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Prevention of Parametric Rolling through Multi-Objective Optimisation

Haipeng Liu[1] , Osman Turan[1], Evangelos Boulougouris[1]

ABSTRACT

International Maritime Organisation is developing new intact stability criteria which include parametric rolling and they will have a larger impact on particular ship types. A benchmark study of those criteria on C11 containership is presented herein. Moreover, the authors investigate the impact to the overall design from the introduction of the new criteria as one of the objectives in a multi-criteria design optimisation which is solved using Genetic Algorithms.

KEY WORDS

Parametric Rolling; Resistance; Ship Design; Multi-Objective Optimisation; NSGA-II Genetic Algorithm

INTRODUCTION

In the late 1930s, parametric rolling was firstly studied in Germany (Paulling 2007). However, in October 1998, a post-Panamax C11 class containership, experienced a very severe storm in the North Pacific Ocean while traveling from Kaohsiung to Seattle. The C11 containership lost one-third of its containers and damaged another one-third containers as well. The investigation revealed that this was caused by parametric rolling (France 2003). After this serious accident, this phenomenon has attracted more attention from researchers to carry out more in depth research studies in order to predict and prevent parametric rolling. Post-Panamax C11 containership has been widely used for benchmark study on parametric rolling.

The existing stability criteria (2008 IS code) are limited to the dynamic stability information provided by the GZ-φ curve. They do not provide enough safety against more complex risks associated with the performance of the intact ship in waves. Therefore, the International Maritime Organisation (IMO) is developing the next generation of intact stability criteria to fill the gap. Five stability failure modes have been taken into consideration by the IMO working group (Working Group 2012):

- Parametric rolling
- Pure loss of stability
- Broaching/Surf-riding
- Dead ship condition
- Excessive acceleration

The proposed criteria have three levels with different sophistication. Level 1 and level 2 constitute a vulnerability layer while level 3 constitutes a performance-based layer. The lower the level it is, the more conservative it is. Level 1 uses a simplistic approximation, while level 3 uses the most advanced method, i.e. time-domain numerical simulation. The procedure starts with level 1 and progresses to next level until the vessel passes the criteria.

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[1] University of Strathclyde, UK

If the vessel passes any level of the criteria, the process is completed and the ship is judged as safe against the relevant stability failure mode. However, if the ship fails to pass the top level criteria, it means the ship is vulnerable and it has to be re-designed until it passes the criteria. At present, IMO is mainly focusing on developing the vulnerable layer.

This paper deals with the first of the failure modes, namely parametric rolling (PR). As a ship vulnerable to PR has to be re-designed, there will be constraints and objectives such as minimizing the impact to resistance and if possible even reduce it. Genetic algorithms have been widely used in multi-objective optimisation due to its population-based nature which allows the several element generation of the Pareto optimal set with a single run (Coello 2002). Here, a multi-objective evolutionary algorithm is proposed as a solution to the multi-objective optimisation problem in integrated parametric rolling and resistance (IPRR) design process. The objectives of IPRR process are optimised by a multi-objective genetic algorithm "Nondominated sorting genetic algorithm II (NSGA II).

In the following paragraphs, the details of vulnerability layer of parametric rolling will be introduced. By applying the checking procedure on a C11 containership model, the ship is judged as vulnerable to parametric rolling. Then, a multi-objective optimisation is processed to decrease or eliminate the parametric rolling problem and reduce the resistance at the same time. The effect of the decision variables on design objectives is established. The optimum design is also achieved through NSGA II algorithm and the result satisfies all the requirements.

PARAMETRIC ROLLING

In the following paragraphs, a short description of the applied criteria and their levels in vulnerability layer will be presented.

Level 1 vulnerability criterion

As defined by current draft criteria (Working Group 2014), if the ratio of GM variation in reference wave $\Delta GM/GM$ is larger than the standard R_{PR}, the ship is vulnerable to parametric rolling; otherwise it is non-vulnerable. Here GM is the metacentric height of the loading condition in calm water including free surface correction and ΔGM is the change of metacentric height which can be estimated using two different methods. In the first method, two different drafts are used and Simpson's rule is applied to calculate the moment of inertia and the average GM variation is achieved. This method is not suitable to a tumblehome hullform but it is applicable to a ship with non-even keel (Working Group 2014). In the second method, ΔGM may be determined as one-half difference between the maximum and minimum GM calculated in sinkage and trim on a series of waves with wave length equals to ship length and the wave height equals to 1/60 of wave length. As C11 is the conventional container ship, the second method is used for the benchmark study.

