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The modeling of seakeeping qualities of Floating Production, Storage and Offloading (FPSO) sea-going ships in preliminary design stage

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ABSTRACT

This paper presents an analysis of a presently applied approach to accounting for seakeeping qualities of FPSO sea-going ships and possible using it in preliminary design stage. Approximations of heaving, pitching, green water ingress on the deck and slamming of FPSO ships, based on main ship design and wave parameters, are presented. The approximations were elaborated with the use of the linear regression method and theory of artificial neural networks for a very wide range of FPSO ship dimensions and hull forms. In the investigations ship operational conditions were limited to those occurring in real service of FPSO ships, described by means of the so called operational scenario. Such approach made it possible to reach simultaneously high approximation accuracy and simple structure of mathematical model.

Keywords: Floating Production; Storage and Offloading (FPSO) unit; offshore; design; preliminary design stage; seakeeping qualities; green water ingress on the deck; slamming; heaving; pitching; main ship hull dimensions

INTRODUCTION

In [10] a classification of transport ships with accounting for their seakeeping qualities has been proposed. According to it transport ships can be split into the following groups [10]:

- ships which are to fulfil their mission irrespective of weather conditions,
- ships of design features which increase their susceptibility to weather conditions,
- passenger carrying ships,
- transport ships for which seakeeping qualities are only one of their limitations.

For each of the groups crucial seakeeping qualities can be determined and on their basis a type of ship which represents a given group can be selected. In [10] attention has been focussed on the group of passenger carrying ships, and design guidelines which account for selected seakeeping qualities possible to be applied in the preliminary design stage of car passenger ferries, have be described.

However in this publication was considered only the group of ships which are to fulfil their mission irrespective to weather conditions, that constitute characteristic feature of the group of ships.

The following kinds of ships can be numbered among the group in question:

1. naval ships (surface ones),
2. sea bed mining industry units such as:
   a. FPSO (Floating Production, Storage and Offloading) units,
   b. FSO (Floating Storage and Offloading) units,
   c. underwater pipe laying ships,
   d. auxiliary servicing ships,
3. research ships,
4. servicing ships:
   a. floating bases,
   b. rescue ships,
5. fishing ships:
   a. fish factory trawlers.

From the point of view of design problems ships of the group are to be characterized by suitable seakeeping qualities in heavy weather and such operational conditions in which the ships have to operate.

The design problems of the group of ships result from functions assigned to them, and seakeeping qualities are only technical limitations to be satisfied by them. From the point of view of modeling seakeeping qualities the crucial problem for ships of the kind is:

- to minimize ship hull vertical motions,
- to minimize rolling motions.

Out of all oscillating motions of ships of the kind, pitching and heaving is first of all controlled since the motions are main cause of ship hull vertical motions.

The necessity of limiting the ship hull vertical motions results from other detrimental phenomena accompanying them, among which the following can be numbered:

1. green water ingress on the deck, causing failure to deck gear,
2. slamming - causing failure to hull bottom elements and generating ship hull shocks and vibrations,
3. accelerations which have influence on:
   - worsened operational effectiveness of devices on the deck (helicopter, production equipment, cranes, sounds, drilling rigs etc),
   - ship weapon systems,
   - operation of weapon monitoring and control systems,
   - underwater operations, e.g. lowering the diving bell,
4. sea-sickness of crew members.

Moreover for some ships of the group, rolling motions which may cause worsening operational effectiveness of certain shipboard devices (helicopter, deck gear etc) are of importance.

For all ships of the group seakeeping qualities usually constitute only a design limitation, however for naval and FPSO ships the qualities are an important design problem. For such ships, in accordance with [36], wave intensity is classified with a view of possibility of fulfiling selected functions of the ships.

For naval ships three levels of sea wave conditions are defined [36]:

1. the conditions in which the ship is capable of operating with ultimate effectiveness at maximum speed,
2. heavy weather conditions in which reduction of ship speed occurs but helicopter landing pad and weapon systems are still capable of operating,
3. the conditions in which the ship should only to survive.

And, for FPSO ships two levels of sea wave conditions are defined [36]:

1. the conditions in which operation (production) is possible,
2. the conditions in which operation is not possible (production is stopped).

From the point of view of ship design problems this is FPSO ship which represents the group of ships.

SEAKEEPING QUALITIES OF FPSO SHIPS

FPSO ships are to operate in arbitrary environmental conditions without possibility of avoidance of storm zone and to be towed for repair. Therefore FPSO ships are required to have a.o. good seakeeping qualities that favourably influence the following [34]:

- crew comfort and safety,
- operational efectiveness of production systems,
- operational effectiveness of process of reloading to shuttle tanker,
- possibility of using helicopter.

Out of all seakeeping qualities important for the considered group of ships the following may be numbered among the crucial ones for FPSO ships:

- pitching and heaving,
- slamming,
- green water ingress on the deck.

Factors conductive to ocurrence of such phenomena are first of all the following:

- large vertical motions resulting from ship length and unfavourable angle of wave encounter with ship,
- continuously changeable draught and trim of FPSO ship,
- heavy weather conditions.

Formal requirements for designing FPSO ships concern first of all problems associated with their construction and are formulated in [34]:

- NORSOK standards (initiated by Norwegian mining industry), first of all NORSOK Standard N-004: *Design of Steel Structures* [29],
- ISO /WD 19904 Standard: *Offshore Structures - Floating Systems*,
- rules of the classification institutions:
  - Lloyds Register of Shipping (LR): *Rules and Regulations for the Classification of a Floating Installation at a Fixed Location*, July 1999 [25],
  - American Bureau of Shipping: *Guide for Building and Classing Facilities on Offshore Installations*, June 2000 [1]
  - Det Norske Veritas (DNV): *Offshore 2000 Rules for Classification of Floating Production and Storage Units*, OSS -102, January 2001 [13].

The above mentioned requirements are compared to each other in the report [22]. The classification rules which deal with the accounting for seakeeping qualities are very general and do not make it possible to take into account sea wave conditions. As results a. o. from the report [30] the formal design reccommendations dealing with green water ingress on the deck and slamming on FPSO ships are not sufficient.

Data and research results on modeling seakeeping qualities of FPSO ships are very scarce. The research results given in [4, 5, 6, 9, 3, 15, 18, 19, 20, 21, 22, 26, 27, 28, 31, 32, 34, 37, 38, 39] cover only a small group of ships and deal first of all with influence of form of selected hull parts of FPSO ships on a given phenomenon.

