LIGHTSHIP WEIGHT ESTIMATION OF WIND FARM SUPPORT VESSELS AT THE INITIAL DESIGN STAGE

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SUMMARY

The issue of the determination of lightship weight estimates of wind farm support vessels (WFSV) is considered. The algorithm of determination of components of the lightship weight is suggested. The hull weight of the ships suggested to be calculated through the surface area of the principal structural elements using the parametrical model. The formula for calculation of weight and volume of the superstructures was obtained by making the 3D model of the superstructures of the most widespread projects of WFSV. Using the statistical data processing the dependences were obtained for the determination of engine, gearbox and waterjet weights, which are used in WFSV. The results of the comparative analysis of the lightship weight of WFSV are given.

NOMENCLATURE

∇_1	Demi-hull displacement volume (m^3)
Δ	Full load displacement (t)
AL	Aluminium
B	Beam overall (m)
B_X	Beam of the demi-hull at DWL (m)
C_M	Coefficient of the maximal section
CPP	Controllable pitch propeller
DWL	Design waterline
D_X	Depth of catamaran at side (m)
d_X	Draft of demi-hull at DWL (m)
FPP	Fixed pitch propeller
GRP	Glassfiber Reinforced Plastic
H_C	Cross bridge height (m)
IPS	Integrated Propulsion System
N_{WTB}	Number of watertight bulkheads
L_{OA}	Length overall (m)
L_{WL}	Length on waterline (m)
P_S	Installed power of main engines (kW)
S_X	Separation of demi-hulls centerline to centerline (m)
TAS	Turbine Access System
W_D	Main engine weight (kg)
$WFSV$	Wind Farm Service (Support) Vessel
W_{FPP}	Propeller weight
W_{GB}	Gearbox weight (kg)
W_{Hull}	Weight of the hull
W_{LS}	Lightship weight (t)
WJ	Water jet
W_M	Machinery weight
W_{Out}	Outfit weight;
W_{SM}	Margin weight
W_{Sup}	Superstructure weight
W_{WJ}	Waterjet weight (kg)

1. INTRODUCTION

The development of offshore wind energy has led to the creation of a new type of vessel – the vessel for the delivery of maintenance technicians, or Wind Farm Service Vessel (WFSV). Although for the sake of fairness, it should be noted that this type of vessels is somewhat similar to vessels for the delivery of crew on drilling platforms. However, the specifics of transfer technicians on the wind turbine has many differences and, therefore, one can talk about their innovative aspect.

One of the tasks to be solved at the initial stages of designing WFSV is the calculation of the displacement and its components.

An analysis of recent studies and publications showed that despite considerable interest in the construction of WFSV, there are practically no scientific works devoted to solving this problem. Partially, to determine the vessels displacement individual components, it is possible to use dependencies that are used for other types of vessels (Barrass, 2004), (Grubisic, Begovic, 2012), (Nazarov, 2010), (Papanikolaou, 2014). First of all it concerns such components of deadweight as maintenance technicians weight, fuel oil weight, crew weight, fresh water weight, general stores weight, and black water weight. Formulas for calculating the weight of these components can be found in works (Nazarov, 2012), (Moraes *et al.*, 2007). To determine the outfit weight, the margin displacement, you can use the data of works (Karayannis *et al.*, 1999), (Molland *et al.*, 2003).

In order to solve the problem of calculating the components of the vessels displacement in this work, it is suggested to use a methodology, the bases of which are articles (Grubisic, 2008), (Grubisic, 2005), (Karayannis *et al.*, 1999) with the amendments and the improvements concerning WFSV operation peculiarities taking into account.

2. WIND FARM SERVICE VESSELS – AN OVERVIEW

The architectural and constructive type of vessels for the delivery of maintenance technicians on offshore wind farms (WF) was formed in accordance with the main functions that they perform during the operation of the WF: transferring maintenance technicians, their tools, materials, equipment, spare parts and other goods to the turbines, carrying out inspection activities, performing diving operations and preventive measures, and cleaning turbine columns.

Also, these vessels can be adapted to transport fuel for the generator of the WF.

In addition to these functions, WFSV at the installation stage of the WF is used to provide the work of cable-laying vessels, support of diving operations.

