ON THE DESIGN OF PROPULSION SYSTEMS AND HULL WEIGHT ESTIMATES FOR HIGH-SPEED FERRIES

T. Coppola, A. Paciolla, F. Quaranta
University of Naples "FEDERICO II", Italy

ABSTRACT

In the last decades an increase of interest of high-speed ferries has been registered and, as consequence, new problems have arisen as regards demand of data and adequate procedures for conceptual and preliminary design analysis. In particular the demand for increased speed and large vessels challenges continually designers to choice propulsions systems to estimate the principal components of propulsion machinery and hull weight. Contemporary, there is a lack of published systematic data and techniques suitable for both conceptual and preliminary analysis.

Firstly, a critical review for vessel dimensions estimation has been carried out. Successively, including Steel and/or Aluminum materials, a new parametric procedure has been carried out for estimating hull weight of both passengers only and passengers/cars monohulls.

The application of the previous procedure allows then individuating feasible and reliable initial calculations for hull weight values, which can be used as starting point of the iterative design process.

Finally, a database of machinery weight is presented, which includes the main component of high-speed diesel engines. The data examined come from the latest generation of high-speed diesel engines; they are much versatile and they have large application fields; the regression data obtained permit to estimate the "size-power" relationship of a diesel engines as primary element at conceptual and preliminary design stages.

KEYWORDS

Propulsion; Hull; Weight; Vessels; Fast; Machinery; Diesel Engines.

INTRODUCTION

The growth of the fast ferry market has given necessity for research in this area. Though a rational approach to high-speed craft design has been developed, at early stage of the design, algorithms, methodologies and practical tools are currently not reliable in the scientific literature.

In particular the demand for increased speed and large vessels challenges continually designers to choice propulsions systems and to estimate the principal components of propulsion machinery and hull weight.

The paper deals with the design problems of high-speed ferry connected to the conceptual and preliminary analysis.

At first, on the basis of a ship capacity (passengers, trucks and cars) a significant review for ship dimensions estimation has been outlined.

Later on, including Steel and/or Aluminum materials, a new parametric procedure has been carried out for estimating hull weight of fast monohulls.

Finally, a database of machinery weight is presented, which includes the main component of high-speed diesels, which come from the latest generation of high-speed diesels.

The analysis of the previous diesel data has furnished regressions and formulae, which can be used as starting point of the iterative design process for determining sizes, dimensions and weight of high-speed propulsion system.

A REVIEW FOR VESSEL DIMENSIONS ESTIMATION

Generally for the fast ferry 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 so synthesized:
Passengers-only monohull; passengers-only catamaran;

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

It is to be pointed out that besides the v speed, to the material type, and to the passenger numbers, the Au range is a variable that influences certainly the displacement.

At first stage for developing a high-speed ferry design an initial set of displacement and main dimensions should be involved. 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 that considers new designs and high speed ferries in the world.

A first tentative displacement can be evaluated through the "net weight " regressions. Two examples which shown a clearly trends have been reported in fig. 1 and fig. 2 respectively for monohull and catamaran only passengers.

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

It needs to point out that the main influence of the size is on the resistance, on the longitudinal strength and on the seakeeping. Of these, the more 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 (Lwl= 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_∇ no clear trends appearing for the previous parameters. A number of approximate formulae can be derived for estimating the design parameters from the design data characteristics. A classical example is a derivation of Posdunine's formula:

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

obtaining the c constant from the regression analysis for hulls in steel and aluminum (in the case of catamaran obviously the volume ∇ is that of demihull).

The considerations till now carried out permit at first stage to estimate the hull volume ∇ and the length water line L_{wl}; and consequently to estimate the length overall L_{oa} considering a simple linear regression with L_{wl} as independent variable.

It is interesting to note that, as for some conventional ships, "cargo capacities" (passengers and vehicles) must be the fundamental data which influencing the mains dimensions. Therefore, as suggested in [1] it is possible to write:

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

where $A_p = f(N_p)$ is the total passengers area and $A_v = f(N_v)$ is the vehicles area.

Deriving then B from (2), T from B/T and $C_B = \frac{\Delta}{\rho L_{wl} BT}$ or T from $T = \frac{\Delta}{\rho L_{wl} B C_B}$ when reliability data has given on C_B (Δ =Displacement; ρ = sea density).

