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On the problem of the machinery choice and hull weight assessment for the design of high-speed vessels

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ABSTRACT: In the last decades an increase of interest for high-speed ferries has been registered and new problems have arisen as regards the request of data and adequate procedures for conceptual and preliminary design analysis. In particular, the request of increasing speed and large vessels is a continual challenge to designers to choose propulsions systems, to estimate the principal components of propulsion machinery and hull weights. Firstly, a large of database has been presented that considers new designs and high speed ferries in the world; the regression analysis of which permits rapidly to estimate the main parameters (Displacement, Length, Breadth etc). Successively, a new parametric procedure has been developed to estimate hull weight of both monohull and catamaran fast ferries, including steel and/or aluminum materials. Finally, a database for the machinery choice is presented, which includes medium and high-speed diesels and gas turbines, the regression of which has been particularly discussed.

1 INTRODUCTION

It is well known that there is a relevant market with hundreds of high-speed ferries operating all over the world. At the same time, there is a lack of published systematic data and techniques suitable for both, conceptual and preliminary analysis.

Apparently, therefore, with such a relevant market, design data and their processing should be easily obtained. However, in most cases, designs of high-speed ferries are carried out in an ad-hoc manner. This gives no clear trends from the analysis of the data, especially when speed, expressed be means Froude number Fn, is considered as an independent parameter/variable. As a result, regressions and formulae, as well as algorithms and methodologies, are not "completely reliable" in the published literature. It is a common experience, infact, that mass estimates and main dimensions for the initial development of feasible monohull and catamaran high-speed ferry designs, have been very different (up to 50%) from their final values, obtained at later stages of design. This paper represents a new tool to generate and analyze data, together with design algorithms for high-speed ferries.

2 A REVIEW OF VESSEL MAIN DIMENSIONS

Generally, for the fast ferries, the market analysis gives the following input design data: Route/Range Au; Operational Speed V; Passengers Number Np, Vehicles Number Nv.

Actually, the most important typologies of fast vessel can be synthesized as follows:

Passengers-only monohull; passengers-only catamaran;

Passengers and vehicles -monohull; Passengers and vehicles -catamaran.

Notably, besides the v speed, the material type, and the passenger numbers, the Au range is a variable that certainly influences the displacement.

At the first stage of the development of a high-speed ferry design, an initial set of displacement and main dimensions should be considered. They should be as close as possible to their final values to avoid recalculations at later design stage. Power tools for reliable initial set of values are regressions analysis of a database.

A large database has been produced considering new designs and high-speed ferries in the world.

A first tentative displacement can be evaluated through the "net weight" regressions. Two examples, showing a clearly trend, have been reported in Figure 1 and Figure 2, respectively for monohull and catamaran.

The aim is to estimate the displacement directly from a regression analysis obtained from the available data, thus preventing the classic resolution of displacement equation, and supplying the experience to the designer directly from the available database.

It is necessary to point out that the size influences mainly the resistance, the longitudinal strength and

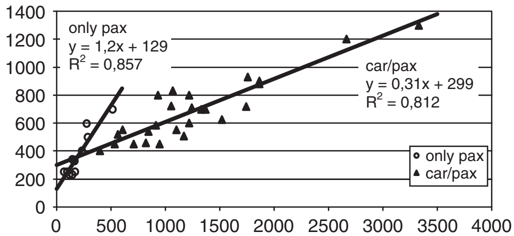

Figure 1. Pass number vs. displacement (t) for monohulls.

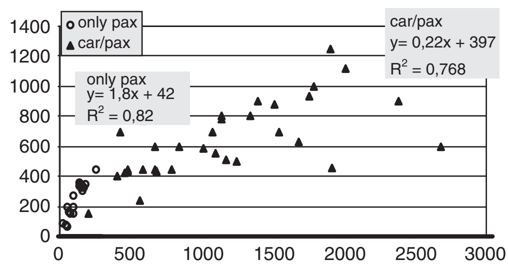

Figure 2. Pass number vs. displacement (t) for cats.

the seakeeping. Among these, the most important in the high-speed craft seems to be the resistance and the seakeeping. Therefore $L_{wl}/\nabla 1/3$, C_B, B/T and consequently L_{wl}/B are based on hull hydrostatic and hydrodynamic requirements (L_{wl} = length water line; B = Breadth; ∇ = Displacement volume; C_B = Block coefficient; T = Draught. At moment from the previous database to a base of Froude number F_N no clear trends appearing for the previous parameters. A number of approximate formulae can be derived to estimate the design parameters from the design data characteristics. A classical example is a derivation of pseudo Posdunine's formula, with:

$$L_{wl}\Big/\nabla^{1/3} = a + c\left(\frac{V}{V+2}\right)^2 \qquad (1)$$

obtaining the c and a constants from the regression analysis.