The classification institutions reccommend to determine seakeeping qualities of FPSO ships on the basis of model tests [1, 13, 25, 34]. If to perform such tests is not possible the institutions propose to apply simplified methods to calculation of selected seakeeping qualities.

Informal design reccommendations are limited first of all to performing the tests on slamming and green water ingress on the deck for a given ship. In the tests a relation is searched for between waving, ship's hull form parameters and e.g. freeboard height and loads resulting from slamming or green water ingress on the deck. Results of the tests do not take into account impact of general geometrical parameters on the phenomena hence they cannot be accounted for in the preliminary stage of ship design.

On the basis of [4, 5, 6, 9, 3, 15, 18, 19, 20, 21, 22, 26, 27, 28, 31, 32, 34, 37, 38, 39] it can be stated that the performed research investigations and formal design reccommendations (given in the classification rules):

- can be used for modeling FPSO ship's hull form and construction in the design stage when ship's dimensions and general hull form (its over and under water parts) have been already determined,
- are not applicable in the preliminary design stage,
- only partly take into account operational conditions in which ship operates (sea waving, motion parameters),

- do not make it possible to predict occurrence probability or frequency of a given phenomenon depending on main ship design parameters and wave parameters occurring in a given water area in heavy weather conditions.

There is a particularly scarce amount of information (or even lack of it) on guidelines concerning calculations of occurrence frequency of green water ingress on the deck and excessive slamming.

The existing design guidelines make it possible to calculate only natural heave and pitch frequencies and to estimate on the basis seakeeping qualities of FPSO ship sailing in a given water area.

AIM OF THE INVESTIGATIONS

The investigations in question have been aimed at elaboration of novel methods of modeling seakeeping qualities of FPSO sea-going ships in the preliminary design stage, i.e. elaboration of approximation functions of:

1. significant amplitudes of heave and pitch motions and occurrence probability of bow slamming and green water ingress on the deck fore on the basis of design parameters avaliable in the preliminary (parametrical) design stage, and sea wave parameters as well,
2. characteristic wave periods at which maximum significant amplitudes of heave and pitch motions as well as occurrence frequencies of slamming and green water ingress on the deck occur depending on FPSO ship's design parameters available in the preliminary design stage, under assumed ship operation conditions.

It was assumed that the above mentioned aim will be reached by analyzing results obtained from numerical calculations of ship motions in waves in conventional operational conditions described by means of operational scenarios. In order to make it possible a supplementary aim of the research, consisting in determination of an appropriate operational scenario for FPSO ship, has been formulated.

RESEARCH METHOD

The general research method covered the following items (Fig. 1):

1. Elaboration of model ship hull variants covering a wide range of their forms and dimensions,
2. Elaboration of operational scenarios describing the most characteristic operational conditions of the ships in service,
3. Simplification of a physical model and its parametrization,
4. Calculation of model values of seakeeping qualities by using numerical methods based on the plane flow hypothesis,
5. Choice of approximation functions for the set of discrete results from numerical model,
6. Verification and assessment of definite modeling methods,
7. Determination of applicability range and limitations for particular models.

OPERATIONAL SCENARIO

The following operational scenario was assumed in the investigations:

A FPSO ship stays on oil field in storm conditions and production process is under way on it (the ship's draught is permanently changing).

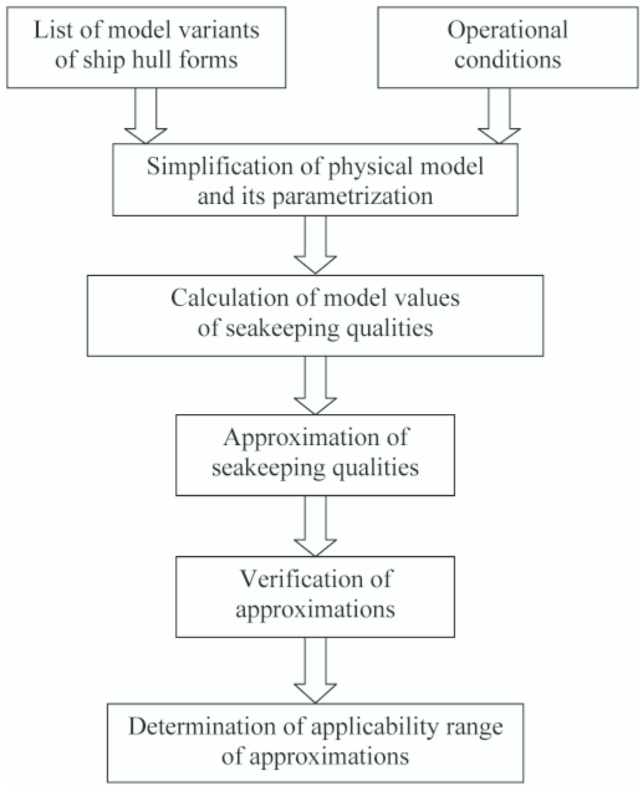

Fig. 1. *General algorithm of modeling ship seakeeping qualities*

Because of possible change in course angle the ship heads the wave (180^o wave encounter angle). In such position influence of waves on loads exerted to mooring system and mining installation is the smallest.

The occurring sea waves is not fully developed and can be desrcibed by means of the JONSWAP wave spectrum of the highest amplification factor. The wave complies with the so called design wave conditions decribed in [29]. The wave is of the most unfavourable characteristic period and generates maximum values of heave and pitch motions, slamming and green water ingress on the deck fore.

The above defined scenario can be described by the following parameters:

- ship speed: v = 0 m/s,
- wave encounter angle: $\beta = 180^o$ (head wave),
- wave spectrum: JONSWAP with amplification factor: $\gamma = 3.3$,
- significant wave height $H_s = 12 \div 17$ m,
- characteristic wave period generating maximum values of heave and pitch motions, slamming and green water ingress on the deck fore,
- ship draught $d = ¼\ d_{max} \div d_{max}$, every ¼ d_{max}.

The model values of seakeeping qualities were calculated by means of numerical methods and the SEAWAY software based on the plane flow theory. To calculate hydrodynamical coeffcients the method described in [16] was applied. The accuracy tests of the SEAWAY software presented in the report [23] show high accuracy of calculations made with its help.