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

To the same objective is possible to achieved bypassing the (1) equation (or an equivalent) and resolving the following systems:

$$\begin{cases} LB = f_2(A_p) \\ L/B = f_1(F_n) \end{cases} \text{in the case of monohull/catamaran passengers only} \qquad (3)$$

$$\begin{cases} LB = f_2(A_p, A_v) \\ L/B = f_1(F_n) \end{cases} \text{in the case of monohull/catamaran cars/passengers} \qquad (4)$$

It point out that the resolution of the (2), (3), and (4) equations/systems request in any case to estimate Ap and Av, which can be easily acquired with an optimum reliability in the published literature (see for example [1]).

NEW PROCEDURE FOR ESTIMATING THE HULL WEIGHT

General

Let assume that the hull weight p_s is a function of n variables $\underline{X} = \lfloor X_1, \ldots X_n \rfloor$:

$$p_S = f(\underline{X}) \tag{5}$$

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

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

where $f\left(\underline{X}^*\right)$ represents the hull weight of a " base ship".

The relation (6) can be also written:

$$p_S = f\left(\underline{X}^*\right) + \sum_{i=1}^{n} \alpha_i \left(x_i - x_i^*\right) \tag{7}$$

where: $\alpha_i = \left(\frac{\partial f}{\partial x_i}\right)_{\underline{X} = \underline{X}^*}$

The variables to the vector $\underline{X}$ seems to be:

-dimensional variables as L, B, D and T; -dimensionless variable as CB;
-variables characteristics of sea status, in which the vessel must operate: Hs, Acg (significant wave height and vertical center gravity acceleration);

To approach the problem with the proposed method is possible when is related to a fit parametric procedure to individualize the derivative α_i for a vessel typology.

Detailed Calculations

The equation (6) is a good instrument to estimate the hull weight. However it need of the following aspects:

1) For one or more "base ships"(reference vessels):
   a) **INITIAL DESIGN DATA**: Autonomy, Velocity, Number of Passengers, Number of Vehicles, Type of vessel (monohull, catamaran);
   b) **MAIN DIMENSIONS**: Beam, Length of waterline/overall, Draught, Displacement volume, Block coefficient, Depth, Total passengers area, Seating area, Demi-hull beam (catamaran), Separation of centerlines of demihull (catamaran);

c) **WEIGHT VALUES AND MATERIALS:** Hull Weight, Outfit Weight, Machinery weight (diesel engines, Gas Turbine, Gearboxes, Waterjet), Deadweight, Type of materials: Steel and/or Aluminum.

These data allow to choice a vessel, which has characteristics as closed as possible to that one required for the design.

2) The individuation of the derivative $\alpha_i = \left(\frac{\partial f}{\partial x_i}\right)_{\underline{X}=\underline{X}^*}$ basing on a simplified or parametric procedure given successively.

The approximate formulae to individuate α_L, α_B, α_D, α_T, α_{C_B} and α_{acg} can be so obtained:

$$\alpha_L = \beta_L^{(j)} \frac{f(\underline{X}^*)}{L^*}; \quad \alpha_B = \beta_B^{(j)} \frac{f(\underline{X}^*)}{B^*}; \quad \alpha_D = \beta_D^{(j)} \frac{f(\underline{X}^*)}{D^*}; \quad \alpha_T = \beta_T^{(j)} L^{*2};$$

$$\alpha_{C_B} = \beta_{C_B}^{(j)} f(\underline{X}^*); \; \alpha_{acg} = \beta_{acg}^{(j)} f(\underline{X}^*);$$

where the coefficients $\beta_L^{(j)}$, $\beta_B^{(j)}$, $\beta_D^{(j)}$, $\beta_T^{(j)}$, $\beta_{C_B}^{(j)}$ and $\beta_{acg}^{(j)}$ depending also by the (j)-ma type of vessel, and can be calibrated by a parametric procedure based on the individuation of a reliable numbers of hull weights. In the following table, basing on the calculations of hull weights and the experienced of the authors, indicative range of values for fast monohull vessels has been shown. It is to be point out that in order to define the crafts 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.