Taking into account the specified tasks and specifics of WFSV operation, the following key factors must be taken into account when designing vessels of this type (Dalgic *et al*., 2014):

- weather-meteorological conditions in the area of operation (wave height, wind speed, frequency and duration of storms);
- WF location and the vessel location, since the distance between them determines the time of work maintenance technician and the time of staff delivery to the turbine requiring repair;
- depth at WF location;
- manoeuvrability for ensuring fast and safe traffic between wind turbines;
- comfort and safety of maintenance technician transfer;
- mobility, that is, the ability to use vessels to perform tasks variety.

The main way to move maintenance technician from WFSV to a wind turbine is to move from the bow to the vertical access ladder that is installed on turbine «bump and jump method». In this case, the vessel with the bow part thrusts in the turbine. Therefore, the main constructive feature of WFSV is the presence of a special shape of the fendered bow and the transition bridge. Recently, WFSV has installed special transfer systems of various types, Turbine Access System, Amplemann, Maxcess and Houlder TAS, MOTS access system (Cockburn *et al*., 2010). The use of such systems makes it possible to land maintenance technician at higher altitudes, increase the safety of staff and increase the so-called "transfer window".

One more constructive feature of vessels of this type is the presence of deck spaces that are open and free from the equipment, on which loads of weight from 1 to 50 tons (spare parts, tools, equipment, containers) are carried. There are also vessels with stern, or bow and stern deck spaces.

Significant efforts in the design of WFSV vessels are designed to improve their efficiency. One of the ways of such an increase due to the reduction of fuel charge and the improvement of the seaworthiness of the vessel is the hull various forms application: monohull, catamarans, Small Waterplane Area Twin Hull vessels (SWATH), trimaran, TriSWATH, Variable draft (S-cat, XSS – Extreme Semi-SWATH), wave piercing (WP), Twin Axe, Z bow, HYSUCAT foil, etc (Jupp *et al*., 2014).

Statistical processing of the collected data showed that more than 85 % of WFSV are catamarans. Therefore, in this work we consider WFSV of catamaran type (Table 1).

Table 1: Characteristics of WFSV

Vessel's name	Gardian	Rix Tiger	Solway Challenger
Design OR Type	Alicat 20 m	Wave Master	Alicat 21 m
Delivery	2010	2013	2013
Hull Material	AL	AL	AL
Hull length, m	20,00	18,90	19,25
Waterline length, m	18,55	18,00	17,81
Beam overall, m	6,40	7,20	7,36
Depth, m	2,56	2,64	2,45
Design draft, m	1,02	1,40	1,10
Maximum draft, m	1,70	–	1,10
Lightweight, t	39,0	37,5	38,4
Design displacement, t	48,0	43,2	52,0
Full load displacement, t	53,0	–	63,0
Main engines	Cat 32	QSK19	MAN V12
Total power, kW	2 × 970	2 × 597	2 × 1030
Max speed, kn	30	25	28
Service Speed, kn	22 – 24	20	25
Propulsion	FPP	FPP	WJ
Propeller diameter, m	0,9	0,9	–
Range, n.m.	600	–	–
Deck area, m^2	–	–	65
Max deck cargo, t	7	7	7
Passengers	12	12	12
Crew	2–3	2–3	2–4

Table 1: Characteristics of WFSV

Vessel's name	Dalby Swale	Spirit of Turmarr	OW 5
Design OR Type	Alicat 23 m	Alicat 13 m	Wave Commander
Delivery	2014	2014	2008
Hull Material	AL	AL	AL

Hull length, m	21,00	12,00	16,00
Waterline length, m	19,71	11,99	15,00
Beam overall, m	7,36	4,50	6,70
Depth, m	2,55	1,60	2,25
Design draft, m	1,11	0,70	0,83
Maximum draft, m	1,11	0,70	1,40
Lightweight, t	41,82	15,60	22,00
Design displacement, t	–	19,20	–
Full load displacement, t	70,0	–	–
Main engines	MAN V12	Iveco C90	DI12 66M
Total power, kW	2 × 1044	2 × 410	2 × 478
Max speed, kn	30	25	26
Service Speed, kn	24	21	–
Propulsion	WJ	WJ	FPP
Propeller diameter, m	–	–	0,8
Range, n.m.	–	225	–
Deck area, m^2	75	35	
Max deck cargo, t	8	1	5
Passengers	12	12	12
Crew	2–3	2	2

