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A New Approach for Seakeeping Performance Assessment of Alternative Hull Forms in Optimization Process

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Abstract: Designing hull forms with superior seakeeping performance demands basic information about the correlation between hull form parameters and ship motions. Classical model testing is still seen to be the most accurate way to get information about wave-induced ship motion characteristics for a hull design. Besides, in the last decades, there is an increased interest in CFD simulations in hydrodynamic optimization studies. Generally, due to the sea environment is generally not definite at the preliminary design phase, hydrodynamic optimization of a ship in terms of seakeeping is realized by comparing RAO graphs in head seas. However, in a systematic optimization study, it becomes impossible to compare these graphs because of the large number of variants. In this study, a new approach will be presented which enables numerical interpretation of a large number of RAOs for systematic optimization studies. A script is developed in order to convert graphical data into numerical and to enable automatic use in an optimization process. As a case study, a systematic planing hull series is developed with 120 variants and RAOs are obtained as a result of viscous CFD analysis. Finally, RAOs of all variants are compared by means of the suggested approach.

Keywords: Seakeeping, optimization, parametric modeling, response amplitude operator, planing hull

Optimizasyon Sürecinde Alternatif Tekne Formlarının Denizcilik Performanslarının Değerlendirilmesi İçin Yeni Bir Yaklaşım

Öz: Tekne formlarının üstün denizcilik performansı ile tasarlanması, tekne form parametreleri ile gemi hareketleri arasındaki ilişki hakkında temel bilgiler gerektirir. Klasik model deneylerinin hala form tasarımı için dalga kaynaklı gemi hareketi özellikleri hakkında bilgi edinmenin en doğru yolu olduğu görülmektedir. Ayrıca, son yıllarda, hidrodinamik optimizasyon çalışmalarında HAD simülasyonlarına ilgi artmaktadır. Genel olarak bir geminin denizcilik açısından hidrodinamik optimizasyonu, deniz ortamının ön tasarım aşamasında genellikle belli olmaması sebebiyle, baştan gelen dalgalardaki RAO grafikleri karşılaştırılarak gerçekleştirilir. Bununla birlikte, sistematik bir optimizasyon çalışmasında çok sayıda değişken nedeniyle bu grafikleri karşılaştırmak imkansız hale gelir. Bu çalışmada, sistematik optimizasyon çalışmaları için çok sayıda RAO'nun sayısal yorumunu mümkün kılan yeni bir yaklaşım sunulacaktır. Grafik verilerini sayısal hale getirmek ve bir optimizasyon işleminde otomatik kullanımı sağlamak için bir betik geliştirilmiştir. Örnek uygulama olarak, 120 alternatif tekne formundan oluşan sistematik tekne serisi geliştirilmiştir ve viskoz HAD analizleri sonucunda RAO grafikleri elde edilmiştir. Son olarak, tüm alternatiflerin RAO grafikleri önerilen yaklaşım ile karşılaştırılmıştır.

Anahtar Kelimeler: Denizcilik, optimizasyon, parametrik modelleme, genlik karşılık fonksiyonu, kayıcı tekne.

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1. Introduction

Fulfilling the expected duties among the waves in rough seas is a sign for good seakeeping performance of a ship. Therefore, seakeeping performance is important for a marine vessel to navigate appropriately for the purpose of design. For instance, warships should have superior seakeeping performance with regards to speed, operational capability and the use of weapons and sensors. The comfort of the crew and the passengers on a passenger or merchant ship with good seakeeping should be at a higher level. Considering the point of view of the crew, the working performance will increase and the operation of the ship will be higher in every respect. As a result, the importance of considering seakeeping calculations in the preliminary design phase of ships can be better understood.

The number of high-speed planing hulls has significantly increased in recent years owing to their speed and performance requested in military, recreational, racing, and transportation purposes. Planing hulls embody simultaneously concept of high relative speed together with flow separation on chine and dynamic trim as result of hydrodynamic lift. Since the first works on planing craft performances in rough water, experimental and semi-empirical methods took place over complicated mathematical modelling of planing hull seakeeping. Fridsma's experimental work and regression formulas [1, 2], which are reviewed in Savitsky and Brown [3] and Savitsky and Koelbel [4], are still the milestones for assessment of added resistance and accelerations values at center of gravity (CG) and bow, at different speed regimes of monohedral planning hulls.