Item	Pass. Only Monoh.	Car/Pass Monoh.
$\beta_L^{(j)}$	1.12-2.80	1.15-3.5
$\beta_B^{(j)}$	0.65-1.80	0.75-2.10
$\beta_D^{(j)}$	0.25-1.20	0.40-1.40
$\beta_T^{(j)}$	0.007-0.01	0.009-0.017
$\beta_{C_B}^{(j)}$	0.40-0.60	0.45-0.68
$\beta_{acg}^{(j)}$	0.014-0.022	0.018-0.026

It is interesting also to note that, as more data are obtainable, the method suggests a respectable basis for additional calibration refinement.

ON THE WEIGHT AND DIMENSIONS OF THE PROPULSION SYSTEMS

The examined vessels are characterized all from the following necessity:

- High-speed service and consequent high value of the installed power;
- Low value of the cargo specific weight and consequent necessity of containing the local propulsions system dimensions;
- Slender Hull form, and consequent necessity of disposing a propulsion system which occupies a contained space above all in plan;
- Necessity to carry a remarkable quantity of combustible, above all, in the long route, and then of disposing a weight contained primary propulsion system;
- Elevated "use coefficient" of the primary propulsion system with mission profile of elevated percentage utilization to the maximum power;
- Necessity of a redundant propulsion system, which guarantee safety of "take home" also in case of failure.

The typologies that more guarantee these necessities are: gas turbines (for the more high powers) and high-speed diesels (for averages and high powers).
In this paper are considered exclusively the solutions using high-speed diesels, because they are able to cover, thanks to their modular structure, wider power fields.
To individualize the diesel engines more used in the field in examination a ship database of remarkable amplitude has been consulted. They have been processed the diesel engines more widespread and has been implemented a process that allows, through the application of simple linear formulas (sometimes quadratics), the disposing of a good suggestions at the early design stage, in connection with the following quantity:

- Size in length of the single primary system engines;
- Size in plan of a single primary system engines;
- Length/Breadth relationship of a primary system engines;
- Single diesel engine weight.

All these variables have been related to the propulsion power (Kw). All the propulsion systems examined come from the latest generation of high-speed diesel engines; these are also much versatile and they have large application fields. In the figures 3 to 6 are reported four profiles of typically missions considered by the MTU, together with typical category of ships, which use such profiles. In our case the process have been made considering the 1B field typical for fast vessels, monohulls, hydrofoils, catamarans, and ships effect surface. In fig. 7 it is shown again a graph that shows the maximum usable power in correspondence of the time between overhauls. The following table re-engages the characteristics of the diesel engines considered:

engine	Power (kW)	Lenght (mm)	Widht (mm)	Height (mm)	Weight (kg)	Cyl nr	rpm	Bore(mm)	Stroke(mm)	Sp. power	v_m (m/s)	Mep (bar)
MTUV396TE	1000	2435	1530	1550	4290	8V	1900	165	185	5845,91	11,72	19,96
MTUV396TE	1500	3040	1530	1785	5670	12V	1900	165	185	5845,91	11,72	19,96
MTUV396TE	2000	3995	1530	1850	7370	16V	1900	165	185	5845,91	11,72	19,96
MTU2000	788	2350	1400	1230	3215	12V	2100	130	150	4947,30	10,50	18,85
MTU2000	525	1920	1280	1160	2260	8V	2100	130	150	4944,16	10,50	18,83
MTU2000	1050	2920	1400	1290	3960	16V	2100	130	150	4944,16	10,50	18,83
RUSTONRK215	1940	3702	1814	2660	12500	12V	900	215	275	4453,01	8,25	21,59
RUSTONRK215	2600	4460	1864	2385	15700	16V	900	215	275	4475,96	8,25	21,70
RUSTONRK270	3750	4285	1825	2645	22000	12V	1000	270	305	5457,99	10,17	21,47
RUSTONRK270	5000	5075	1830	2820	27000	16V	1000	270	305	5457,99	10,17	21,47
RUSTONRK270	6250	5965	1960	2820	33500	20V	1000	270	305	5457,99	10,17	21,47
RUSTONRK280	4860	5490	2100	3180	30000	12V	900	280	330	6577,32	9,90	26,58
RUSTONRK280	6480	6410	2100	3180	37000	16V	900	280	330	6577,32	9,90	26,58
RUSTONRK280	8100	7330	2100	3180	46000	20V	900	280	330	6577,32	9,90	26,58
RUSTONVP185	2000	2971	1660	2175	7500	12V	1800	185	196	6200,34	11,76	21,09
RUSTONVP185	3000	3798	1450	2178	10200	18V	1770	185	196	6200,34	11,56	21,45
MTU4000	1740	3620	1520	1830	7620	12V	2000	165	190	6781,26	12,67	21,41
MTU4000	1160	3060	1380	1990	5800	8V	2000	165	190	6781,26	12,67	21,41
MTU4000	2320	4525	1520	1890	8945	16V	2000	165	190	6781,26	12,67	21,41
CumminsQSM11	433	1354	982	1012	1125	6L	2800	127	147	5696,91	13,72	16,61
Cummins6CTA83	261	1177	849	954	712	6L	2500	114	135	4261,77	11,25	15,15
Caterpillar3406E	597	1823	954	1178	1586	6L	2300	137	165	6749,82	12,65	21,34
RUSTONRK215	970	2595	1480	2145	7000	6L	900	215	275	4453,01	8,25	21,59
RUSTONRK215	1300	2712	1705	2250	9440	8L	900	215	275	4475,96	8,25	21,70
RUSTONRK270	1875	4020	1325	2490	13000	6L	1000	270	305	5457,99	10,17	21,47
RUSTONRK270	2500	4585	1300	2480	17500	8L	1000	270	305	5457,99	10,17	21,47