Table 1: Characteristics of WFSV

Vessel's name	Xplorer	Iceni Venture	Wind Transfer
Design OR Type	Wave Commander	22 m WFSV	Wave Master
Delivery	2007	2015	2011
Hull Material	AL	AL	AL
Hull length, m	13,50	22,80	20,90
Waterline length, m	12,50	21,30	18,95
Beam overall, m	5,70	7,73	6,90
Depth, m	2,50	3,91	3,00
Design draft, m	0,64	1,39	1,36
Maximum draft, m	–	2,30	–
Lightweight, t	17,20	58,75	40,00
Design displacement, t	–	68,00	–
Full load displacement, t	–	75,00	–
Main engines	QSC 8.3	MAN V12	MTU 8V
Total power, kW	2 × 361	2 × 1029	2 × 720
Max speed, kn	22	30	24
Service Speed, kn	–	25	20
Propulsion	WJ	CPP	CPP
Propeller diameter, m	–	1,225	1,075
Range, n.m.	200	–	–
Deck area, m^2	–	80	–
Max deck cargo, t	–	15	–
Passengers	12	12	12
Crew	2	2–3	2

Table 1: Characteristics of WFSV

Vessel's name	Marianarray	Spirit of Sunthorp
Design OR Type	Alicat 18 m	Alicat 17 m
Delivery	2011	2014
Hull Material	AL	AL
Hull length, m	17,00	16,60
Waterline length, m	15,70	14,27
Beam overall, m	6,40	6,64
Depth, m	2,38	2,40
Design draft, m	1,00	1,10
Maximum draft, m	–	–
Lightweight, t	28,00	34,50
Design displacement, t	38,00	40,00
Full load displacement, t	42,00	47,00
Main engines	MAN V12	MAN V12
Total power, kW	2 × 882	2 × 875
Max speed, kn	26	27
Service Speed, kn	24	22
Propulsion	WJ	WJ
Propeller diameter, m	–	–
Range, n.m.	–	–
Deck area, m^2	30	56
Max deck cargo, t	2,5	5
Passengers	12	12
Crew	2	2

3. METHODOLOGY

3.1 GENERAL

WFSV full load displacement can be obtained by the author by the way of the statistical data processing (figure 1) with use of the approximate relation (Bondarenko, 2015).

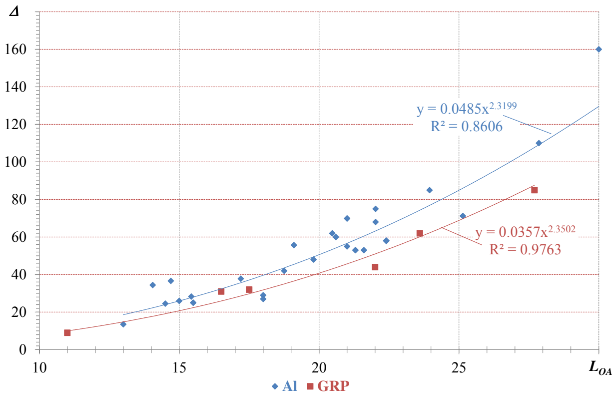

Figure 1: L_{OA} (m) Vs. Full Load Displacement (t) for Different Types of Materials

At the initial stages of the design the necessity of the components calculation of the ship displacement is appeared. In such cases, WFSV full load displacement is given by:

$$\Delta = W_{LS} + DW$$

where Δ – full load displacement, t; W_{LS} – lightship weight, t; DW – deadweight, t.

The executed analysis of WFSV data built has showed that the main components of their deadweight are: the crew weight, the maintenance technicians weight, the weight of technician's equipment and the tools, the weight of fresh water, the weight of fuel, the weight of black water, the weight of deck cargo, the stores weight and the weight of TAS – Turbine Access System (in the presence).