Although model tests are the most reliable way for seakeeping calculations, relatively limited number of systematic researches is presented generally considering so called prismatic hulls or monohedral hulls. Hearn et al. [5] presented a new approach to implementing seakeeping analysis procedures in hull form design. This approach is based on the presentation of the seakeeping analysis results of systematically developed alternative hull forms in the form of design diagrams according to the form parameters. While alternative vessel forms were being generated, the main dimensions and displacement volume were kept constant, while waterplane area coefficient CWP, longitudinal center of buoyancy (LCB) and longitudinal center of floatation (LCF) were systematically altered. All alternative hulls were analysed with a seakeeping software based on strip theory and the results were presented as graphs in the form of form parameters. Kükner and Sarıöz [6] studied to optimize the hull form of high-speed vessels in terms of seakeeping. In their study, a hull form series was developed from a main hull by altering firstly the length (L) and beam-draught ratio (B/T) and then the secondary parameters. They investigated heave and pitch motions of the variants and tried to find the optimum hull form. As a result of the study, it was found that the increase in L and B/T ratio decreased the resistance and vertical motions and that the form parameters were less effective in vertical motions and that CWP, and LCF should be examined separately. Sarıöz [7] aimed predicting the seakeeping performance of planning crafts in the preliminary design phase. Transfer functions were obtained for regular waves by using strip theory and appropriate formulations were determined by using wave spectrum. At the end of the study, the results were compared with the model tests with taking into account the dynamic effects of lifting. The applied procedure gave good results at low speed and sea conditions. The same procedure can be used to compare different hull forms. Sarıöz [8] introduced a numerical procedure developed to determine the seakeeping performance capability of surface warships. This procedure consists of five main stages: representation of seas with irregular waves, calculation of motions in regular waves, determination of motions in rough seas, definition of the related seakeeping criteria and definition of the operation restrictions according to exceeding these criteria. NATO (North Atlantic Treaty Organization) standards were considered as seakeeping criteria. The seakeeping characteristics calculated for each wave direction and speed in each different sea and sea state were compared with the relevant seakeeping standard to determine which sea state, wave direction and ship speed combination exceeded the criteria. These results were expressed in polar diagrams, and the rate at which any motions at any sea and any sea state can be performed without exceeding the relevant criteria has been determined. The procedure was applied to assault boats, corvettes and destroyer-type warships. Özüm et al. [9] studied on the effect of some primary and secondary parameters including main dimensions, form coefficients and specific positions on seakeeping performance of planning hulls. A systematic series was developed from a main hull and seakeeping analyses were made with using strip theory for head seas.

The motions of a high-speed craft are highly influenced by speed and dynamic forces that begin to be important for high Froude numbers. Seakeeping methods, based on linear and non-linear assumptions applicable on displacement ships, are not able to account for flow separation on hard chine and take into account dynamic lift therefore they will result in an not accurate evaluation of motions and loads in waves. However, vertical viscous forces are also sometimes included by semi-empirical methods. For instance, the influence of these forces have been studied by Arribas and Fernandez [10] for high speed mono-hull vessels. They have studied some theories for the prediction of seakeeping behavior of high-speed vessels taking into account dynamic forces and have proved the validity of theories with some model tests. The tests are focused on the vertical plane motions in head seas, where the most intense accelerations occurred for the high-speed vessels. Experimental results of vertical movements were compared with numerical calculations and results were obtained about the application limits of presented theories.

Classical model testing is still seen to be the most accurate way to get information about wave induced ship motion characteristics for hull design [11]. But because of the time and cost, the number of considered hull form variations is always very limited. In most cases the complete test series covers less than 10 different configurations. Consequently, the results can only offer limited data on trends. Systematic researches with semi-empirical or computational fluid dynamics (CFD) methods are preferred to investigate a huge number of variants, but this brings about the problem of comparing variants. In the present paper, a new approach is presented which enables numerical interpretation of the large number of response amplitude operators (RAOs) for the systematic optimization studies. As a case study, 120 alternative hull forms is created from a main planning hull by systematic variation. In order to be able to calculate the RAOs, viscous CFD analysis are made for Fn=1.5, and the time-domain calculations are converted to the frequency domain by Fourier transformation. A script is developed to convert RAOs to a numerical value.

2. Methodology

2.1. Determination of sea environment and calculation method

In order for a high-speed craft to perform well in terms of seakeeping, the parameters affecting the form must be optimized to meet the objective function during the preliminary design phase. Various methods have been developed to examine these parameters. Şaylı et al. [12] investigated the effects of parameters by making regression analysis on fishing-type hulls and gave an idea for preliminary design. By creating a new hull form group from a main hull, seakeeping analyses were made for each hull and the results were interpreted with the help of graphs. The parameters to be searched for seakeeping were divided into two groups and examined separately. Kükner and Sarıöz [6] investigated the effect of block coefficient of high-speed hulls on seakeeping. In this study, Sarıöz's "forward analysis" method was used for seakeeping calculations of alternative vessels during optimization [13]. The form parameters determined for the alternative hulls were investigated in terms of seakeeping according to the flow chart shown in Figure 1. In his study, Sarıöz [7] found that the maximum oscillations for vertical-plane motions occurred as a result of head seas. Therefore, this can be regarded as the worst-case scenario.

In the present study, since the vessels to be analyzed have not a specific working environment, the method of calculating the transfer functions of the accelerations around the center of gravity will be used in head seas instead of determining a wave energy spectrum and sea state.