Where the specific power is:

$$P_s = \frac{P}{z\,\pi\,D^2/4} = 25\,p_m\,v_m \qquad (8)$$

with: P= power(Kw); D= bore in m; p_m = mep in bar; v_m = medium speed.

Obviously the relative process to sizes estimation resent to the disposition of the cylinders, L or V; while the weight, instead of not resent of such disposition. For such reason all the process are here to present uniform for engine with V configuration and engine with L configuration.

The parameter that more conditions the engine choice in this ship typology as in nearly all the other is the length.

The figure 8 gives the values of the length (m) versus the power (Kw), and generally it is distinguished for engines with V and L dispositions. Using the least square method is possible to make the linear regression curve, for which it is furnished the equation and its regression coefficient R^2:

$$L_V = 0{,}6414\ P + 2178{,}5 \qquad R^2 = 0.926 \tag{9}$$

where L_V = length (mm) and P = power (Kw) (engines with V disposition).
It is worth to point out that the regression coefficient R^2 is very close to 1.
Same procedure has been made for engines with L disposition (figure 9):

$$L_L = 1{,}5746P + 824{,}34 \qquad R^2 = 0{,}9798 \tag{10}$$

where L_L = length (mm) (engines with L disposition).
Another useful relationship can be established between the area filled by the engine and the power (fig.10 and fig.11), so we can find the area we need (A_V or A_L) to install the required power.

We found:

$$A_V = 0{,}1611\ P + 238{,}15 \qquad R^2 = 0{,}9412 \tag{11}$$

where Av = length x width expressed in dm^2.
Considering the L disposition we can write:

$$A_L = 0{,}2367\ P + 71{,}924 \qquad R^2 = 0{,}9074 \tag{12}$$

where A_L = length x width expressed in dm^2.

By the way in case of two or more engines placed side by side we must increase the total area considering the distance between the two engines required by its maintenance and conduct. We have attempted also to find a relationship that expresses the length/width ratio in function of the power. This length/width ratio for the engines with V disposition is better expressed by two relationships corresponding to two power fields. So we can write:

$$L/W_V = 0{,}0571\ P + 1{,}247 \quad R^2 = 0{,}5508 \quad \text{if } P< 30 \text{ daW} \tag{13}$$
$$L/W_V = 0{,}0192\ P + 1{,}8297 \quad R^2 = 0{,}8799 \quad \text{if } P> 30 \text{ daW} \tag{14}$$

In the fig.12 we can see also a strip of length/width ratio variation in the field of P< 3000 kw.

In case of L disposition, instead, we can write only one relationship effective in the whole field of power (fig.13):

$$L/W_L = 0{,}0958\ P + 0{,}9967 \qquad R^2 = 0{,}8464 \qquad (15)$$

The last relationship we offer to a first state designer concerns the weight versus power correlation.