In the Figures 3, 4, 5 and 6 are shown the linear regression analysis respectively for monohull only pax, monohull car/pax, catamaran only/pax and catamaran car/pax. The results of figure 3 are very sparse, therefore no regression is proposed; for such vessels the parameter $L_{wl}/\nabla 1/3$ can be estimate assuming a value at say mid range.

The above considerations allow at first stage to estimate the hull volume ∇ and the length water line L_{wl}; and consequently to estimate the length overall L_{oa},

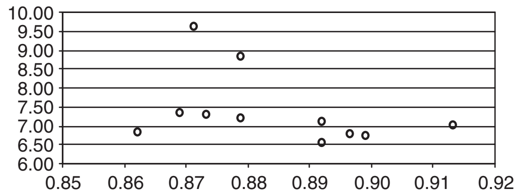

Figure 3. Formula ($L/V^{1/3}$ vs. $(v/v + 2)^{\wedge 2}$) for monohulls only pax.

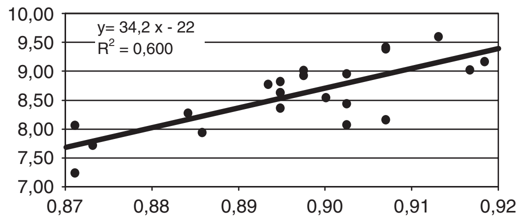

Figure 4. Formula ($L/V^{1/3}$ vs. $(v/v + 2)^{\wedge 2}$) for monohulls car pax.

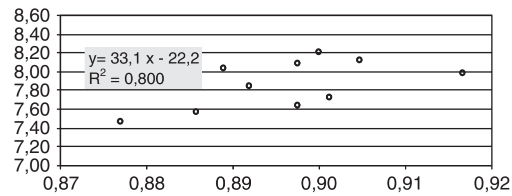

Figure 5. Formula ($L/V^{1/3}$ vs. $(v/v + 2)^{\wedge 2}$) for cats only pax.

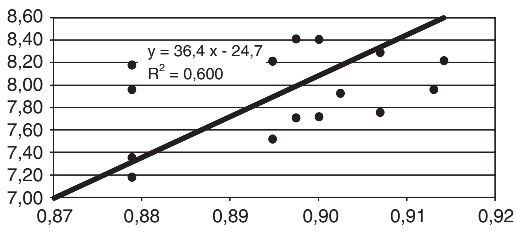

Figure 6. Formula ($L/V^{1/3}$ vs. $(v/v + 2)^{\wedge 2}$) for cats car pax.

while considering a simple linear regression with L_{wl} as an independent variable.

Interestingly, as in some conventional ships, "cargo capacities" (passengers and vehicles) are the fundamental data, which influence the main dimensions. Therefore, as suggested in T. Karayannis & et al (1997), it is possible to write:

$$L_{oa}B = f_1(A_p, A_v) \qquad (2)$$

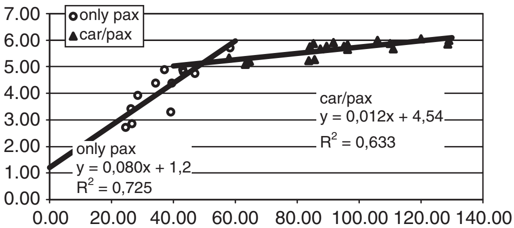

Figure 7. L_{WL}/B_{WL} vs. L_{WL} for monohulls.

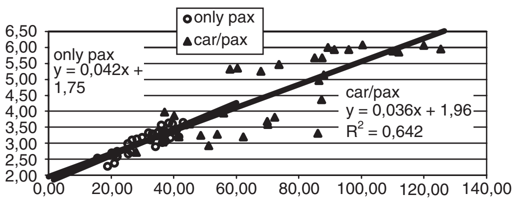

Figure 8. L_{WL}/B_{WL} vs. L_{WL} for cats.

where: $A_p = f_2\ (N_p)$ is the total passengers area and $A_v = f_3(N_v)$ is the vehicles area.