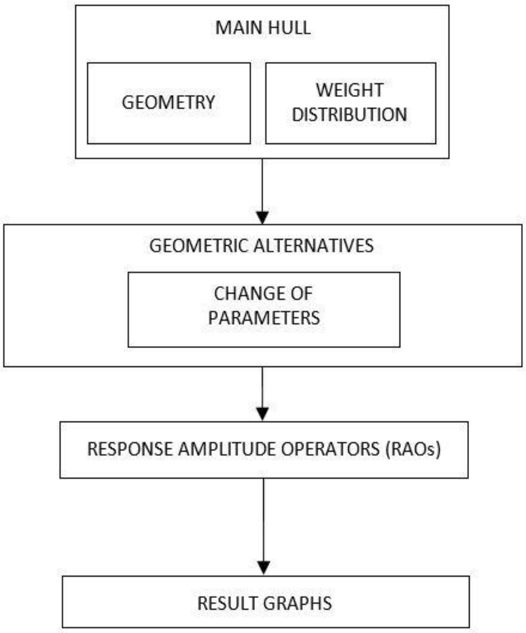

Figure 1. Forward analysis method flow chart

During calculations, the amplitudes originating from the waves having different frequencies are summed according to the superposition law and the RAO (transfer function) is obtained for each alternative hull by assuming that the hulls make harmonic motions in sinusoidal head seas.

2.2. Determination of sea environment and calculation method

For a systematic optimization study a fully parametric hull form must be created to generate the necessary variations. In fully parametric modelling approach the geometry is entirely described by and created from parameters. Parameters are high-level descriptors that reflect the functional characteristics of the product. Variants are simply created by different instances of the parameter set's values.

In the present study, CAESES (formerly called Friendship-Framework), a unique computer aided design (CAD) and CFD integration platform, was used to create a fully parametric model from a set of parameters and manage the entire optimization process [14, 15]. A fully parametric model was created with an inductive method: Coordinates of the points, dependent variables of the parameters, were used to create curves that allow the generate surfaces. As a first step, appropriate design variables and major dimensions for the objective function should be determined. Then, the characteristic points were associated with these variables so that the parametric curves were generated. Afterwards, parametric surfaces were generated by passing sections through these curves with the help of various codes. Parameters could be created within constraints and controls except for surface parameters, for instance for stability criteria or surface smoothness. The parameters considered to be systematically altered were also associated with the design variables. Thus, variation in the desired range was provided.

2.3. Calculation of RAOs

If there is any specific objective function or working environment, the RAOs have to be calculated and compared to be able to compare alternative hull forms. Systematic researches with semi-empirical or CFD methods are preferred to investigate a lot of variants, but this brings about the problem of comparing them. Main aim of this work is to present a new approach to compare and evaluate a large number of RAOs. Thus, numerical interpretation of the large number of RAOs will be possible. With regard to this, a script, given in next chapter, is developed to convert RAOs to a numerical value. This method can be used independently of hull type and calculation method of RAOs. In the present study, the methodology will be applied for high-speed planing hulls as a case study.

3. Case Study: Application of the Methodology in a Systematic Optimization of Planing Hulls

3.1. Creating the hull form series

Since this study was done with the aim of showing that the approach is feasible, a systematic variation was applied by selecting a random form. In the present study, a high-speed planing hull form was developed as a main hull. As mentioned in the previous chapter, this main hull was modeled as fully parametric in CAESES software to be able to create variants by altering some parameters. The basic form curves modeled according to the parameters and the parametric section curve are shown in Figure 2. Fully parametric surface of the main hull was obtained by using these basic curves. The lines plan of the main hull form was given in Figure 3, and the geometric properties are given in Table 1.

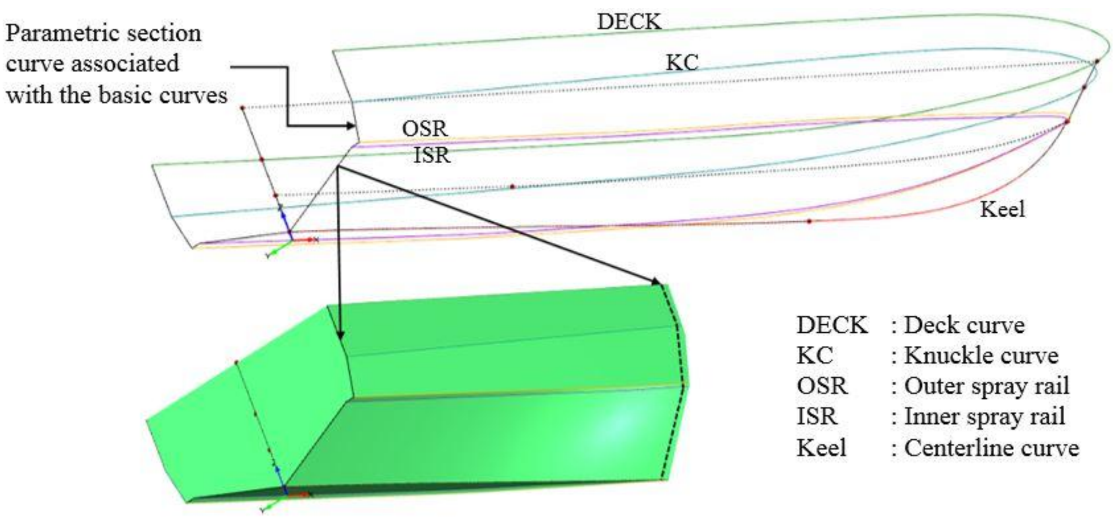

Figure 2. Basic curves and fully parametric surface of the main hull form

Table 1. Main specifications of the main hull form

Length overall, L_{OA}	45.00 m	**Draft, T**	1.89 m
Length waterline, L_{WL}	39.56 m	**Prismatic coefficient, C_P**	0.82
Maximum breadth, B_{MAX}	9.375 m	**L_{OA} / B_{MAX}**	4.80
Breadth waterline, B_{WL}	8.50 m	**$L / \nabla^{1/3}$**	6.30
Depth, D	5.50 m	**Deadrise angle, β**	20^0

In order to apply the systematic variation to the parametric form, it is important to determine the fixed and variable parameters. Table 2 and 3 show the fixed and variable parameters determined in this study.