In this case we have found a regression coefficient R^2 very close to 1, including all the data both of L and V dispositions engines in the same elaboration (fig. 14):

$$W = 5{,}7901\ P - 1141 \qquad R^2 = 0{,}9625 \qquad (16)$$

where W is expressed in kg end P in kw.

CONCLUSION

A general procedure has been carried out for the vessel dimensions estimation.

A new approach for the hull weight estimation has been obtained, within a developed formulation assuming as hull weight that one obtained by Taylor equation. What allows, when weights of reference vessel is known, to calculate hull weight of passengers and passengers/vehicles monohulls. The numerical parameters $\beta_L^{(j)}$, $\beta_B^{(j)}$, $\beta_D^{(j)}$, $\beta_T^{(j)}$, $\beta_{C_B}^{(j)}$ and $\beta_{a_{cg}}^{(j)}$ defined can be also calibrated in case of passengers and passengers/vehicles catamarans; this position will be object of a successive research.

A discussion has been carried out about the weight and dimensions of the propulsion system for the conceptual and preliminary design stage. Particularly, the length, length x width, length/width ratio and weight versus power regressions has been carried out. The analytical formulations so obtained have been particularly discussed.

ACKNOWLEDGEMENTS

The paper has been financially supported by the University of Naples “Federico II” and MIUR University Department (PRIN 2003 founds).

FIGURES

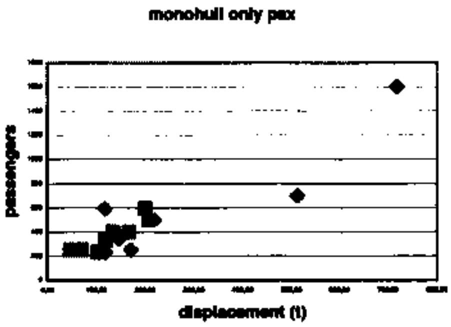


Fig. 1

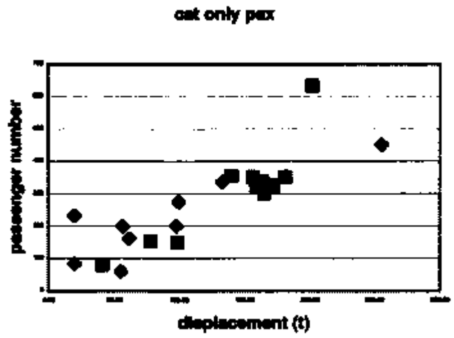
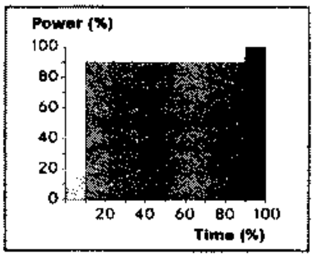
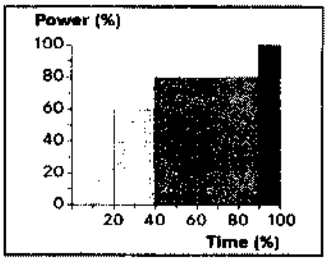


Fig.2



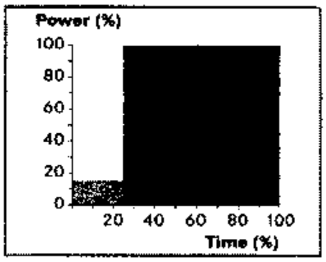
Standard load profile 1A, M60R
Typical examples:
- ☐ Work boats, tug boats, barges, ferries
- ☐ Sailing yachts
- ☐ Governmental vessels

Fig 3



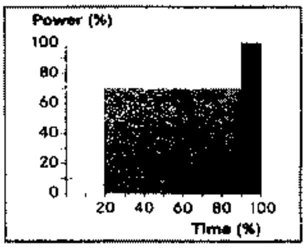
Standard load profile 1A, M60
Typical examples:
- ☐ Work boats, tug boats, barges, ferries
- ☐ Sailing yachts
- ☐ Governmental vessels

Fig. 4



Standard load profile 1B, M70
Typical examples:
- ☐ Fast commercial vessels
- ☐ Monohulls, hydrofoils, catamarans, surface effect ships

Fig. 5



Standard load profile 1DS, M90
Typical examples:
☐ Fast patrol boats, police craft, fire-fighting vessels
☐ Fast yachts