That's why WFSV deadweight can be calculated by use of the following relation:

$$DW = W_{PL} + W_{FOil} + W_{CR} + W_{FW} + W_{GS} + \\ + W_{TE} + W_{BW} + W_{CRG} + W_{TAS}$$

where W_{PL} – maintenance technicians weight, t; W_{FOil} – fuel oil weight, t; W_{CR} – crew weight, t; W_{FW} – fresh water weight, t; W_{GS} – general stores weight, t; ; W_{TE} – weight of technician's equipment, t; W_{BW} – black water weight, t; W_{CRG} – deck cargo weight, t; W_{TAS} – Turbine Access System (TAS) weight, t.

The part of these components are the specified characteristics (deck cargo weight, TAS weight), and another part of them can be identified by use of the known relations of the ship design theory. That's why the formulas for their identification were not introduced at this paper. The main attention was directed into the identification of the lightship weight components.

To estimate the lightship weight of the vessel we can use the dependence shown in Figure 2 (Bondarenko, 2015).

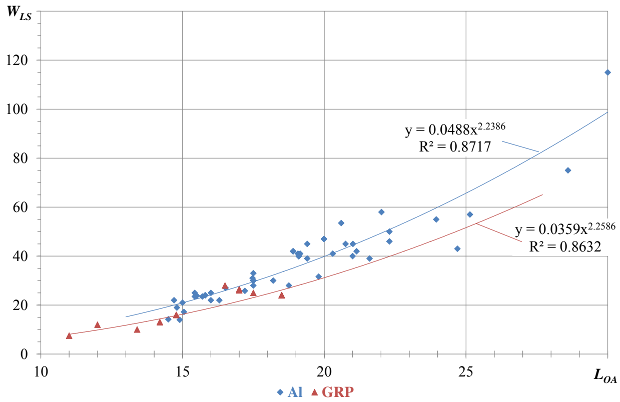

Figure 2: Relation of Lightship Weight of the Vessel (t) from L_{OA} (m) for Different Types of Materials

The lightship weight can be calculated by this formula in accordance with these articles (Grubisic, 2008), (Grubisic, 2005):

$$W_{LS} = W_{Hull} + W_M + W_{Out} + W_{SM}$$

where W_{Hull} – hull weight; W_M – machinery weight; W_{Out} – outfit weight; W_{SM} – margin.

3.2 HULL WEIGHT MODEL

The weight of the hull catamaran can be calculated like the sum of the hull structures and the superstructure weight

$$W_{Hull} = W_{Str} + W_{Sup}.$$

The weight of catamaran hull structures depends on the material and is calculated by use of the following formula:

$$W_{Str} = k_2\left(W_{100} + W_{TF}\right)$$

where k_2 – compensation for structural weight (welding, inserts, doublers, local stiffening). Is in range 1,05–1,125; $q_{al} = 4,2C_N^{0,3}$ – Specific stiffened plating weight; $C_N = L_{WL}\left(2B_X D_X + (S_X - B_X)H_C\right)$ – Cubic number for catamarans; $W_{100} = q_{al}S_R$ – stiffened plating weight; $W_{TF} = k_1 W_{100}$ – the weight of the transverse web framing of the hull.

The coefficient k_1 takes into account the weight of the transverse framing. WFSV hull construction has been researched for its identification. The transverse framing of one of the projects (figures 3 and 4) has been restored. The analogous researches have been executed for another WFSV projects. The values of k_1 are recommended to take in the range 0,25…0,30 as a result of these researches.