Table 2. Design variables for systematic variation

Design variables	
$\mathbf{L_{OA}/B_{MAX}}$	4.8, 5.0, 5.2, 5.4
$\mathbf{L / \nabla^{1/3}}$	5.7, 5.9, 6.1, 6.3, 6.5, 6.8
$\boldsymbol{\beta}$	10.0, 12.5, 15.0, 17.5,20.0

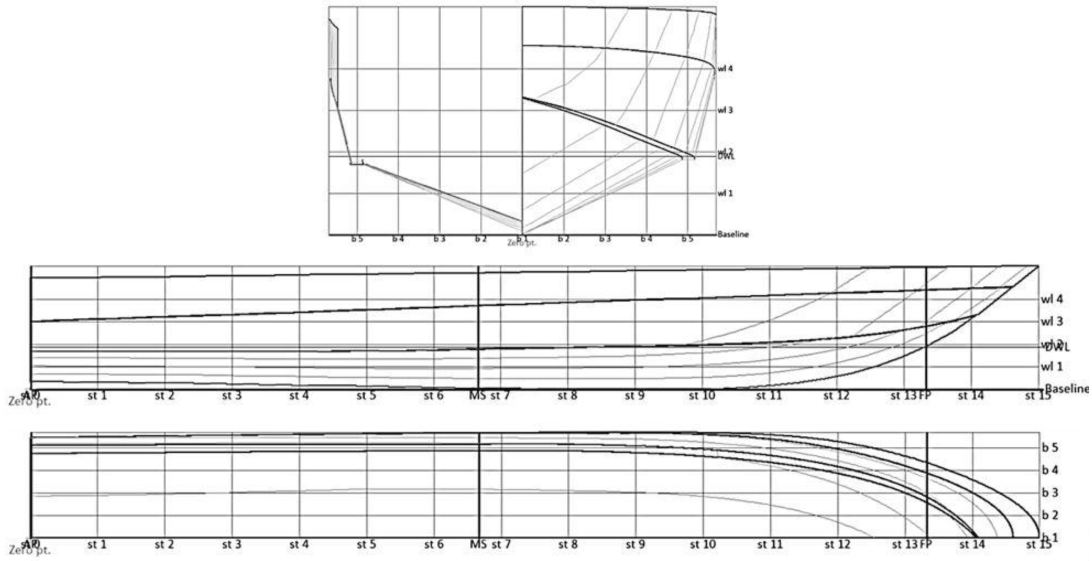

Figure 3. Lines plan of the main hull form

According to the selected design variables and fixed parameters 120 new variants were derived from the main parametric hull form as a result of systematic variation, given in Figure 4.

Table 3. Fixed parameters for systematic variation

Fixed parameters	
$\mathbf{L_{OA}}$	45 m
$\mathbf{C_p}$	0.80 (for same displacement groups)
$\mathbf{T_{stern}}$	0.35 m
Fn	1.5

In order to get more detailed information about the mechanism of the systematic variation process, the previous article of the authors [9] can be examined.

3.2. Calculation of the RAOs

In this study, a planning regime will occur because seakeeping analyses are carried out at Fn=1,5. Therefore, viscous solution is thought to be more appropriate because of the high impact of spray effects and hydrodynamic lift forces generated in this case [16]. Since the main purpose of this study is to present a methodology where seakeeping analysis results of a large number of variants can be easily compared, detail of CFD analysis were not given in this paper. However, a brief information about the grid structure, computational domain and boundary conditions are given in following paragraph.

The hydrodynamic analyses of the high-speed planing hulls have been performed by a commercial unsteady RANS (Reynolds-averaged Navier-Stokes) equations solver. The fluid flow around the hull has been considered as 3-D and incompressible. During the simulations, the free surface effects have been considered using the volume of fluid (VOF) method and utilized by the Eulerian fluid approach. The free water surface is initially assumed as calm water. The Reynolds stresses have been computed using Standard Realizable k-ε turbulence model. Dynamic (overset) grid technique is adopted for the seakeeping simulations.

The grid sizes are gradually increased away from the hull (Figure 5). The hull form is assigned as no-slip walls. The wall effects have been eliminated by identifying the side faces of the computational domain as symmetrical boundaries.