To approximate maximum significant amplitudes or occurrence frequencies of assumed seakeeping qualities the following set of explicating variables was assumed; it was consisted of:

- ship hull design parameters within a wide range of its dimensions,
- wave parameters resulting from the assumed operational scenario.

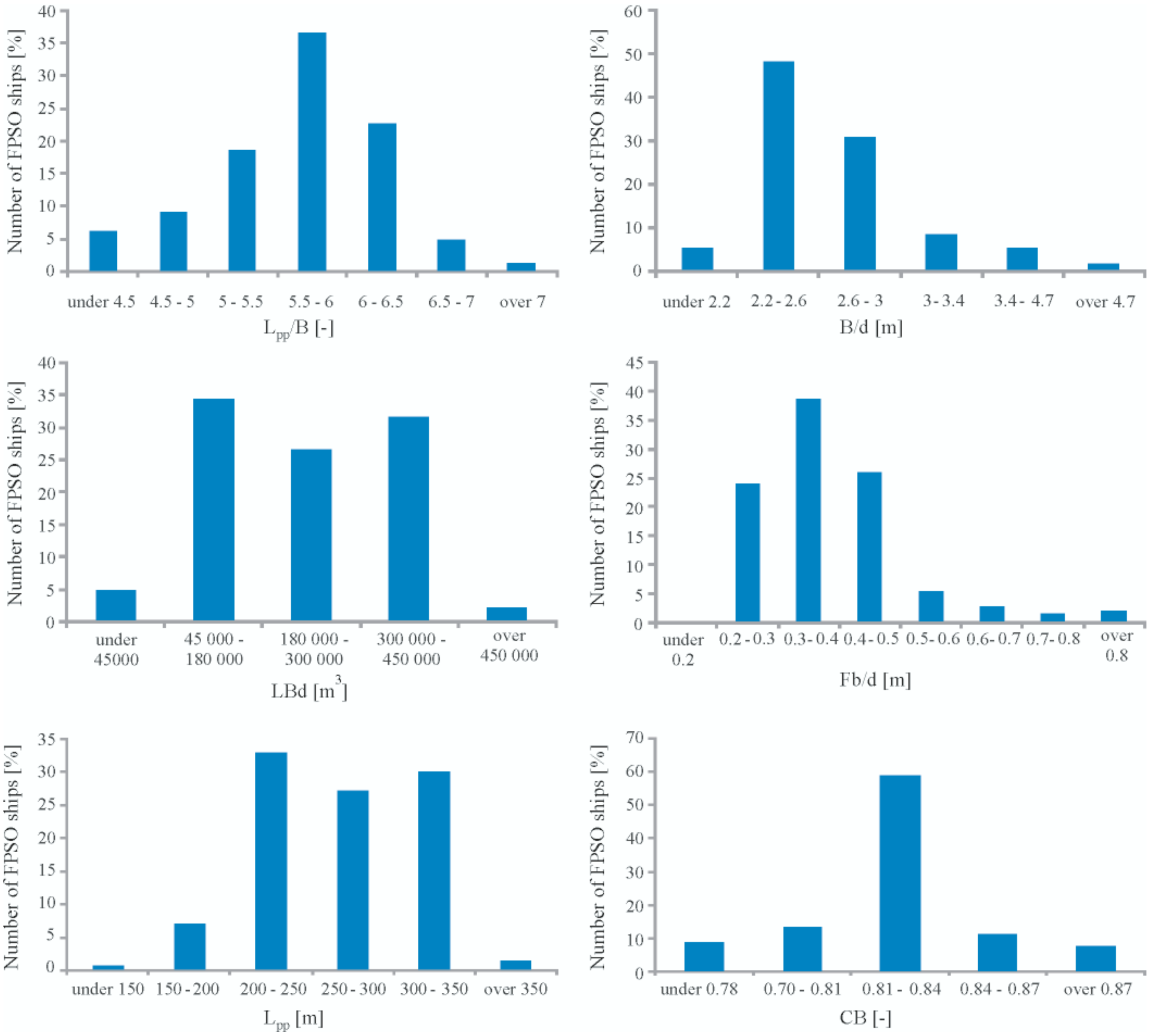

Fig. 2. *Percentage number of new-built FPSO ships depending on the hull block coefficient CB[2], length between perpendiculars L_{pp}, freeboard height – ship draught ratio Fb/d, volume LBd, ship breadth – draught ratio B/d, ship length b.p. – breadth ratio Lpp/B, respectively*

SHIP HULL DESIGN PARAMETERS

In Fig. 2 are presented histograms of percentage amounts of new-built FPSO ships of determined geometrical parameters, elaborated with the use of the Lloyd Register[1] data base. The histograms concern only FPSO ships under building, i.e. in the design, production or operational stage.

In the modeling of seakeeping qualities the following ranges for hull geometrical parameters were assumed in accordance with Fig. 2:

- for LBd volume = 45 000, 176 667, 308 333, 440 000 m^3,
- for L/B ratio = 4, 5, 6, 7,
- for B/d ratio = 2.18, 3.02, 3.86, 4.7.

Also, the hull forms typical for FPSO ship, characterized by the block coefficient values in the range CB = 0.81 ÷ 0.87, were assumed. The hull forms are presented in Fig. 3, and the general hull form coefficients - in Tab. 1.

Tab. 1. *Hull form variants of FPSO ship, where:* ***CB*** *– block coefficient of hull underwater part,* ***$CB_{(L)}$*** *– longitudinal prismatic coefficient of hull underwater part,* ***$CB_{(V)}$*** *– vertical prismatic coefficient of hull underwater part,* ***CWL*** *– waterplane coefficient,* ***XF*** *– distance from waterplane geometrical centre to aft perpendicular, related to ship length b.p.,* ***XB*** *– distance from buoyancy centre to aft perpendicula, r related to ship length b.p.,* ***WC*** *– percentage length of midship body, related to ship length b.p.,* ***CBA*** *– block coefficient of hull aft underwater part,* ***CBF*** *– block coefficient of fore underwater part*

Variant No.	CBA [-]	CBF [-]	WC [%]	CWL [-]	XF [%]	CB [-]	XB [%]	$CB_{(L)}$ [-]	$CB_{(V)}$ [-]
1	0.73	0.78	35	0.91	50.3	0.83	52.5	0.84	0.92
2	0.74	0.73	55	0.93	46.9	0.87	49.2	0.88	0.94
3	0.74	0.50	55	0.88	44.1	0.81	46.4	0.82	0.93