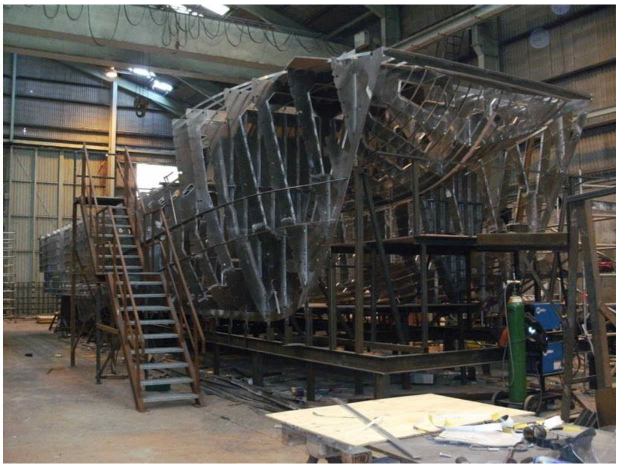

Figure 3: Framing System of WFSV

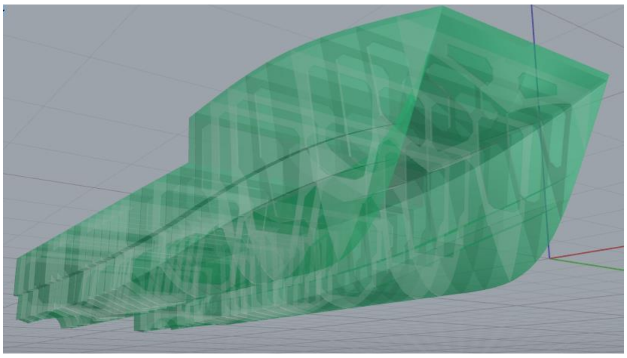

Figure 4: Computer Model of the Web Framing System WFSV

The calculation of the total reduced surface area S_R has been executed by the way of the identification of the surface area of the bottom S_1, sides S_2, decks S_3, bulkheads S_4 and cross bridge S_5 (Grubisic, 2005):

$$S_1 = 2\nabla_1^{1/3}\left(3,51\nabla_1^{1/3} + 0,568L_{WL}\right)\ (\text{m}^2)$$
$$S_2 = 2,1\left(L_{OA} + L_{WL}\right)\left(D - d\right)(\text{m}^2)$$
$$S_3 = 2,3L_{OA}B\ (\text{m}^2)$$
$$S_4 = 1,3N_{WTB}C_M B_X D\ (\text{m}^2)$$
$$S_5 = 0,92L_{WL}\left(S_X - 1,4B_X\right)\left(1,96 + H_C\right)\ (\text{m}^2)$$

where ∇_1 – demi-hull displacement volume (m^3); L_{WL} – length on waterline (m); L_{OA} – length overall (m); D_X – depth of catamaran at side (m); d_X – draft of demi-hull at DWL (m); B – beam overall (m); B_X – beam of the demi-hull at DWL (m); S_X – separation of demi-hulls centreline to centreline (m); H_C – cross bridge height (m); N_{WTB} – number of watertight bulkheads; C_M – coefficient of the maximal section.

From 3 up to 5 watertight bulkheads are provided for WFSV depending on the ship length and the type of propulsion.

The total reduced surface area S_R:

$$S_R = S_1 + 0,73S_2 + 0,71S_3 + 0,67S_4 + 0,81S_5.$$

The results of the comparative calculation of the areas in accordance with the specified formulas and the parametrical models of the hull are in the table 2.

The superstructure weight can be calculated in accordance with this formula:

$$W_{Sup} = q_{Sup}V_{Sup}\ (\text{t})$$

where q_{Sup} – specific weight of superstructure; V_{Sup} – superstructure volume, m^3.

The formula for the superstructure volume identification has been got by the way of 3D models construction of the most known WFSV (figure 5).

Table 2: Results of areas calculation.

Name	Pos.	Gardian	Rix Tiger
Bottom, m^2	S_1	123,69	109,98
Sides, m^2	S_2	124,67	98,11
Deck, m^2	S_3	294,40	293,60
Bulkheads, m^2	S_4	28,49	23,23
Bridge, m^2	S_5	59,21	85,55
Common, m^2	S_R	490,77	474,92
Real, m^2	S_R	484,658	478,08
Error, %		–1,26%	0,66%