Then B can be obtained from (2) or in alternative utilizing the regressions show in the Figures 7 and 8:

T from B/T and $C_B = \Delta/\rho L_{wl}BT$ or T from $T = \Delta/\rho L_{wl}BC_B$ when reliability data has given on C_B (Δ = Displacement; ρ = sea density).

For catamarans, B is the breadth of a demihull b and it is needed to estimate the additional parameter L_{wl}/S, where S is the separation of the demihull centerlines.

The same objective can be achieved in bypassing the (1) equation (or an equivalent) and resolving the following systems:

$$\begin{cases} LB = f_1(A_p) \\ L/B = f_4(F_n) \end{cases} \text{ in the case of monohull/catamaran}$$

only passengers (3)

$$\begin{cases} LB = f_1(A_p, A_v) \\ L/B = f_4(F_n) \end{cases} \text{ in the case of monohull/catamaran}$$

cars/passengers (4)

It shows that the resolution of the (2), (3), and (4) equations/systems requires, in any case, the estimation of Ap and Av, which can be easily achieved with an optimum reliability in the published literature.

3 PROCEDURE FOR ESTIMATING THE HULL WEIGHT

Let's assume that the hull weight P_S is a function of n variables X = $[X_1, \ldots, X_n]$:

$$P_S = f(\mathbf{X}) \tag{5}$$

The development in series of Taylor (arresting to the first order) supplies:

$$P_S = f\left(\mathbf{P}^*\right) + \sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)_{\underline{X} = \underline{X}^*}\left(x_i - x_i^*\right) \tag{6}$$

where $f(P^*)$ represents the hull weight of a "base ship" (reference ship).

Due to the integrated nature of the hull and superstructure for most high-speed ferries, the total hull weight has been taken to include both hull and superstructures.

The relation (6) can be also written as:

$$P_S = f\left(\mathbf{P}^*\right) + \sum_{i=1}^{n}\alpha_i\left(x_i - x_i^*\right) \tag{7}$$

where: $\alpha_i = (\partial f/\partial x_i)_{x=x^*}$

The main variables of the vector X seems to be:

- Dimensional variables as L, B, D and T;
- Dimensionless variable as C_B;
- Additional dimensionless variable for catamaran L_{wl}/S
- Variables characteristics of sea status, in which the vessel must operate:

Hs, Acg (significant wave height and vertical center gravity acceleration);

Notably, in order to define the craft operating conditions, the center of gravity acceleration Acg has been considered, accounting for both the effects of wave height and ship speed. This has been taken as severity indicator using U.N.I.T.A.S. high-speed Rules of Bureau Veritas, Registro Italiano Navale and Germanisher Lloyd.

It is possible to approach the problem with the proposed method when it is related to a fit parametric procedure that individualizes the derivative α_i for a vessel typology.

The equation (6) is a good tool to estimate the hull weight. However, it needs the following aspects:

(1) For one or more "base ship"(reference vessel):
   (a) INITIAL DESIGN DATA: Autonomy, Velocity, Number of Passengers, Number of Vehicles, Type of vessel (monohull, catamaran);

Table 1. Beta coefficients.

Item	Pass. Only Monoh.	Car/Pass Monoh.	Pass. Only Cat.	Car/Pass Cat.
$\beta_L^{(j)}$	1.12–1.80	1.15–2.20	1.15–2.4	1.18–2.8
$\beta_B^{(j)}$	0.65–1.20	0.75–1.40	0.75–1.80	0.75–2.10
$\beta_D^{(j)}$	0.45–1.20	0.5–1.40	0.50–1.42	0.45–1.48
$\beta_T^{(j)}$	0.0007–0.001	0.0008–0.0017	0.0008–0.0019	0.0011–0.0022
$\beta_{CB}^{(j)}$	0.40–0.60	0.45–0.68	0.45–0.67	0.49–0.72
$\beta_{acg}^{(j)}$	0.014–0.022	0.018–0.026	0.014–0.022	0.018–0.026

(b) MAIN DIMENSIONS: Beam, Length of waterline/overall, Draught, Displacement volume, Block coefficient, Depth, Total passengers area, Seating area, Demihull beam (catamaran), Separation of centerlines of demihull (catamaran);

(c) HULL WEIGHT VALUES AND MATERIALS: Hull and Superstructures Weights; Type of materials: Steel and/or Aluminum.