[1) 2)] www.sea-web.com, Lloyds Register of Shipping: Sea-web's Ships Database

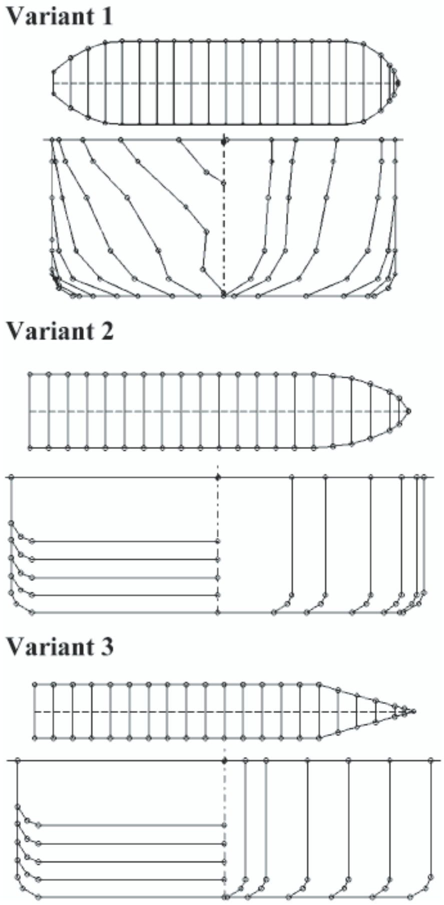

Fig. 3. Variants of FPSO ship's hull form

As results from subject-matter literature, the freeboard height F_b greatly influences intensity of green water ingress on the deck. Therefore it has been decided to examine the freeboard influence on green water ingress on the deck for the wide range of the freeboard height – ship draught ratio: F_b/d = 0.25, 0.5, 0.75, 1.0, 1.5.

A specially characteristic feature of FPSO ships is permanently changeable loading state resulting first of all from changeable mass of loads and ballast in consequence of conducted production and reloading processes. This generates changes in buoyancy, draught, trim and hydrostatic parameters of ship's hull.

Since the assumed seakeeping qualities are first of all influenced by ship draught, only mean draught change was taken into account out of all parameters which describe ship loading state. Change in the mean draught d was expressed in the form of its relation to the design draught d_k: d/d_k = 0.25, 0.5, 0.75.

Change in draught affects change in freeboard height.

On the basis of the above given assumptions was elaborated a set of 192 variants of forms and dimensions of underwater hull part, for which hull body lines were designed. For each of the hull variants four loading states described by mean draught values and five additional variants accounting for the effect of the freeboard height – ship draught ratio, were prepared.

WAVE PARAMETERS

To calculate the model seakeeping qualities the following wave parameters resulting from the assumed operational scenario, were taken:

- JONSWAP wave spectrum, and amplification factor γ = 3.3,
- values of the significant wave height H_s = 12, 15, 17 m,
- values of the characteristic wave period T_1 in the range from 2 to 20 s, every 0,5 s.

In the operational scenario it was assumed to account for occurrence of maximum values of seakeeping qualities depending on characteristic wave period. In consequence of such assumption the characteristic wave period has been eliminated from the set of explicating variables. Hence to approximate significant amplitudes and occurrence frequencies of the assumed seakeeping qualities only the significant wave height H_s was selected out of all the wave parameters.

ELABORATION OF APPROXIMATION FUNCTIONS FOR THE ASSUMED SEAKEEPING QUALITIES OF FPSO SHIPS AND ASSESSMENT OF THEIR ACCURACY

By making use of statistical methods and the theory of artificial neural networks a set of approximation functions was elaborated for the assumed seakeeping qualities of FPSO ships. At first approximations were searched for in the form of analytical functions elaborated with the use of linear regression in the domain of functions of the simplest forms. In the case when an elaborated model has appeared too little accurate analytical relationships were searched for by using the theory of artificial neural networks. As results from the investigations the approximations of heaving, pitching and occurrence frequencies of green water ingress on the deck fore, elaborated with the use of linear regression were rather accurate. Consequently was elaborated a set of analytical relationships which make it possible to approximate the following quantities:

- the maximum significant heave amplitudes:

$$z_{1/3\max} = H_S\left(0.668 - 1.71\cdot 10^{-6}\cdot\ L_{pp}{}^2 + \right. \left. + 1.8\cdot 10^{-9}\cdot\ L_{pp}{}^3 + 0.001\cdot d - \frac{0.23}{CBF^2} + \frac{0.09}{CBF^3}\right) \tag{1}$$

where:

$x_{1/3\max}$ – maximum significant heave amplitudes [m],
H_S – significant wave height [m],
L_{pp} – ship length between perpendiculars [m],
d – ship draught [m],
CBF – block coeffcient of fore part of underwater hull [-],

- the maximum significant pitch amplitudes:

$$\Psi_{1/3\max} = H_S\left(0.007 + \frac{136.3}{L_{pp}} - 15.09\frac{CBF}{d} + \right. \left. + 11.28\frac{CBF^2}{d} + 0.09\frac{L_{pp}}{d^2}\right) \tag{2}$$

where:

$\Psi_{1/3\max}$ – maximum significant pitch amplitudes [°].

- the maximum occurrence frequency of green water ingress on the deck fore:

$$n_{zp.max} = \exp\left[6.71 + \left(-0.122 - \frac{19.3}{H_s{}^2}\right)\cdot Fb\right] \tag{3}$$

where:

$n_{zp.max}$ – maximum occurrence frequency of green water ingress on the deck fore per one hour [l/h],
Fb – freeboard height at bow [m],
H_S – significant wave height [m].

In Tab. 2 are presented selected statistical parameters describing the above given relationships, and in Fig. 4 through 7 – the approximations are compared with the model values. As results from the above given data the elaborated approximations are very accurate. The seakeeping qualities described by the relationships (1) and (2) are greatly influenced by the ship length between perpendiculars, L_{pp}, and significant wave height H_s. Hence they were simplified to the following form:

$$z_{1/3max} = H_S\left(0.47 - 8.33 \cdot 10^{-7} \cdot L_{pp}^{2}\right) \qquad (4)$$

$$\Psi_{1/3max} = H_S\left(-0.043 + \frac{92.15}{L_{pp}}\right) \qquad (5)$$

In Tab. 2 are presented selected statistical parameters decribing the above given relationships, and in Fig. 4 through 8 the approximations are compared with the model values. The approximations (4) and (5) are characterized by a lower accuracy as compared with the approximations (1) and (2), but they are based only on the significant wave height and ship's length between perpendiculars.