Level 2 vulnerability criteria

Level 2 criteria (Working Group 2014), are comprised by "two checks". If the vessel doesn't pass any check, it is judged as vulnerable to parametric rolling and the vessel has to be checked in performance-based layer.

- ***First Check***

The first check aims to test whether the vessel's speed is within the vulnerable region for PR and GM variation satisfies the PR safety requirement. The probability of C_1 in the first check is a sum of the product of C_i and the wave weighting factor W_i. The 16 wave series applied in this check are discretisation of the applied wave spectrum. The weighting factor is the occurrence probability among the wave series for each wave case. The wave lengths vary from 22.57 m to 63.68 m and the wave heights vary from 0.35 m to 5.95 m. The value for criterion 1 in each case, C_{1i} is 0 if both speed check and GM relevant check satisfy with the specific condition as the vessel is considered not vulnerable to PR; otherwise C_{1i} is 1.

Parametric rolling occurs when the encounter frequency is equal to the double of the natural roll frequency. The speed corresponds to the resonance speed V_{PRi} which is given by the following Equation 1.

$$V_{PRi} = \left| \frac{2\lambda_i}{T_\phi} \cdot \sqrt{\frac{GM(H_i,\lambda_i)}{GM}} - \sqrt{g\frac{\lambda_i}{2\pi}} \right| \qquad [1]$$

For GM relevant conditions for avoiding the PR risk region are that $\Delta GM(H_i, \lambda_i)/GM(H_i, \lambda_i) < Rpr$ and $GM(H_i, \lambda_i) > 0$. Here, the average metacentric height corresponding to the loading condition under consideration, $GM(H_i, \lambda_i)$; and the one-half of the difference between the maximum and minimum values of the metacentric height GM in wave, $\Delta GM(H_i, \lambda_i)$; are calculated considering the ship balanced in sinkage and trim in the series of waves characteristic by Hi and λ_i.

If total probability of C_1 is greater or equal to the standard value R_{pr0} of 0.06 the ship is judged as potentially vulnerable and it needs to be checked by the second check; otherwise the vessel is not vulnerable and it passes the evaluation of parametric rolling problem.

- ***Second Check***

When C_1 is not smaller than R_{pr0}, the designer should apply the second check. The ship performance is simulated under NO.34 standard wave cases (IACS 2001). Each wave case has the corresponding weighting factor W_i, which represents the sample wave's occurrence probability among all the 306 wave cases, as shown in table 1.According to the criteria, if the vessel in each wave case experiences the roll angle which is larger than 25 degrees, the vessel is judged as vulnerable to parametric rolling and C_{2i} is 1, otherwise is 0. An analytical method based on the simplification of Mathieu's equation is used to predict the roll amplitude as given in equation [2] (CGIS 2014). GM variation in waves is calculated quasi-statically. Ikeda's simplified method, based on an empirical formula, is used for the damping prediction (Kawahara 2009). It divides the roll damping into the frictional, the wave, the eddy, the bilge keel and the lift damping components.

$$(I_{xx}+J_{xx})\cdot\ddot{\phi}\ \cdots\ (\dot{\phi})\ \cdots\ M\cdot\phi=0 \qquad [2]$$

where Ixx+Jxx: virtual moment of inertia in roll;
R: nonlinear roll damping;
W: ship weight
GM: metacentric height

For the second check, if the total probability sum C_2 which is the product of C_{2i} and wave weighting factor W_i, is greater than standard R_{pr0} 0.06, the ship is judged vulnerable to parametric rolling and the ship should be checked by level 3; if not, it is judged as non-vulnerable to parametric rolling and the ship passes the parametric rolling failure mode and it should be checked for the other stability failure modes.