These data allow the choice of a vessel, whose characteristics are as close as possible to the ones required for the design.

(2) The individuation of the derivative $\alpha_i = (\partial f/\partial_{xi})_{\underline{X}=\underline{X}^*}$, can be carried out basing on a simplified or parametric procedure given successively.

The approximate formulae to individuate αL, αB, αD, αT, α_{C_B}, $\alpha_{a_{cg}}$ and $\alpha S/Lwl$ can be so obtained:

$$\alpha_L = \beta_L^{(j)} \frac{f\left(\mathbf{P}^*\right)}{L^*} \tag{8}$$

$$\alpha_B = \beta_B^{(j)} \frac{f\left(\mathbf{P}^*\right)}{B^*} \tag{9}$$

$$\alpha_D = \beta_D^{(j)} \frac{f\left(\mathbf{P}^*\right)}{D^*} \tag{10}$$

$$\alpha_T = \beta_T^{(j)} L^{*2} \tag{11}$$

$$\alpha_{CB} = \beta_{CB}^{(j)} f\left(\mathbf{P}^*\right) \tag{12}$$

$$\alpha_{a_{cg}} = \beta_{acg}^{(j)} f\left(\mathbf{P}^*\right) \tag{13}$$

$$\alpha_{S/Lwl} = \beta_{S/Lwl}^{(j)} f\left(\underline{P}^*\right) \tag{14}$$

where the coefficients $\beta_L^{(j)}$, $\beta_B^{(j)}$, $\beta_D^{(j)}$, $\beta_T^{(j)}$, $\beta_{CB}^{(j)}$, $\beta_{a_{cg}}^{(j)}$ and $\beta_{S/Lwl}^{(j)}$ depending also by the $^{(j)}$- mo type of vessel, and can be calibrated by a parametric procedure based on the individuation of reliable numbers of hull weights noted.

Interestingly, as more data are available, the method suggests a remarkable basis for additional calibration refinement.

In the following Table 1, based on the calculations of hull weights and of the experience of the authors, indicative range of values for fast monohull and catamaran vessels are shown. The investigation has been based on the use of aluminium alloy for hull and superstructures.

The $\beta_{S/Lwl}^{(j)}$ coefficient has been not included, because data were not sufficient.

4 THE WEIGHT AND DIMENSIONS OF THE MACHINERY SYSTEMS

In a previous paper Coppola & et al (2004) we considered the diesel propulsion of fast vessels. The diesels taken under consideration were, naturally, the most compact, that is, those giving the highest power while taking up as little room as little.

The most widespread diesel engines were processed and a process has been implemented, that supplies a good suggestion at the early design stage, through the application of simple linear formulas (sometimes quadratics), in connection with the following quantity:

- Size in length of main engines;
- Size in plan of main engines;
- Length/Breadth ratio of main engines;
- Single diesel engine weight.

All these variables were related to the propulsion power (Kw). All the propulsion systems examined came from the latest generation of high-speed diesel engines; these are also very versatile and they have large application fields.

From Coppola & et al (2004) the Figure 9 and Figure 10 gives the values of the length (m) against the power (Kw), respectively for V and L disposition.

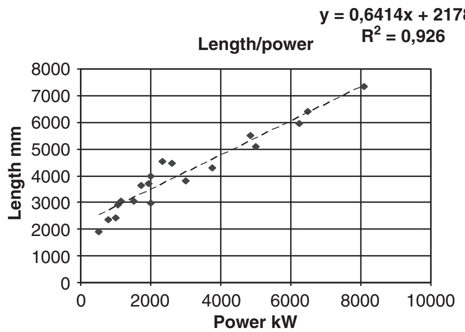

Figure 9. Length (mm) against Power (kw) V disposition.

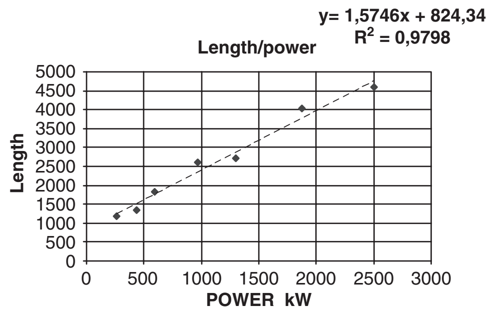

Figure 10. Length (mm) against Power (kw) L disposition.