And, the approximation (3) is characterized by a high correlation, but large values of the frequency of green water ingess on the deck produce a relatively large value of estimation standard error. To solve the problem was elaborated an artificial neural network which predicts occurrence probability of green water ingress on the deck, expressed in the form of the two-state variable Ω_n of the two values:

- „1" – assigned when the occurrence probability of green water ingress on the deck exceeds its dangerous threshold equal to 0.05 (acc. the recommendations given in [24]),
- „2" – assigned when the occurrence probability of green water ingress on the deck does not exceed its dangerous threshold equal to 0.05.

The above described network is presented graphically in Fig. 12c, and analytically expressed by means of the following relationship:

$$\Omega_{zp} = \frac{1}{1+e^{-\left(\left(\left[Fb.\ \frac{100 \cdot Fb}{d}.\ L_{pp}.\ C_B.\ H_S\right] \times S + P\right) \times A - B\right)}} \times$$

$$\times C + 0.05 \qquad (6)$$

where:

Ω_{zp} – two-state nominal variable which describes occurrence probability of green water ingress on the deck: „1" – if the green water ingress on the deck exceeds its dangerous threshold, and „2" – if it does not exceed its dangerous threshold,

d – ship draught [m],

C_B – block coefficent of hull underwater part,

A – matrix of weighing factors:

$$\begin{bmatrix} 0.616 & 13.521 & -19.178 & -18.131 & 16.863 \\ 4.472 & -0.799 & 3.924 & -0.412 & 2.459 \\ 3.038 & -0.144 & 4.114 & -4.835 & -1.001 \\ -1.695 & -9.208 & 6.682 & 2.450 & 0.476 \\ -1.684 & -2.051 & 0.956 & 2.240 & -4.404 \end{bmatrix}$$

S – matrix of coefficients:

$$\begin{bmatrix} 0.024 & 0 & 0 & 0 & 0 \\ 0 & 0.008 & 0 & 0 & 0 \\ 0 & 0 & 0.003 & 0 & 0 \\ 0 & 0 & 0 & 5.931 & 0 \\ 0 & 0 & 0 & 0 & 0.200 \end{bmatrix}$$

B – vector of threshold values:
[1.956 -3.126 7.385 -5.794 5.793],

C – column vector of weighing factors:
[7.772 -12.540 -14.094 -11.717 6.419],

P – vector of displacement values:
[-0.010 -0.198 -0.332 -4.201 -2.400].

The classifying statistics presented in Tab. 3 indicate that the network is of very high capability of predicting.

Tab. 2. *Statistical parameters of the elaborated relationships, where: $z_{1/3\,max}$ – maximum significant heave amplitude, $\Psi_{1/3\,max}$ – maximum significant pitch amplitude, $n_{zp.max}$ – maximum occurrence frequency of green water ingress on the deck, per one hour*

Parameter	No. of equation	Determination coefficient R^2	Estimation standard error
$z_{1/3\,max}$	(1)	0.98	0.07 [m]
$\Psi_{1/3\,max}$	(2)	0.92	0.51 [°]
$n_{zp.max}$	(3)	0.98	31 [l/h]
$z_{1/3\,max}$	(4)	0.94	0.12 [m]
$\Psi_{1/3\,max}$	(5)	0.84	0.69 [°]

Tab. 3. *Statistics for artificial neural network classification problems in predicting the function values Ω_{zp}*

Number of	Teaching set		Validating set		Testing set	
	$\Omega_{zp}=1$	$\Omega_{zp}=2$	$\Omega_{zp}=1$	$\Omega_{zp}=2$	$\Omega_{zp}=1$	$\Omega_{zp}=2$
Total	7280	720	1616	144	1614	146
correct cases	7026	694	1567	141	1564	141
erroneous cases	254	26	49	3	50	5
Erroneous cases [%]	3.49	3.61	3.03	2.08	3.10	3.42

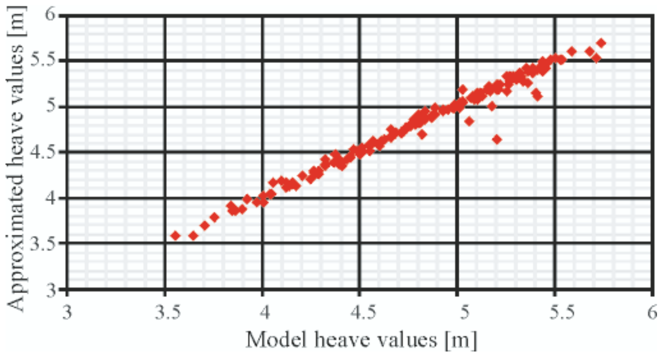

Fig. 4. *Comparison of approximations of maximum significant heave amplitudes calculated by using Eq. 1, with their model values, for the significant wave height Hs = 12 m*

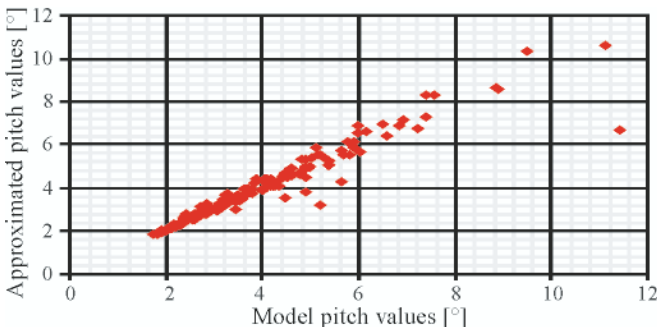

Fig. 5. *Comparison of approximations of maximum significant pitch amplitudes calculated by using Eq. 2, with their model values, for the significant wave height Hs = 12 m*