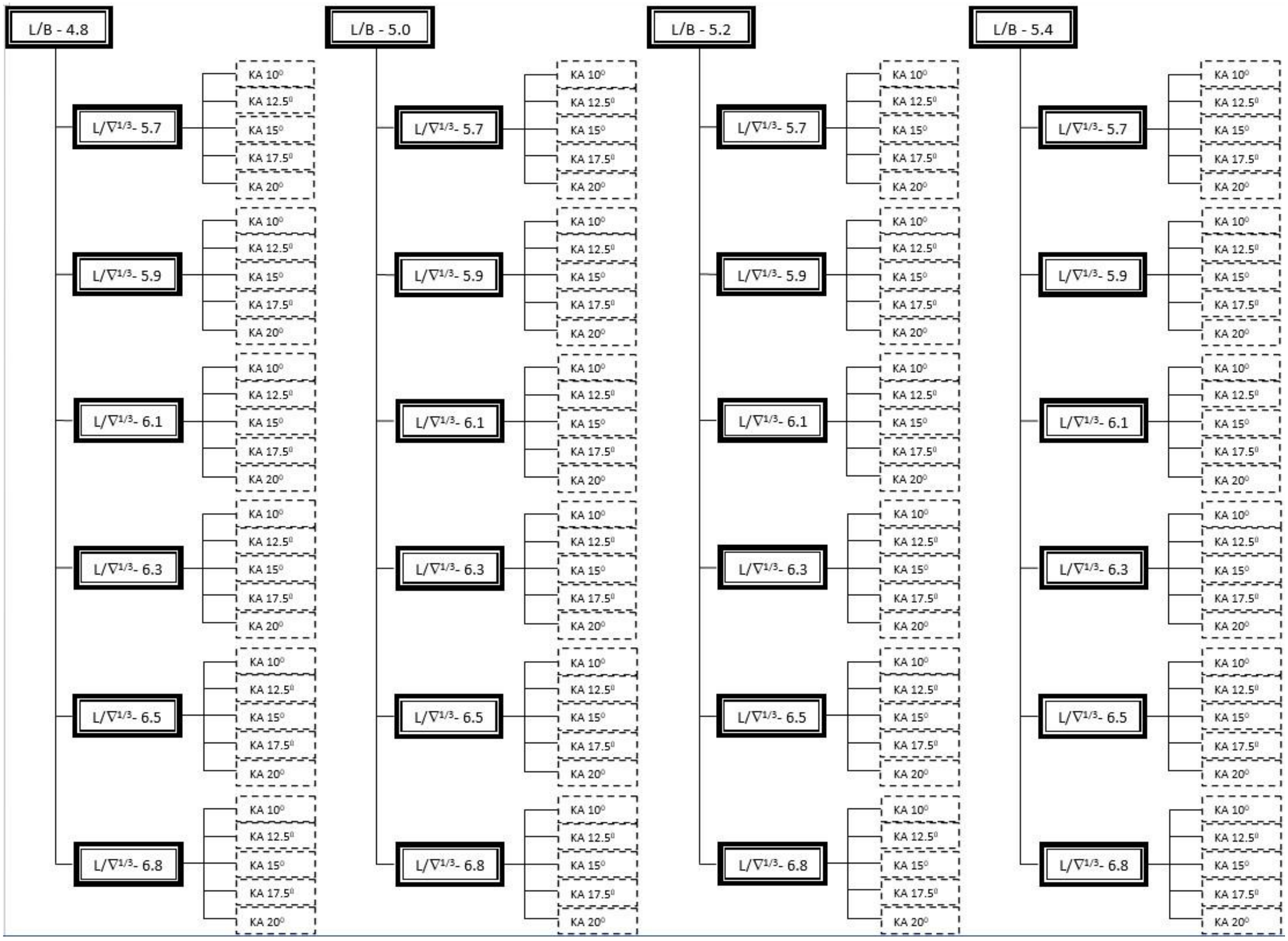

Figure 4. Generated hull form series as a result of systematic variation

Inlet side of the domain have been defined as velocity inlet while the outlet side have been defined as pressure outlet. The result of CFD analysis of an alternative hull form is given as an example in Figure 6.

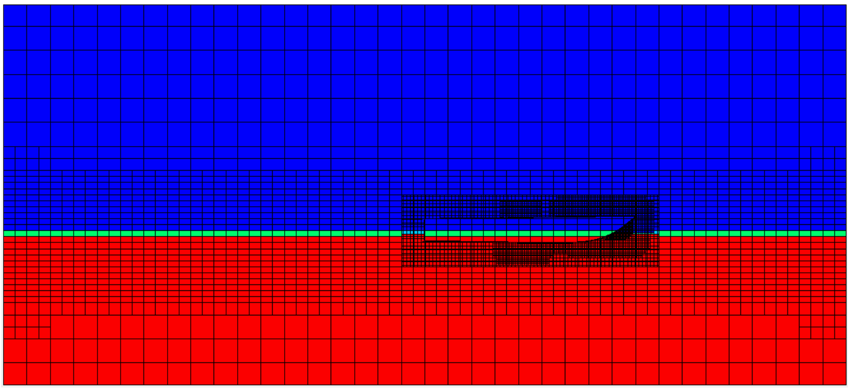

Figure 5. Overset grid topology

During the viscous analyses, in order to be able to calculate the RAOs, the time-domain calculations were converted to the frequency domain by exposing the alternative hulls to regular head seas. The ITTC's (International Towing Tank Conference) proposal [17] in this regard is to continue the analysis until the ratio of the wave height to the vessel length is 2 times, starting from the half of the vessel length, assuming the ratio of the wave height to the vessel length is fixed 1/50.