Table 1: No.34 Wave Scatter Relevant Weighting Factor of Sea State in the North Atlantic

Hs/Tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0.0000	0.0000	0.0000	0.0013	0.0087	0.0119	0.0063	0.0019	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0305
1.5	0.0000	0.0000	0.0000	0.0003	0.0099	0.0498	0.0774	0.0557	0.0238	0.0070	0.0016	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.2258
2.5	0.0000	0.0000	0.0000	0.0000	0.0020	0.0216	0.0623	0.0745	0.0486	0.0207	0.0064	0.0016	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.2381
3.5	0.0000	0.0000	0.0000	0.0000	0.0003	0.0070	0.0323	0.0568	0.0510	0.0284	0.0111	0.0034	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.1913
4.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0020	0.0135	0.0329	0.0386	0.0269	0.0128	0.0046	0.0013	0.0003	0.0001	0.0000	0.0000	0.0000	0.1329
5.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0050	0.0160	0.0237	0.0201	0.0113	0.0046	0.0015	0.0004	0.0001	0.0000	0.0000	0.0000	0.0833
6.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0017	0.0069	0.0126	0.0127	0.0083	0.0039	0.0014	0.0004	0.0001	0.0000	0.0000	0.0000	0.0481
7.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0027	0.0059	0.0070	0.0052	0.0028	0.0011	0.0004	0.0001	0.0000	0.0000	0.0000	0.0259
8.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0010	0.0026	0.0035	0.0030	0.0017	0.0008	0.0003	0.0001	0.0000	0.0000	0.0000	0.0131
9.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003	0.0010	0.0016	0.0015	0.0010	0.0005	0.0002	0.0001	0.0000	0.0000	0.0000	0.0063
10.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0004	0.0007	0.0007	0.0005	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0028
11.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0012
12.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005
13.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002
14.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
15.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
16.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SUM	0.0000	0.0000	0.0000	0.0017	0.0209	0.0928	0.1992	0.2488	0.2087	0.1290	0.0624	0.0248	0.0084	0.0025	0.0007	0.0002	0.0000	0.0000	1.0000

SAMPLE SHIP

The vessel used in this paper is the well-known post-Panamax C11 class containership which is frequently chosen in parametric rolling benchmark studies. The main particulars are presented in table 2 and the geometry is shown in figure 1. The availability of experimental results for this vessel is particularly helpful for researchers and for organisations who develop tools to apply the new generation of intact stability criteria.

Table 2: Main Parameters of C11 Containership

Item	Value	Unit
Length btw. waterline (L_{wl})	255.30	m
Breadth (B_{DWL})	40.00	m
Depth (D)	24.45	m
Draught (T)	11.500	m
Displacement (Δ)	69,034.40	tons
Block coefficient (C_B)	0.573	/
Midship coefficient (C_m)	0.956	/
Transverse metacentric height (GM_T)	1.928	m
Vertical Centre of Gravity (VCG)	18.418	m
Service Speed (Vs)	12.86	m/s
Natural Roll period (T_Φ)	24.49	s
Bilge Length (L_{BK})	76.54	m
Bilge Breadth (B_{BK})	0.40	m

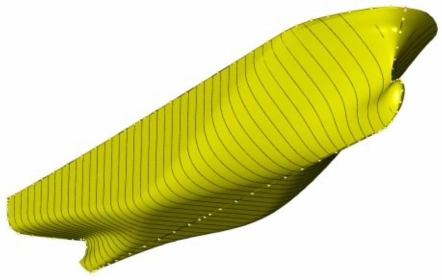


Figure 1: C11 Container Ship Hullform Model in Maxsurf

A tool has been developed at the Department of Naval Architecture, Ocean & Marine Engineering at the University of Strathclyde. It is based on a code written in MS VBA in MS Excel using the automation tools of the Maxsurf suite (Maxsurf Modeler 2014).

With analysis from the existing tool, the result of the benchmark study is summarised in table 3 and it has a good agreement. As shown, C_1 and C_2 is both larger than standard R_{pr0} 0.06, and it demonstrated that the C11 container vessel is vulnerable to parametric rolling. Therefore, it is necessary to improve the ship hull to avoid parametric rolling occurrence.