Fig. 6

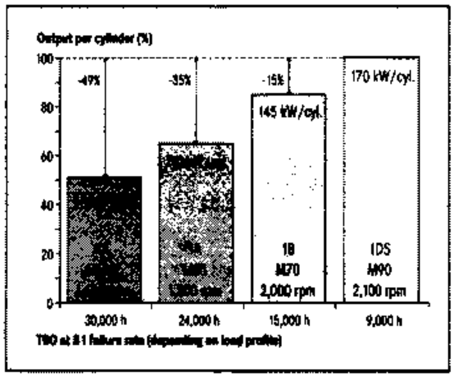


Fig. 7

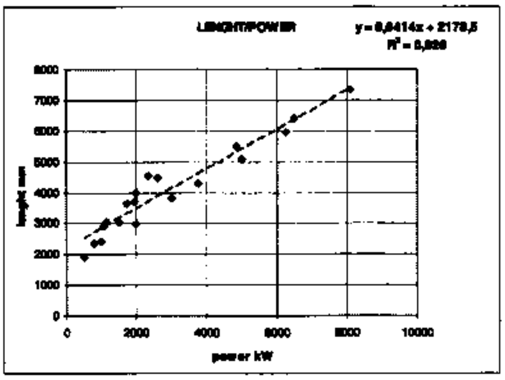


Fig. 8 length against power V

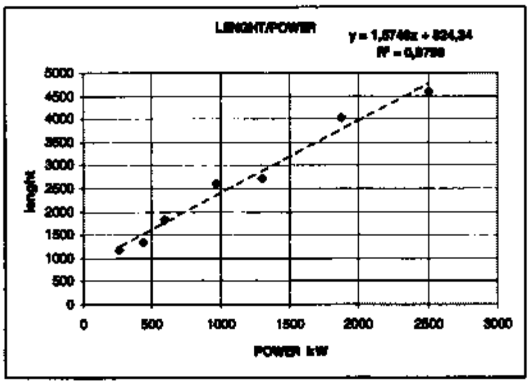


Fig 9 length against power L

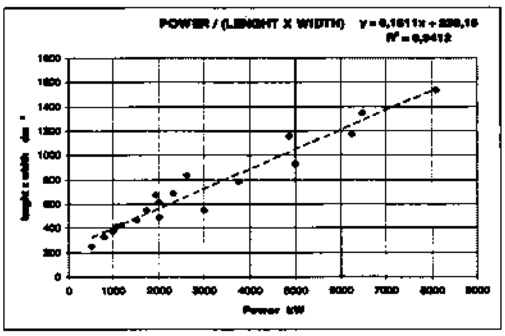


Fig. 10(length x width) against Power L

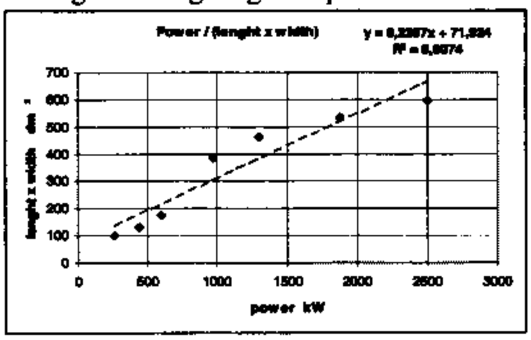


Fig. 11 (length x width) against Power V

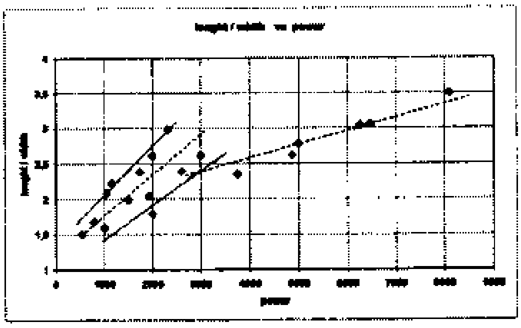


Fig. 12 length / width ratio vs power dispos.