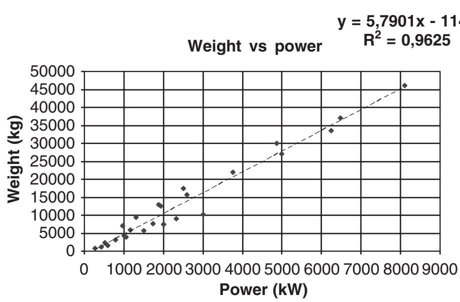

Figure 11. Weight against power L and V dispositions.

Including all the data both of L and V dispositions; in the same elaboration, it is possible to relate power and weight of diesels:

$$W = 5.7901\ P - 1141\ R^2 = 0.9625 \qquad (9)$$

where W is expressed in kg end P in kw.

Figure 11 shows the points given in the equation (9).

The diesel engines must offer such high characteristics because of the gas turbine competition. The gas turbine is, actually, the most suitable engine for these vessels, once we accept the disadvantages it has, that is, the use of a more expensive fuel and a higher consumption.

Another element we have to consider is the period of life of gas turbine, in general, shorter than in the case of the diesel.

The gas turbines used in marine propulsion are basically of two types: industrial and aero derivative.

The first one is, in the field of fast passenger and/or merchandise transport, more convenient for big ferries. In smaller vessels, the aero derivative gas turbines are preferred. They are lighter, take up less room, and are quickly ready for use.

Of course the performance reached by this engine come from progressive improvements in gas turbine design that resulted, over the last 50 years, in continual increases in cycle efficiency.

The most significant improvements include:

- Higher compression pressure ratios
- Higher turbine inlet temperatures
- Improved compressor stage efficiencies
- Improved turbine stage efficiencies
- Increase of loading on a single compressor or turbine stage that allows the reduction of stage number.
- The use of intercooling in the compression process
- Increase of recuperation from the exhaust gases
- Use of any waste-heat-recovery feature that seems to be economically acceptable.

All gas turbines are practical applications of the Brayton thermodynamic cycle.

The field of power covered by marine gas turbine plant is very large; it starts from a few hundred kw and reaches several hundreds of thousands of kw.

Another limitation shown by the gas turbine is the serious decline in efficiency due to a reduction in running speed. Consequently, the vessels using gas turbine should follow a mission profile with only one running speed, or, at least, with a clearly predominant value of running speed.

As an alternative, the vessels having a mission profile characterized by two or more running speed is offered by the combined cycles named A combined cycles (COGAG, CODAG, COSAG, COGAS, CONAG) or O combined cycles (CODOG, COGOG).

The first element we must consider in choosing a propulsion plant is the efficiency or, in other words, the specific fuel consumption.

The gas turbine has an efficiency that depends upon the power at maximum output. While the diesel engine shows efficiency not very reliant at maximum power, the efficiency of gas turbine shows values in competition with diesel only in correspondence of high value of maximum power.

This paper shows some graphics based on the data of most recent plants.

The first graphic relates the fuel specific consumption to the maximum power.

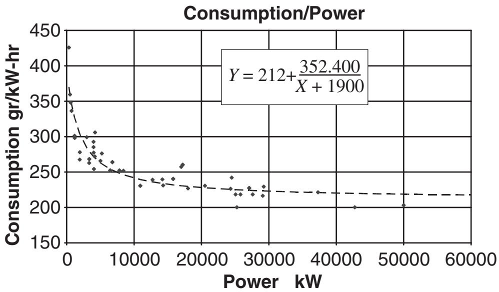

Figure 12. Fuel consumption against power.

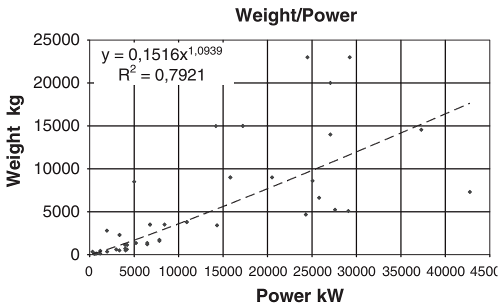

Figure 13. Weight against power.