Table 3: Comparison between Current Calculation Result and IMO Published Result of Parametric Rolling

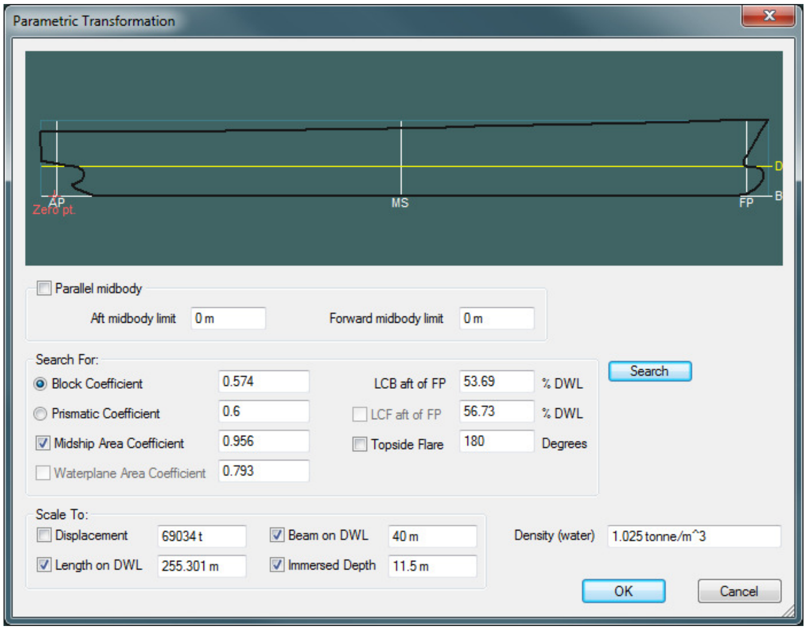
Organisation	L_{pp} (m)	ΔGM/GM	R_{PR}	C1	C2
SLF- IMO	262	1.056	0.356	0.437	0.073
University of Strathclyde	262	1.067	0.400	0.436	0.068
Note					
	Non-vulnerable				
🟥	Vulnerable				

OPTIMISATION

The optimisation was implemented in *modeFRONTIER* software (modeFRONTIER 2014). The objectives used are the minimisation of the parametric rolling, resistance and displacement difference between new design and original design. The optimisation procedure is comprised by a hullform generator, the performance analysis tools and the optimisation software that manages the hull design variables. The hullform is generated by *Maxsurf Modeler* software by the Lackenby transformation method (Lackenby 2001). Parametric roll amplitude is computed using the analytical method which is proposed by Japan in the relevant IMO sub-committee (CGIS 2014). The proposed method considers the roll motion assuming heave and pitch balanced quasi-statically. Resistance was processed by *Maxsurf Resistance* software. The optimised hull will then also be tested by the existing parametric rolling criteria. A case study on the optimisation of a containership based on C11 has been performed and is presented herein.

1) Hull Generator

Input variables in optimisation are the waterline length Lwl, breadth B, draft T, block coefficient C_b and midship coefficient C_m. To investigate these decision variables' effect on design objectives, the new design series were generated by *Maxsurf Modeler* software. The hull geometry is produced from an original ship by a "parametric transform" method, as shown in figure 2, based on Lackenby hull variation method (Lackenby 2001). The transformation moves the sections fore and aft until the required parameters are met. The reasonable variations of C_b, C_p or LCB are restricted within a ±5%. In *Maxsurf Modeler*, the new LCB position and either a new block or prismatic coefficient can be searched, followed by constraint values for a maximum of three of displacement, waterline length, beam and draft. The scenario studied here is that the designer would like to search for better solution in the proximity of the existing design whether the weights and the general arrangement are mature and acceptable. In that respect the difference between the new and the original design displacements are minimised.



☐ Parallel midbody
Aft midbody limit: 0 m
Forward midbody limit: 0 m

Search For:
● Block Coefficient: 0.574
○ Prismatic Coefficient: 0.6
☑ Midship Area Coefficient: 0.956
☐ Waterplane Area Coefficient: 0.793
LCB aft of FP: 53.69 % DWL
☐ LCF aft of FP: 56.73 % DWL
☐ Topside Flare: 180 Degrees

Scale To:
☐ Displacement: 69034 t
☑ Length on DWL: 255.301 m
☑ Beam on DWL: 40 m
☑ Immersed Depth: 11.5 m
Density (water): 1.025 tonne/m^3

Figure 2: Parametric Transform Dialogue in Maxsurf

2) Stability Analysis

There are several stability issues which should be checked in practice. In this paper, the parametric rolling problem is involved in the optimisation process. After identifying the optimum design candidates, the existing parametric rolling criteria are applied to these designs and then the optimum design can be selected. All the stability calculations were carried out using the *Maxsurf Stability* software (Maxsurf Stability 2014).