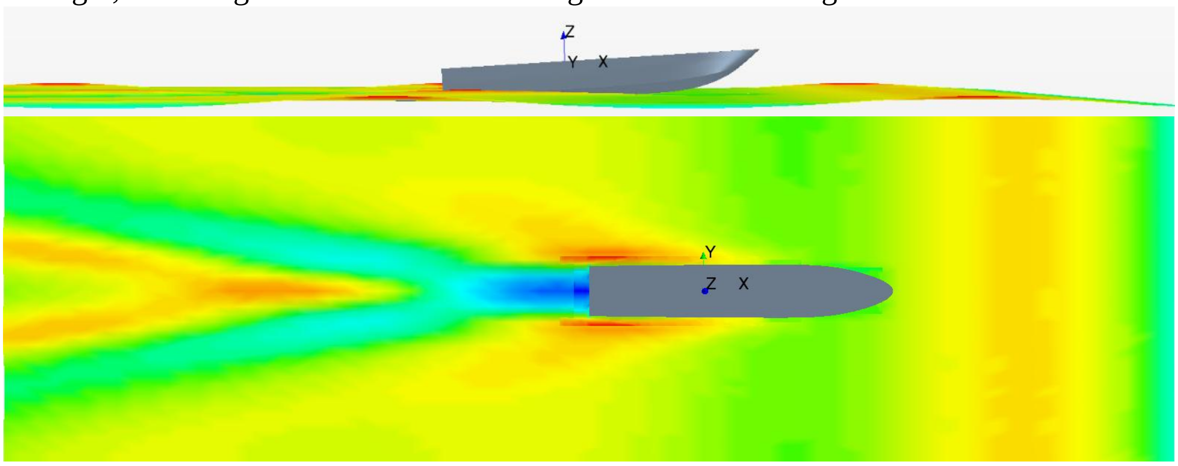

Figure 6. CFD analysis result of an alternative hull form

Table 4 summarizes the wave lengths and amplitudes used in this study during viscous analyses of all alternative hulls to calculate the RAOs.

Table 4. Wave lengths and amplitudes at the regular head seas

	λ	**ζ (m)**
	0.5 L	0,225
	1.0 L	0.450
Fn 1.5	1.5 L	0.675
	2.0 L	0.900
	3.0 L	1.350

Fourier transformation has been used to convert time-domain to frequency domain. The acceleration around the center of gravity for 14 seconds for the parametric main hull form is given in Figure 7 with the wave amplitude of 0.45 m and the wave length of 45 m.

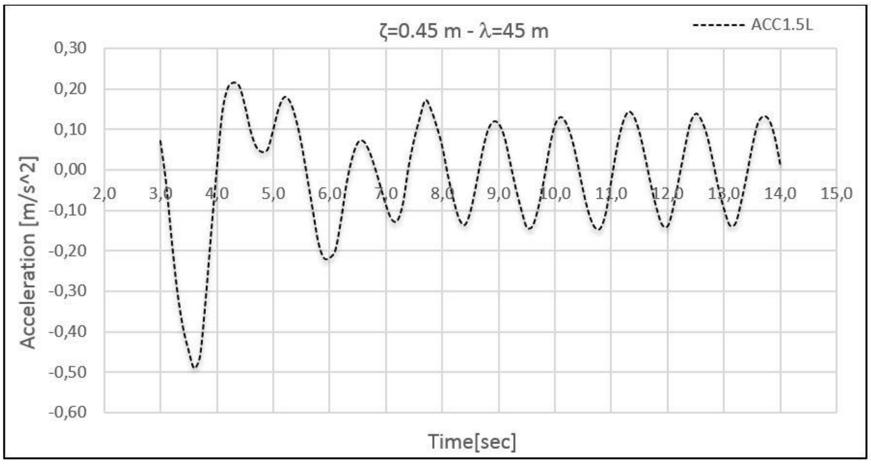

Figure 7. Acceleration around c_g for ζ=0.45m and λ=45 m

The following Fourier series transformation was used to convert this time-dependent acceleration graph into frequency domain.

$$\eta(t) = \eta(0) + \sum_{n=1}^{N} \eta_n \cos(\omega_e t + \beta_n), \mathrm{n} = 1,2,3... \text{ , n=1, 2, 3…} \tag{1}$$

$$\eta_0 = \frac{1}{T_e} \int_0^{T_e} \eta(t)dt \tag{2}$$

Here, η_0 is the zero-order harmonic for an irregular signal, i.e. the mean value of the signal. η_n and β_n in Equations 3 and 4 represent the harmonic amplitude and phase angle of the nth order, respectively. This value is calculated with the help of the Equations 5 and 6.

$$\eta_n = \sqrt{a_n^{\ 2} + b_n^{\ 2}} \tag{3}$$

$$\beta_n = \arctan(\frac{b_n}{a_n}) \tag{4}$$

$$a_n = \frac{2}{T_e} \int_0^{T_e} \eta(t)\cos(\omega_e nt)dt \tag{5}$$

$$b_n = \frac{2}{T_e} \int_0^{T_e} \eta(t)\sin(\omega_e nt)dt \tag{6}$$

Here, T_e represents the encounter period of the generated signal. When vertical ship motions are considered in uniform waves, the dimensionless amplitude response functions for acceleration are shown in Equation 7.

$$RAO_{[a_z]} = \frac{\eta_{1[a_z]} L}{g\zeta} \tag{7}$$

As shown in Figure 8, the time-domain signals are transformed quite closely into the frequency domain using the Fourier transform. As can be seen in the graph, there is a big difference in the curves until to the 5th second because the regime is being in order after this. So the disagreement of the part up to the 5th second may be neglected. Thus, only the value of the RAO in the case corresponding to this frequency is calculated. The same procedure is repeated for each alternative vessel for wave length and amplitudes given in Table 4.