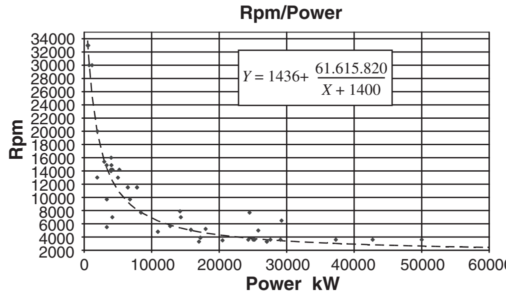

Figure 14. Rpm against power.

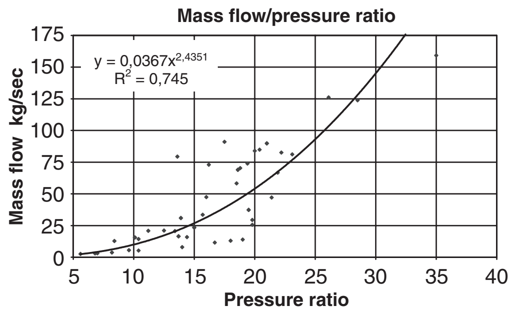

Figure 15. Air mass flow against pressure ratio.

The regression line most apt to these data is a hyperbola having the asymptotes translated form the axis X = 0 and Y = 0. The equation of this curve is:

$$y = 2.12E2 + \frac{3.52E5}{x + 1.9E3} \tag{15}$$

Where y is the specific fuel consumption in gr/kw-hr and x is the maximum power of the gas turbine set in kw. This curve (Fig. 12) represents quite well the average values at various powers, while considering the different values of compression pressure ratios, and shows very well the steep rise of specific consumption at lower values of power.

Another very important characteristic for this kind of propulsion plant is the weight of the engine. Figure 13 shows the weight of the various apparatuses versus power. It results in a regression curve whose equation is:

$$Y = 0.1516\ X^{1.0939} \tag{16}$$

The regression factor R^2 is 0.79, some points are far from the linear regression line, and we plan to see into this subject in the near future and to consider other parameters that influence it.

The total weight of a power plant will be increased by the reduction gear weight that is necessary for this kind of propulsion plant. The weight of the reduction gear will be a function of the total reduction ratio. Considering the optimum revolution number of the screw as not very variable, the total reduction ratio is basically functioning of gas turbine absolute revolution number.

The Figure 14 supplies available indicative values of revolution number of gas turbines.

The regression curve that best represents this variable is a hyperbola having the following equation:

$$Y = 1.44E3 + \frac{6.16E7}{X + 1.40E3} \tag{17}$$

In the gas turbines, the air mass flow needed by the engine is very important as well. In this case the mass flow is well over the one required by the diesel engines.

The air inlet represents a factor that must be serious taken into consideration from the designer in the first stage of ship design.

The mass flow can be put in relation with the pressure ratio of the turbine; it will increase with the power. The Figure 15 shows a typical trend of this function.

The equation of the regression curve is

$$Y = 0.0367\ X^{2.4351} \tag{18}$$

The R^2 coefficient is 0.745.

5 CONCLUSIONS

A review has been carried out for estimating the main dimension of high-speed ferries. The linear regression analysis of a large database furnishes reliable value to utilize at conceptual and preliminary design stages.

A new methodology has been proposed for the hull weight estimation, assuming as hull weight that one obtained by Taylor equation; what allows, when weights of reference vessel are known, to estimate the hull weight of only passengers and passengers/vehicles (monohull and catamaran). The coefficients $\beta_L^{(j)}$, $\beta_B^{(j)}$, $\beta_D^{(j)}$, $\beta_T^{(j)}$, $\beta_{C_B}^{(j)}$, $\beta_{a_{cg}}^{(j)}$ and $\beta_{S/Lwl}^{(j)}$, depending by the $^{(j)}$-mo type of vessel, can be interiorly calibrated when more data are known.

A discussion has been carried out about the weight and dimensions of the propulsion system for the conceptual and preliminary design stage. Particularly reference has been given to the diesel engine and gas turbines, showing some graphics based on recent data. The paper gives first aids to the choice between diesel propulsion and TAG propulsion. A deeper analysis of this subject requires the determination of a more specific type of ship. The authors undertake to deal with this subject in a new paper starting from the data and formulas given in this paper applied to a more of typical ship design.

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