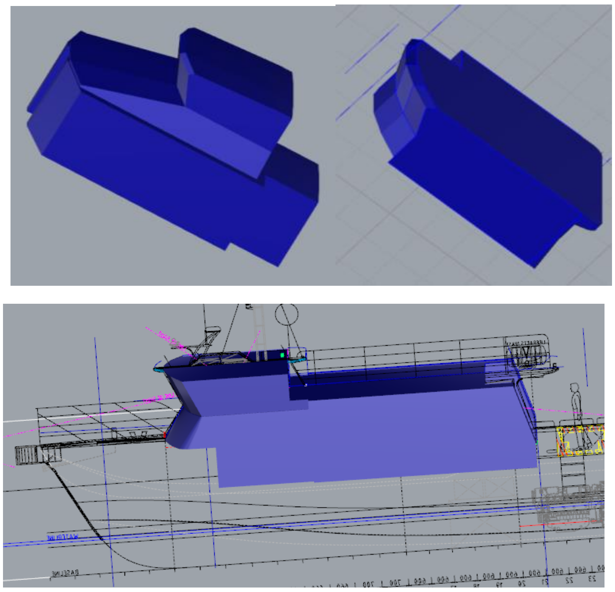

Figure 5: 3D Models of the Most Typical WFSV Superstructures

3.3 OUTFIT WEIGHT MODEL

Catamaran outfit weight, t (Karayannis *et al*., 1999):

$$W_{Out} = 0{,}03 L_{OA} B.$$

3.4 MACHINERY WEIGHT MODEL

The machinery weight is calculated by use of the formula

$$W_M = W_P + W_{RM}$$

where W_P – total propulsion weight: $W_P = W_D + W_{GB} + W_{WJ}$; W_D – main engine weight; W_{GB} – Gearboxes weight; W_{WJ} – waterjet or propeller weight; $W_{Rm} = 0{,}55 W_P$ – remaining machinery weight.

At the initial stages of design, the gearboxes weight is calculated by use of the following relation (Karayannis *et al*., 1999):

$$W_{GB} = 0{,}00348\ P^{0{,}75}\ \text{(t)}$$

where *P* – installed power of main engines, kW.

The executed analysis of the statistical data has showed that the gearboxes of ZF, Twin Disc, Reintjes, ServoGear Companies are used for WFSV. Unfortunately the information about the gearboxes of ServoGear Company has not be found. The data about the gearboxes of another companies are introduced at figure 6. The statistical data has the great dispersion at figure 6. The best way for the identification of the gearboxes weight is the catalogue use at the stage of the initial design although the formula has been got for the weight calculation for each producer of the gearboxes units depending on the power. This method has been developed at department of theory and ship design for design of another ship types mathematical models.

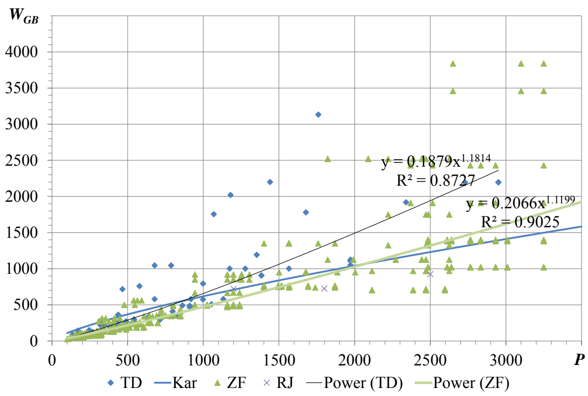

Figure 6: Main Engine Power (kW) Vs. Gearboxes Weight (kg)

The statistical analysis of data has shown that on WFSV the propellers and water jets are used but sometimes IPS are used too. The author has analysed the statistical data by use of the water jets weight, which are used on WFSV: Rolls-Royce Kamewa A3 series and FF series, HamiltonJet series HJ and HM, MJP series DRB, Ultra Dynamics (UltraJet). The results of analysis are shown at figures 7 and 8. At this graphic, the results of water jets weight are introduced by use of the formula (Karayannis *et al*., 1999):

$$W_{WJ} = 0{,}00018\ [P]^{1{,}18}\ \text{tonnes}$$

where *P* – installed power of main engines, kW.