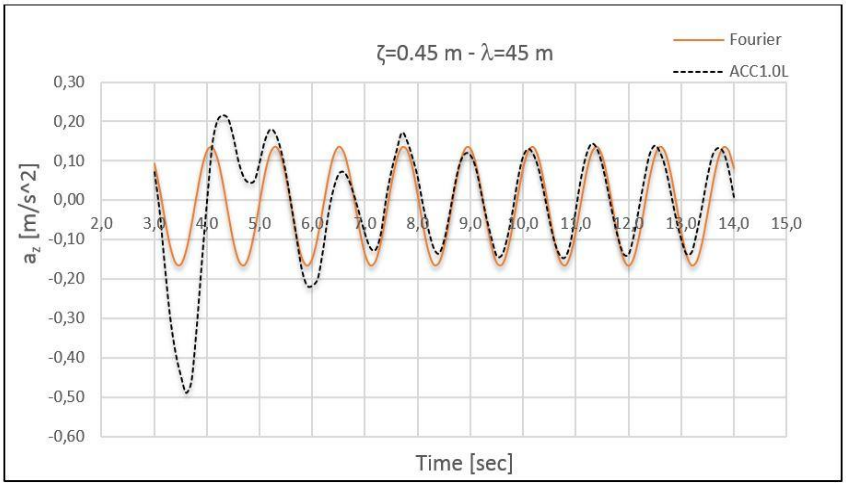

Figure 8. Acceleration around c_g for ζ=0.45m and λ=45 m and its expression by Fourier transformation

After the Fourier transform is complete, the corresponding acceleration for each frequency range is found and the non-dimensional RAO [a_z] graph is plotted as expressed in Equation 7 (Figure 9).