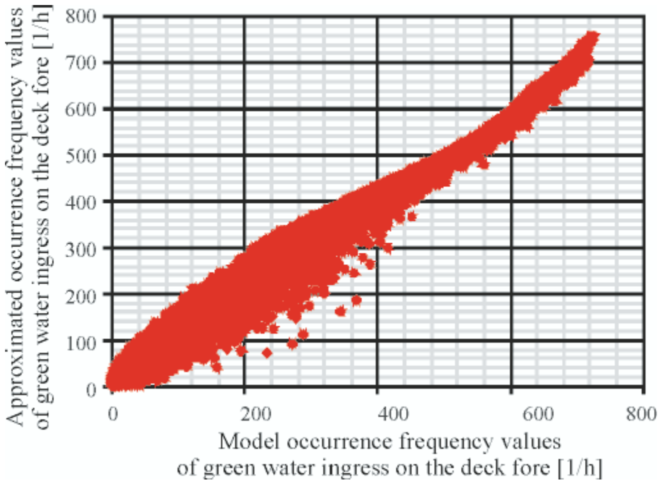

Fig. 6. *Comparison of maximum occurrence frequencies of green water ingress on the deck fore with their model values*

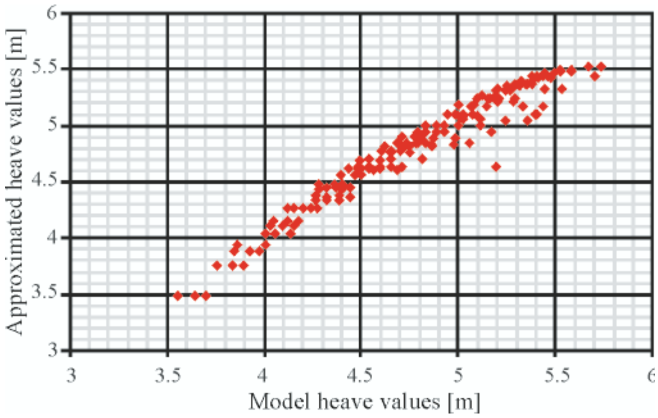

Fig. 7. *Comparison of approximations of maximum significant heave amplitudes calculated by using Eq. 4, with their model values, for the significant wave height Hs = 12 m*

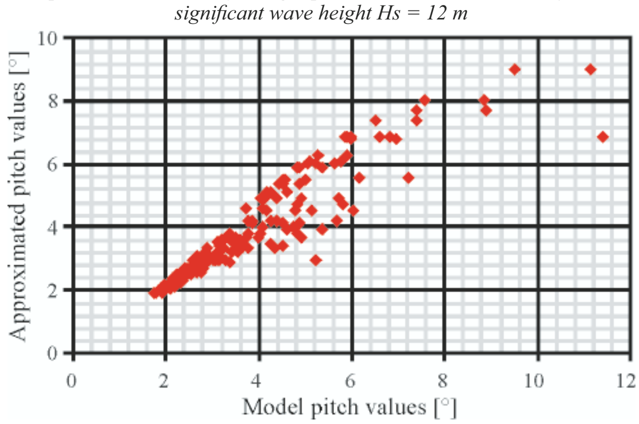

Fig. 8. *Comparison of approximations of maximum significant pitch amplitudes calculated by using Eq. 5, with their model values, for the significant wave height Hs = 12 m*

The approximations of:

- slamming occurrence frequencies,
- characteristic wave period at which maximum frequency of green water ingress on the deck occurs,
- characteristic wave period at which maximum slamming frequency occurs, elaborated by using the linear regression method, appeared not sufficiently accurate.

Just the use of the theory of artificial neural networks enabled to solve the problem. As a result of the investigations were elaborated the artificial neural networks of multi-layer perceptron structure, which made it possible to approximate:

- maximum occurrence frequencies of bow slamming:

$$n_{sl.max} = \tag{7}$$

$$= H_S \cdot \frac{\dfrac{1}{1+e^{-\left(\left([d.\ \ CBF.\ \ L_{pp}]\times S+P\right)\times A-B\right)}} \times C + 0.009}{3.72 \cdot 10^{-3}}$$

where:

$n_{sl.max}$ – maximum occurrence frequency of bow slamming per one hour [l/h],

CBF – block coefficient of hull fore underwater part,

A – matrix of weighing factors values:

$$\begin{bmatrix} -0.489 & -1.994 & -4.747 \\ 0.180 & 7.268 & -4.653 \\ -6.218 & -8.546 & -7.206 \end{bmatrix}$$

S – matrix of coefficients:

$$\begin{bmatrix} 0.046 & 0 & 0 \\ 0 & 3.571 & 0 \\ 0 & 0 & 0.003 \end{bmatrix}$$

B – vector of threshold values:

[1.542 7.755 0.385]

C – column vector of weighing factors values:

[-1.268 5.999 4.581]

P – vector of displacement values:

[-0.324 -1.786 -0.390]

- characteristic wave period at which maximum frequency of green water ingress on the deck fore occurs:

$$T_{nzp} = \tag{8}$$

$$= 10.5\left(\frac{1}{1+e^{-\left(\left(\left[WC.\ \ L_{pp}.\ \ \frac{XF\cdot 100}{L_{pp}}.\ \ CB.\ \ CM.\ \ GM_L\right]\times S+P\right)\times A-B\right)}} \times C - 0.379\right)$$

where:

T_{nzp} – characteristic wave period at which maximum frequency of green water ingress on the deck occurs [s],

CB – block coefficient of hull underwater part [-],

CM – midship section coefficient [-],

GM_L – initial longitudinal metacentric height [m],

XF – abscissa of logitudinal centre of floatation relative to aft perpendicular [m],

A – matrix of weighing factors values:

$$\begin{bmatrix} 0.650 & -0.632 & -0.506 & 0.650 & -0.632 & -0.506 \\ -0.076 & 2.127 & 0.894 & -0.076 & 2.127 & 0.894 \\ -0.428 & 1.090 & 0.964 & -0.428 & 1.090 & 0.964 \\ -0.270 & -0.799 & -1.208 & -0.270 & -0.799 & -1.208 \end{bmatrix}$$

S – matrix of coeffcients:

$$\begin{bmatrix} 0.005 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.003 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.106 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5.931 & 0 & 0 \\ 0 & 0 & 0 & 0 & 54.945 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.26\ 10^{-4} \end{bmatrix}$$

B – vector of threshold values:
[-1.435 0.467 -0.378]
C – column vector of weighing factors values:
[2.260 2.510 -2.920]
P – vector of displacement values:
[-0.189 -0.332 -4.689 -4.201 -53.670 -0.024].