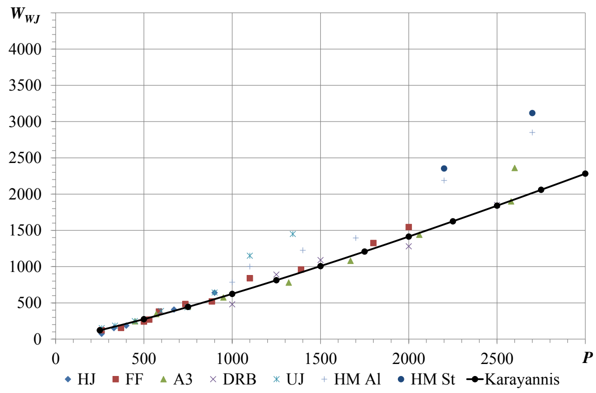

Figure 7: Main Engine Power (kW) Vs. "Dry" Weight of Waterjet (kg)

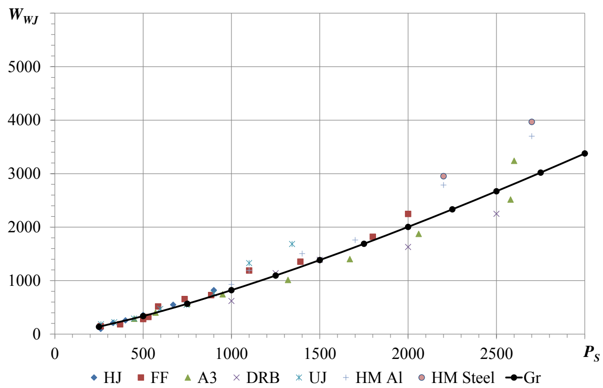

Figure 8: Main Engine Power (kW) Vs. Total Weight of Waterjet (kg) includes entrained Water

The formula (Karayannis *et al*., 1999) is the best for the identification of the «dry» weight water jets of Rolls-Royce Kamewa A3 series and FF series at figure 7. At the initial stages of WFSV design in the calculation of displacement need to know the total weight of water jets, or, with the "dry" weight to account for the presence of water in waterjets by deducting the volume of this water from the volumetric displacement of the hull.

The total weight of waterjets can be got by use of the formula (Grubisic, 2008)

$$W_{WJ} = \frac{P_S^{1{,}286}}{8771}\ \text{(t)}$$

or by use of the relation of the author.

$$W_{WJ} = 0{,}0725\ [P_S]^{1{,}3587}\ \text{(kg)}$$

where P_S – installed power of main engines, kW.

The catalogues of the producer's companies should be used for the most exact identification of water jets weight if it is necessary.

If on WFSV as propulsion are used propellers, that's why the following formula can be used for their weight calculation (Grubisic, 2008):

$$W_{FPP} = 1{,}1 D_P^3 \frac{A_E}{A_0}\ \text{(t)}$$

where D_p – propeller diameter, m; $\frac{A_E}{A_0}$ – Expanded Area Ratio.

Weight propulsion type IPS can be got by the formula:

$$W_{IPS} = 443{,}74 e^{0{,}0027P}\ \text{(kg)}$$

where P – main engines power, kW.

There are several formulas for the main engine weight identification. The author has analysed the statistical data of WFSV main engines. The engines are used on ships of the following companies: Caterpillar, Volvo Penta, Scania, MTU, MAN, Cummins, Yanmar, Deutz, Iveco, John Deere.

The data about the specified companies engines weight has been collected and the graphic of the engine weight from the power has been plotted (figure 9).

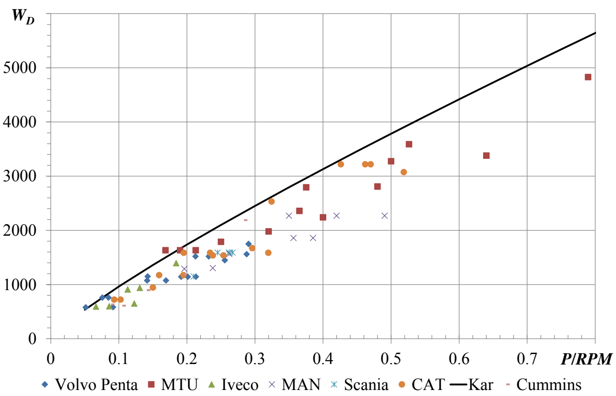

Figure 9: Statistical Data of Different Companies Engines Total Weight (kg)

The data of the engines weight has been plotted at figure 9, which have got by use of the formula (Karayannis *et al.*, 1999):

$$W_D = 6{,}82 \left(\frac{P}{RPM} \right)^{0{,}85}\ \text{(kg)}$$

where RPM – number of main engine revolutions, r/minute.

