more delicate handling) are at a disadvantage, for the time being.

Capital Costs and Charges. This is another area where accurate estimates are not easy to obtain, as most often manufacturers are not willing to disclose prices and, furthermore, figures are often distorted by the terms of finance, including subsidies (Buxton, 1976). It can be said, however, that, with the exception of low power levels, the gas turbine is cheaper than the diesel engine, with the price differential increasing fast as installed power increases. Femenia (1973) suggests initial costs being proportional to: (Power)^n, with the index n having a value of approximately ½ for the diesel and ¼ for the gas turbine—aeroderivative type. As it is often the case that capital costs (for the whole ship) can account for more than 50% of the total annual costs, it is understood that initial cost represent one of the most important factors in the selection of the prime mover.

Fuel and Lub. Oil Costs. Efficiencies of gas turbines have improved considerably over the years, even for the simple cycle (the only cycle employed at present in marine applications) and efficiencies of the order of 40% are now being suggested (Reid, 1991). However, diesel engine efficiency has also been increased and efficiencies in excess of 50% are now easily achieved. Most significant, however, is the price differential between heavy residual (diesel) and distillate (gas turbine) oil, which can lead to fuel costs of a gas turbine ship being twice as great as the equivalent diesel engine ship. Clearly a large tanker spending 300 days per year at sea, in the present economic climate, would not be able to tolerate such fuel costs. Furthermore, operation at economic speeds, again under the present economic circumstances, is not unlikely for this type of vessel and the poor part load performance of the gas turbine is a further handicap. (As compared with the diesel engine—where "flat" consumption characteristics are obtained almost across the whole torque/speed range (Bakountouzis 1991b)). Effects due to changes in ambient conditions and, also, deterioration in performance with time, can lead to further increases in fuel costs (with the diesel engine much less seriously affected by such effects).

Assuming that fuel-efficiency has a dominant effect in merchant marine applications, the only application where the gas turbine could possibly compete with the diesel engine is the LNG carrier. (This is the only type of steam merchant ship being built at present; re-liquefaction of the natural gas boil-off is not economically viable and the best solution found is to use it as a fuel in a boiler.) The gas turbine can readily operate on gas, whereas the diesel engine would require substantial modifications. Furthermore, the gas turbine, having effectively all its waste heat rejected in the exhaust gases, at a rather high temperature, offers great potential for waste heat recovery through a conventional steam cycle, augmenting the overall efficiency significantly.
Studies suggest that efficiencies comparable to those of diesel engines are possible (Hieda, and Kusano, 1986). The latest design of SSDs, on the other hand, achieve their high efficiencies through high scavenging ratios (air/fuel ratios in excess of 50 are common) leading to exhaust gas temperatures as low as 235°C (M.A.N./B&W, 1985) with their potential for waste heat recovery, for the purpose of work production, being reduced significantly as a result. (Things made worse for the diesel engine due to presence of sulphur in the fuel; temperatures at boiler exit restricted to around 160°C.)

Potential Future Developments

There are at least three potential areas where possible future developments may lead to an improvement in the position of the gas turbine, over its other internal combustion rival, in marine propulsion.

As it was already mentioned before, efforts are being made to increase speeds of transport for a variety of crafts carrying vehicles, passengers or high value cargoes (the latter in competition with aircrafts, for certain routes). Speeds as high as 50 knots are being quoted for hull forms varying from monohulls to SWATH and catamarans. The only competition to the gas turbine in these applications is expected to come from the HSD, but only for the smaller sizes and/or speeds.

Another area is potential developments in new materials and in particular the use of ceramics. The contribution towards higher efficiencies from the raising of the maximum temperature of the cycle is much more significant in the case of the gas turbine. On the other hand, the efficiency of the diesel engine has been increased to the point were the amount of energy rejected to cooling water represents an insignificant 10%, of the total energy balance. Even with perfect insulation (adiabatic cooling water represents an insignificant 10%, of the total energy balance. Even with perfect insulation (adiabatic combustion/expansion), the additional amount of work extracted is a mere fraction of that percentage (although the waste heat recovery potential is improved). Besides potential improvements in materials, developments in the working cycles for the marine gas turbine can lead to further efficiency improvements. Inercooled/regenerative gas turbine for marine propulsion, at present under development, promise 30% improvement in efficiency over existing systems (MER, 1992) and even "flat" efficiency characteristics over an extended load range; achieved through the use of variable geometry power turbine (Doyle, Kornbau, et al., 1992). Efficiencies as high as 55% have also been calculated for regenerative cycles (Korakianitis and Wilson, 1987).

Perhaps the most significant development in years to come, could be in relation to possible future regulations regarding exhaust emissions, such as SO2 and NOx. In relation to fuel costs, the major advantage of the diesel engine over the gas turbine is due 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 SO2 emissions could 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 NOx and, since formation and destruction mechanisms are rate-controlled (Heywood, 1989), significant amounts of the NOx produced at the high temperatures "freeze", appearing thus in the low-temperature exhaust gases. It appears that primary measures (combustion control) to reduce NOx, 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 SCR appears to present problems, at present, due to capital costs and space constraints (MER, 1991b). 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 NOx. Furthermore, application of other artificial methods to control NOx production (such as water injection) can be accommodated much more easily in gas turbine applications.

CONCLUSIONS

The marine power plant design methodology (or design philosophy) has been the major objective of this paper. Due to lack of suitable data, no numerical results were given here but the author hopes to be able to present such results on another occasion. A systems approach was followed in the present paper with the view to properly identify and classify the complete spectrum of machinery constraints that enter the marine power plant design problem.

Considering the most important of the machinery constraints, the gas turbine was compared to its major rival in marine propulsion, the diesel engine. This was done in relation to different ship applications, with suitable groupings of pertinent characteristics having been identified in the first instance.

The detailed consideration of the major constraints (with due reference to other factors of minor importance, as well) helps to explain the predominance of one type of prime mover over the other in different applications. As expected, in the great majority of cases, fuel costs and power density are the two major factors most severely affecting the selection of the prime mover.

Finally, considerations of potential developments in terms of high speed marine transportation demands, possible legislation requirements for environmental protection and advances in prime movers themselves suggest that the gas turbine might well assume a more prominent role in the future.

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