- characteristic wave period at which maximum slamming frequency occurs:

$$T_{nsl} = 8.5\left(\frac{1}{1+e^{-\left(\left(\left[L_{pp}.\ B.\ \frac{XF\cdot 100}{L_{pp}}.\ CM.\ BM_L\right]\times S+P\right)\times A-B\right)}}\times C + 0.795\right) \quad (9)$$

where:
T_{nsl} – characteristic wave period at which maximum slamming frequency occurs [s],
BM_L – longitudinal metacentric radius [m],

A – matrix of weighing factors values:

$$\begin{bmatrix} 1.328 & -1.701 & 0.452 & 1.311 & 1.328 \\ 0.483 & 1.538 & -1.757 & -0.836 & 0.483 \\ 1.002 & 1.360 & 2.847 & 3.509 & 1.002 \\ -5.255 & 1.152 & 2.192 & 2.470 & -5.255 \\ -3.132 & -1.427 & 7.693 & 4.662 & -3.132 \end{bmatrix}$$

S – matrix of coefficients:

$$\begin{bmatrix} 0.0029 & 0 & 0 & 0 & 0 \\ 0 & 0.018 & 0 & 0 & 0 \\ 0 & 0 & 0.106 & 0 & 0 \\ 0 & 0 & 0 & 54.645 & 0 \\ 0 & 0 & 0 & 0 & 2.65\ 10^{-4} \end{bmatrix}$$

B – vector of threshold values:
[3.012 3.507 2.824 2.641],
C – column vector of weighing factors values:
[-1.950 -2.366 -2.464 2.335],
P – vector of displacement values:
[-0.332 -0.429 -4.688 -53.372 -0.021].

Structures of the above given networks are presented in Fig. 12, statistical parameters - in Tab. 4, and in Fig. 9 though 11 – comparison of the approximated values with the relevant model values. As results from the above specified data the elaborated approximations are of simple structure and very good accuracy, simultaneously.

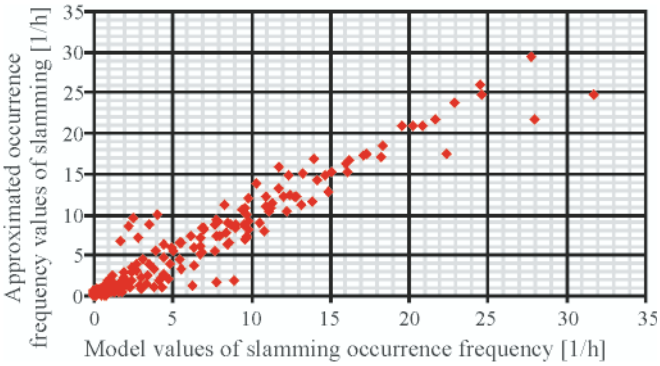

Fig. 9. *Comparison of approximations of maximum occurrence frequencies of slamming with their model values, for Hs = 12 m*

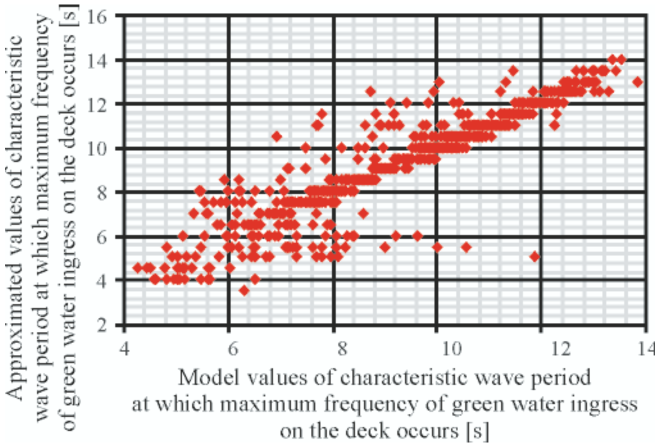

Fig. 10. *Comparison of approximations of characteristic wave period at which maximum frequency of green water ingress on the deck occurs, with their model values*

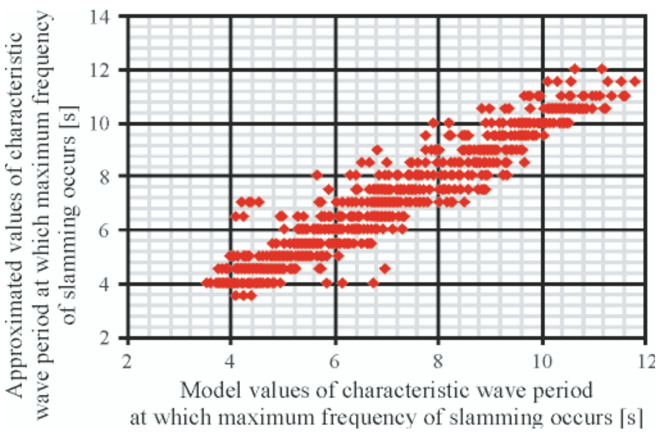

Fig. 11. *Comparison of approximations of characteristic wave period at which maximum frequency of slamming occurs, with their model values*

Tab. 4. *Statistical parameters of the elaborated artificial neural networks, where:* ***U*** *– teaching set,* ***W*** *– validating set,* ***T*** *– testing set,* $n_{sl.max}$ *– maximum occurrence frequency of bow slamming per one hour [l/h],* T_{nzp} *– characteristic wave period at which maximum frequency of green water ingress on the deck occurs [s],* T_{nsl} *– characteristic wave period at which maximum slamming frequency occurs [s]*

	$n_{sl.max}$			T_{nzp}			T_{nsl}		
	U	**W**	**T**	**U**	**W**	**T**	**U**	**W**	**T**
Standard deviation	4.33 [l/h]	4.30 [l/h]	3.63 [l/h]	2.29 [s]	2.26 [s]	2.34 [s]	2.20 [s]	2.04 [s]	1.95 [s]
Mean absolute error	0.60 [l/h]	0.30 [l/h]	0.38 [l/h]	0.47 [s]	0.52 [s]	0.46 [s]	0.46 [s]	0.47 [s]	0.53 [s]
Correlation	0.96	0.99	0.98	0.93	0.92	0.91	0.96	0.95	0.92