The relation for main engines weight calculation has been got by use of the statistical data processing (figure 10).

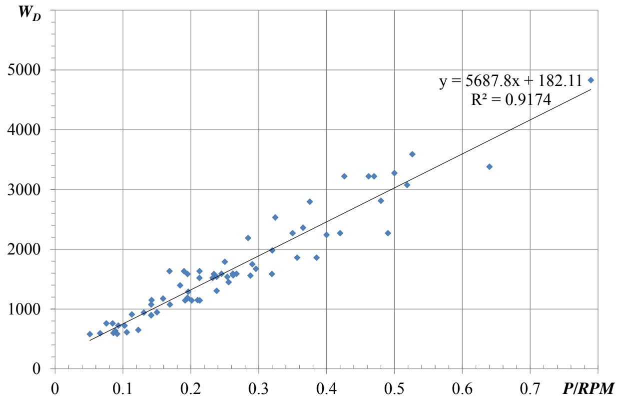

Figure 10: *P*/*RPM* Vs. Main Engine Weight (kg)

3.5 MARGINS

The margins of the displacement is considered in % from full load displacement at the initial stages of design

$$W_{SM} = 0{,}025\Delta, t.$$

4. VERIFICATION OF THE METHOD

The author has executed the set of the comparative calculations (table 3) which have showed the accepted for the initial stages error of calculations. It was executed for the assessment of the results adequacy, which have been got by use of the advised methodology.

Table 3: Results of comparative calculation of lightship weight of WFSV

Name	Gardian	Rix Tiger	Solway Challenger
Hull	15,72	15,59	17,17
Superstructure	3,55	5,82	3,55
Machinery	13,68	8,62	13,96
Outfit	5,12	5,11	6,11
Margin	1,33	1,08	1,58
Lightship calc.	39,40	36,22	42,37
Lightship real.	39,00	37,50	38,40
Error, %	1,04%	3,42%	10,33%

Table 3: Results of comparative calculation of lightship weight of WFSV

Name	Marianarray	Spirit of Sunthorp
Hull	11,91	10,80
Superstructure	2,37	3,62

Machinery	11,24	11,88
Outfit	4,38	4,41
Margin	1,05	1,18
Lightship calc.	30,95	31,88
Lightship real.	28,00	34,50
Error, %	10,54%	7,59%

Table 3: Results of comparative calculation of lightship weight of WFSV

Name	Dalby Swale	Spirit of Turmarr	OW 5
Hull	19,23	4,72	9,81
Superstructure	4,72	1,44	2,06
Machinery	13,39	5,20	6,90
Outfit	6,18	2,16	4,29
Margin	1,75	0,50	0,68
Lightship calc.	45,27	14,03	23,74
Lightship real.	41,82	15,60	22,00
Error, %	8,25%	10,09%	7,90%

Table 3: Results of comparative calculation of lightship weight of WFSV

Name	Xplorer	Iceni Venture	Wind Transfer
Hull	7,11	28,30	18,78
Superstructure	1,35	5,07	3,04
Machinery	4,67	15,61	9,45
Outfit	3,08	7,05	5,77
Margin	0,47	1,88	1,25
Lightship calc.	16,67	57,90	38,28
Lightship real.	17,20	58,75	40,00
Error, %	3,07%	1,44%	4,31%

5. CONCLUSIONS

Thus, as a result of the conducted research, an algorithm and formulas for the determination of WFSV displacement components at the initial stages of design are proposed. In this algorithm, hull weight of the vessel is determined by the surface area of the main structural elements using the parametric 3D model of the hull surface. The weight and volume of superstructures are calculated according to the formulas obtained by constructing 3D models of the superstructures of the most common WFSV projects. The dependencies for determining the engines weight, gearboxes and waterjets are obtained by statistical data processing.

The proposed method of calculating the vessels displacement components provides acceptable results for the initial stages of designing. The biggest error of calculations does not exceed 11 % (table 3).

The obtained dependences can be used in mathematical models for determining the design characteristics of wind farm service vessel.

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