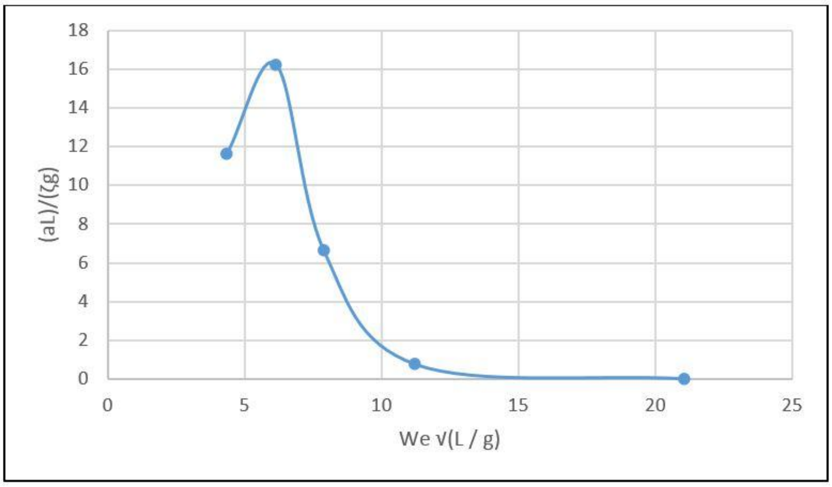

Figure 9. Non-dimensional RAO[a_z] graph

3.3. Evaluation of the results

It is important to convert these graphs to a numerical value because it is not possible to make comparisons of the non-dimensionless RAOs for 120 forms. For this, it is considered to compare the areas under the graph or the peak points in same frequency range. In order to convert graphical data into numerical and to enable automatic use in an optimization process, developed script was used, as shown below.

```
import rhinoscriptsyntax as rs
#Select a file to open
filename = rs.OpenFileName("Open CSV file","*.csv|", None, None, None)
 #open the file for reading
file = open(filename, 'r')
 lines = file.readlines()
file.close()
print(lines)
#Point1
```

```
p2 = rs.AddPoint((x2,y2,0))
rs.ObjectLayer(p2,Layer)
#Point3
line3 = (lines[2]).strip()
ptInfo3 = line3.split('/')
L3 = str(ptInfo3[0])
if rs.IsLayer(L3):
   Layer = L3
else:
   Layer = rs.AddLayer(L3)
```

```
line1 = (lines[0]).strip()
ptInfo1 = line1.split('/')
L1 = str(ptInfo1[0])
if rs.IsLayer(L1):
   Layer = L1
else:
   Layer = rs.AddLayer(L1)
x1 = float(ptInfo1[1])
y1 = float(ptInfo1[2])
p1 = rs.AddPoint((x1,y1,0))
rs.ObjectLayer(p1,Layer)
#Point2
line2 = (lines[1]).strip()
ptInfo2 = line2.split('/')
L2 = str(ptInfo2[0])
if rs.IsLayer(L2):
   Layer = L2
else:
   Layer = rs.AddLayer(L2)
x2 = float(ptInfo2[1])
y2 = float(ptInfo2[2])
   Layer = L5
else:
   Layer = rs.AddLayer(L5)
x5 = float(ptInfo5[1])
y5 = float(ptInfo5[2])
p5 = rs.AddPoint((x5,y5,0))
rs.ObjectLayer(p5,Layer)
sv = [-1,0,0]
C
=rs.AddInterpCurve([p1,p2,p3,p4,p5],start_tangent=sv)
rs.ObjectLayer(C,Layer)
C1 = rs.AddLine(p1,[x1,0,0])
rs.ObjectLayer(C1,Layer)
C2 = rs.AddLine(p5,[x5,0,0])
rs.ObjectLayer(C2,Layer)
x3 = float(ptInfo3[1])
y3 = float(ptInfo3[2])
p3 = rs.AddPoint((x3,y3,0))
rs.ObjectLayer(p3,Layer)
#Point4
line4 = (lines[3]).strip()
ptInfo4 = line4.split('/')
L4 = str(ptInfo4[0])
if rs.IsLayer(L4):
   Layer = L4
else:
   Layer = rs.AddLayer(L4)
x4 = float(ptInfo4[1])
y4 = float(ptInfo4[2])
p4 = rs.AddPoint((x4,y4,0))
rs.ObjectLayer(p4,Layer)
#Point5
line5 = (lines[4]).strip()
ptInfo5 = line5.split('/')
L5 = str(ptInfo5[0])
if rs.IsLayer(L5):
C3 = rs.AddLine([x1,0,0],[x5,0,0])
rs.ObjectLayer(C3,Layer)
JC =
rs.JoinCurves([C,C1,C2,C3],delete_input=True)
rs.ObjectLayer(JC,Layer)
A = (rs.CurveArea(JC))[0]
CP = (rs.CurveAreaCentroid(JC))[0]
T = rs.AddText( A, CP, height=1.0, font="Arial",
font_style=0, justification=None )
rs.ObjectLayer(T,Layer)
H = y5
Th = rs.AddText( H, p5, height=1.0,
font="Arial", font_style=0, justification=None )
rs.ObjectLayer(Th,Layer)
```

As mentioned above, time domain solutions were converted to frequency domain by Fourier transformation and since graphical comparison of the RAOs is not possible, they have been converted into numerical data. Also the peak points of the RAOs examined in terms of acceleration were also determined.

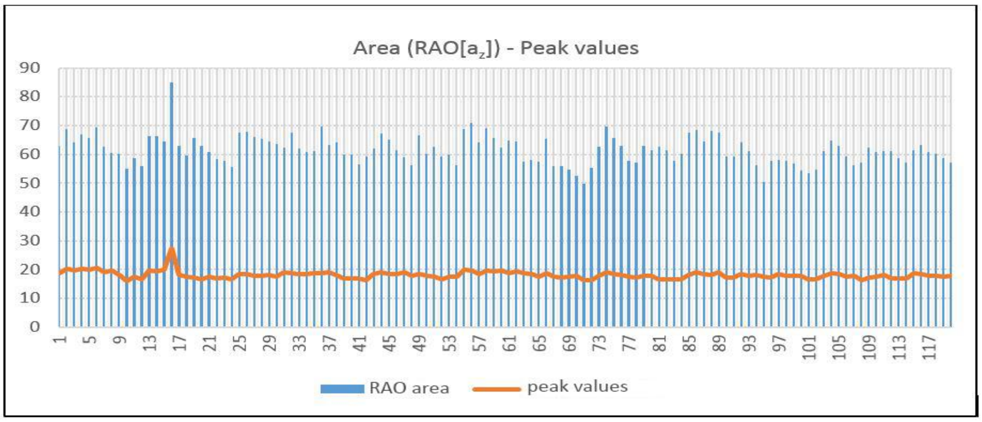

Figure 10. Max values of the amplitudes and areas under RAO[a_z]

As can be seen from Figure 10, there is no difference in the comparison of the maximum values of the amplitudes or in the areas under the RAO when the variants are compared in the results of the studies performed in the same frequency range. It is seen that the variant with the bigger area under the curve is also bigger in peak value. In consideration of this result it can be said that seakeeping analyses of variants can be evaluated according to the areas below their RAOs or according to their peak values. It means that if the area or peak value increases seakeeping performance is getting worse.

4. Conclusion

In the present study, it is aimed to propose a solution to the problem encountered in studies that it is needed to compare a lot of variants in terms of seakeeping. The developed script enables to convert RAO graphs to a numerical value, so it will be possible to make comparisons of the non-dimensionless RAOs of the desired number of variants. This method can be used independently of hull type and calculation method of RAOs. Since this method allows designers to compare a lot of variants in a short time period, it can be used as an important tool for defining the best variant in automatic optimization algorithms where seakeeping is an objective function. In the following studies, the authors aim to develop a high-speed planing hull form series optimized in terms of seakeeping, stability and resistance also by using the method offered in this paper.

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