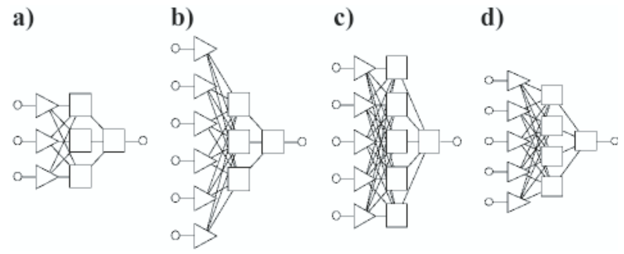

*Fig. 12. Structures of the artificial neural networks: **a)** approximating maximum slamming occurrence frequencies, **b)** approximating characteristic wave period at which maximum frequencies of green water ingress on the deck occur, **c)** predicting either safe or dangerous green water ingress on the deck, **d)** approximating characteristic wave period at which maximum frequencies of slamming occur.*

SUMMARY

The presented approximations of seakeeping qualities of FPSO ships, described by Eq. (1) through (9), can be used for:
- the determining of crucial design parameters which affect pitching, heaving, slamming and green water ingress on the deck, at an assumed significant wave height,
- the predicting of the characteristic wave height which causes increasing intensity of green water ingress on the deck and slamming, on the basis of ship design parameters,
- the predicting of the phenomena of heaving, pitching, slamming and green water ingress on the deck, on the basis of ship design parameters,
- the assessing of ship seakeeping qualities,
- the optimizing of ship design parameters with a view of assumed seakeeping qualities.

By narrowing ship operational conditions with the use of a deterministic scenario it was possible to obtain a high approximation accuracy in the wide range of values of design parameters and relatively simple structure of the considered model, simultaneously.

The elaborated approximation functions may find application to the modeling of seakeeping qualities of FPSO ships in the domain as follows:
- the assumed ranges of ship hull geometrical parameters on the basis of which model values of seakeeping qualities have been calculated, in particular, of:
  - the ratio of ship length b.p. and breadth: $L_{pp}/B = 4 \div 7$,
  - the ratio of ship breadth and draught: $B/d = 2.18 \div 4.7$,
  - the block coefficient of hull underwater part: $CB = 0.71 \div 0.87$,
  - the midship section coeffcient: $CM = 0.97 \div 0.99$,
  - the block coefficient of hull fore underwater part: $CBF = 0.5 \div 0.78$,
  - the midship body length: $WC = 40 \div 256$ m,
  - the distance from waterplane centre to aft perpendicular: $XF = 50 \div 250$ m
  - the ship length between perpendiculars: $L_{pp} = 116 \div 466$ m,
  - the ship breadth: $B = 24 \div 80$ m,
  - the ship draught: $d = 6.5 \div 28.5$ m,
  - the underwater hull volumetric displacement: $V = 36\,829 \div 385\,908$ m^3.
  - the waterplane area: $Fw = 3000 \div 29\,000$ m^2
  - the freeboard height: $Fb = 0.4 \div 42.75$ m;
- the assumed wave conditions:
  - the significant wave height:
    - for predicting maximum occurrence frequency of green water ingress on the deck: $Hs = 12 \div 17$ m,
    - for the remaining seakeeping qualities Hs value - unlimited, however wave effects are non-linearly changing along with Hs value increasing,
  - JONSWAP wave spactrum,
  - the characteristic wave period: $T = 2 \div 20$ s;
- the assumed ship motion parameters:
  - the ship speed: V = 0 m/s,
  - the wave encounter angle β = 180° (head wave).

The calculations of model seakeeping qualities were performed on the basis of the linear oscillating motion theory. In [4] have been presented results of the model tests aimed at determining effects of a.o. form parameters of ship hull over-water and under-water parts on the phenomenon of green water ingress on the deck. The tests have revealed some non-linearities in the wave effects, which result from:
1. influence of water entering forcastle deck,
2. influence of ship hull over-water part on green water ingress on the deck at large values of wave height and oscillating motions,
3. inaccuracies in the linear model of calculating relative motions at large values of significant wave height.

As results from [4] it is not possible to consider particular non-linearities separately. In the investigations in order to account for the above mentioned non-linearities, were introduced the additional general coefficients α and β which take into account differences between experimentally obtained and computed values (Fig. 4.12), as follows:

$$r_p = \alpha r + \beta r^2 \tag{10}$$

where:
r_p – predicted value,
r – measured value,
α, β – coefficients.

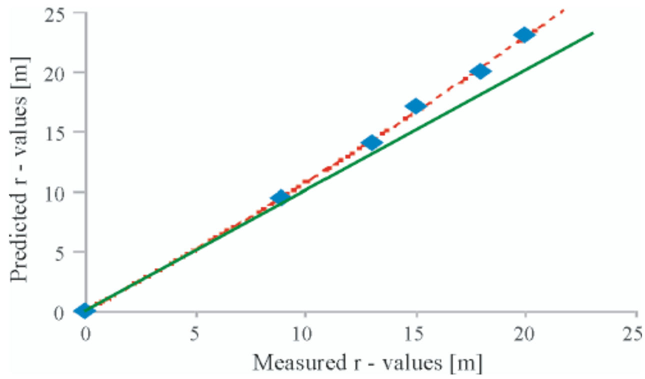

Fig. 13. Non-linearity between values calculated by using linear methods and experimetally measured ones [4]

It is not possible to determine values of the coefficients by using analytical methods but only by model tests for definite hulls. It means that to account for the above mentioned non-linearities in the parametric design stage, is not possible.

Many approximations have been elaborated by using linear regression method, that has resulted in a great simplification of approximation function's form. In the case when linear models have appeared inaccurate the theory of artificial neural networks has been applied.

Approximating occurrence frequency of green water ingress on the deck constituted the greatest difficulty in modeling seakeeping qualities of FPSO ships. In some cases as a result of numerical calculations very large model values of the frequency were achieved. It was a consequence of the assumed operational conditions (large values of significant wave height) and the wide range of freeboard height values. Therefore despite the elaborated approximations appeared rather accurate, the standard error was rather large. To solve the problem the theory of artificial neural networks was applied to recognizing (classifying) seakeeping qualities. The artificial neural network applicable to assessing occurence frequency of green water ingress on the deck on the basis of both ship design and wave parameters, was prepared. In consequence was obtained the solution showing high accuracy in estimating occurrence frequency of green water ingress on the deck.

In the subject-matter literature there are no data which could be used for verifying the approximations presented in this paper, in the range of the made assumptions. Therefore the verification of the elaborated approximations was performed only on the basis of model values used for elaborating the approximations. As results from the relationships the approximations show trends which are in line with literature sources.

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