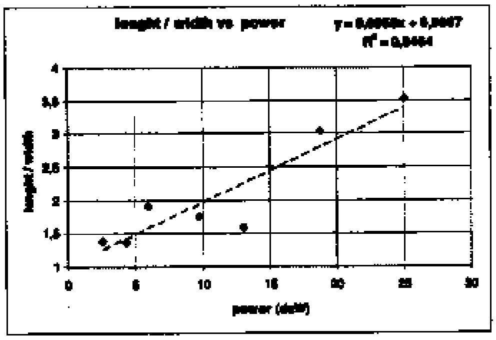


Fig. 13 length/width ratio vs power L

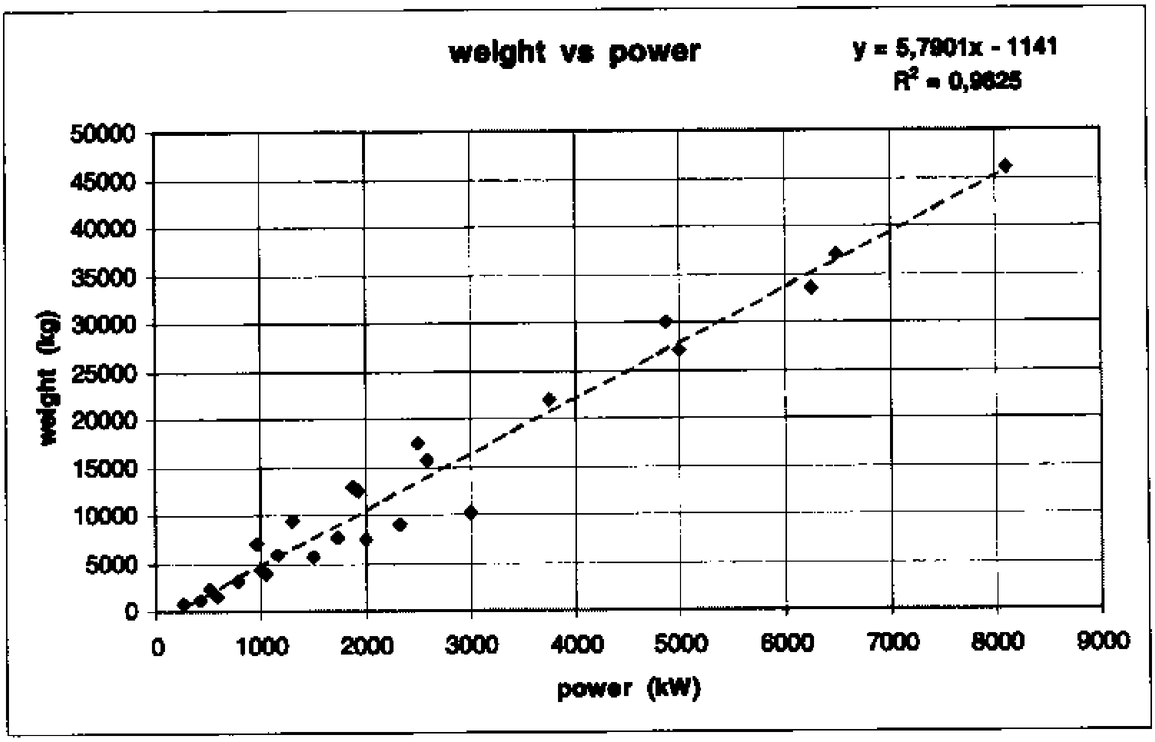


Fig. 14 weight vs power L and V dispositions

REFERENCES

[1] T. KARAYANNIS, A.F. MOLLAND and Y.SARAC WILLIAMS, *Design Data for High-Speed Vessels*, School of Enginneering Sciences, Univesity of Southampton, pages: 605-615.
[2] MOLLAND A.F. AND KARAYANNIS T. 1997 Development of a Concept Exploration and Assessment Mode for Advanced Fast Marine Vehicles. The Sixth International Marine Design Conference Design IMDC'97 Newcastle upon Tyne.
[3] CESARE MARIO RIZZO, 2003 *An optimization method for High Speed Craft design: technical problems and project financing*, HSMV "03 October 2003 Baia Naples Italy.
[4] MICHAEL G. PARSONS *Ship Design and Construction I*° Volume Chapter 11 Parametric Design Tomas Lamb editor.
[5] DONALD L. BLOUNT and ROBERT J. BARTEE *Design of Propulsion Systems for high- speed Craft Marine Technology*, vol. 34 Oct. 1997 pp. 276-292.