3) Resistance Analysis

As the procedure to eliminate the parametric rolling vulnerability is affecting the hullform, the resistance was also included as a design objective. Holtrop's method (Holtrop1982) calculated in *Maxsurf Resistance* software was selected for the calculation of the total resistance (Maxsurf Resistance 2014). The objective is to minimise the resistance at a service speed of 25 knots. The resistance result of the sample vessel is listed in figure 3.

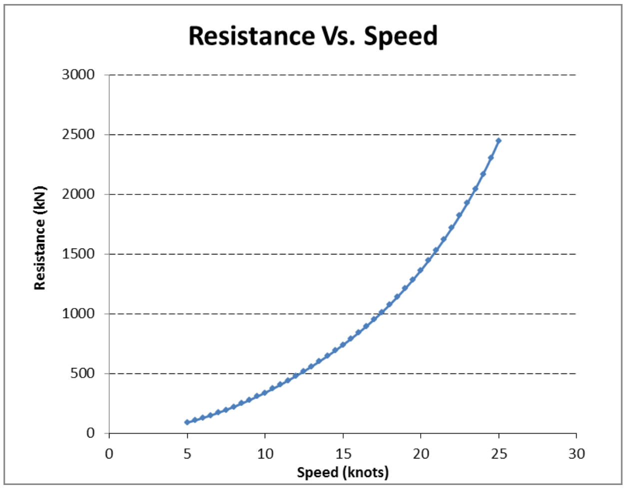


Figure 3: Resistance Calculated by Holtrop's Method

4) Multi-objective Optimisation

The optimisation was performed using the *modeFRONTIER* software (modeFRONTIER 2014). As shown in figure 4, the flow integrates the input decision variables, design objectives, optimisation loop which is programmed with VBA code in MS Excel, initial designs and optimisation algorithms. All evaluations of ship performance have been automated.

There are five input variables of ship principal parameters, ship length L, Breadth B, draft T, block coefficient C_b and midship coefficient C_m. All variables are set in the reasonable small range. Due to the fact that GM is affected by breadth (B), the lower boundary of B is restricted to change within -3% to avoid negative GM. These input parameters are sent to Excel application where ship hull transformation, parametric rolling prediction and resistance automated prediction are completed.

The displacement difference between the new design and the original design and the C_2 value in level 2 second check in parametric rolling are set as constraints. The design objectives are minimisation of displacement difference (DispDif) between original design $\Delta_{original}$ and new design Δ_{new}, resistance R_t, parametric rolling C_1 value and C_2 value. The variable range, design objectives and constraints are summarised in table 4.

The selected main particulars of hullform were searched by Deb's Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb 2002). The optimisation process combined with relevant softwares to achieve the optimum design is described in figure 5. 20 initial DOE designs combined with 150 generations are set in *DOE properties* and *scheduler properties* and 3000 designs have been generated. After deleting duplicated and error designs, it involves 1342 (44.7%) feasible designs and 184 (6.1%) Pareto designs.

Table 4: Input Variables, Objectives and Constraints Setting in modeFRONTIER

Parameter (Unit)	Upper Boundary	Lower Boundary	Maximum Value	Minimum Value	Optimisation Objectives and Constraints
Lwl (m)	+3%	-3%	262.96	247.64	$Minimise\ (DispDif\ (Lwl, B, T, Cb, Cm))$ $Minimise\ (C_1(Lwl,B,T,Cb,Cm))$ $Minimise\ (C_2\ (Lwl,B,T,Cb,Cm))$ $Minimise\ (R_t\ (Lwl,B,T,Cb,Cm))$ $DispDif = \left\|\Delta_{new} - \Delta_{original}\right\| < 0.01 \times \Delta_{original}$ $C_2 < R_{pr0} = 0.06$
B (m)	+5%	-3%	42.00	38.80	
T (m)	+3%	-3%	11.85	11.16	
C_b (/)	+3%	-3%	0.590	0.556	
C_m (/)	+2%	-2%	0.975	0.937	

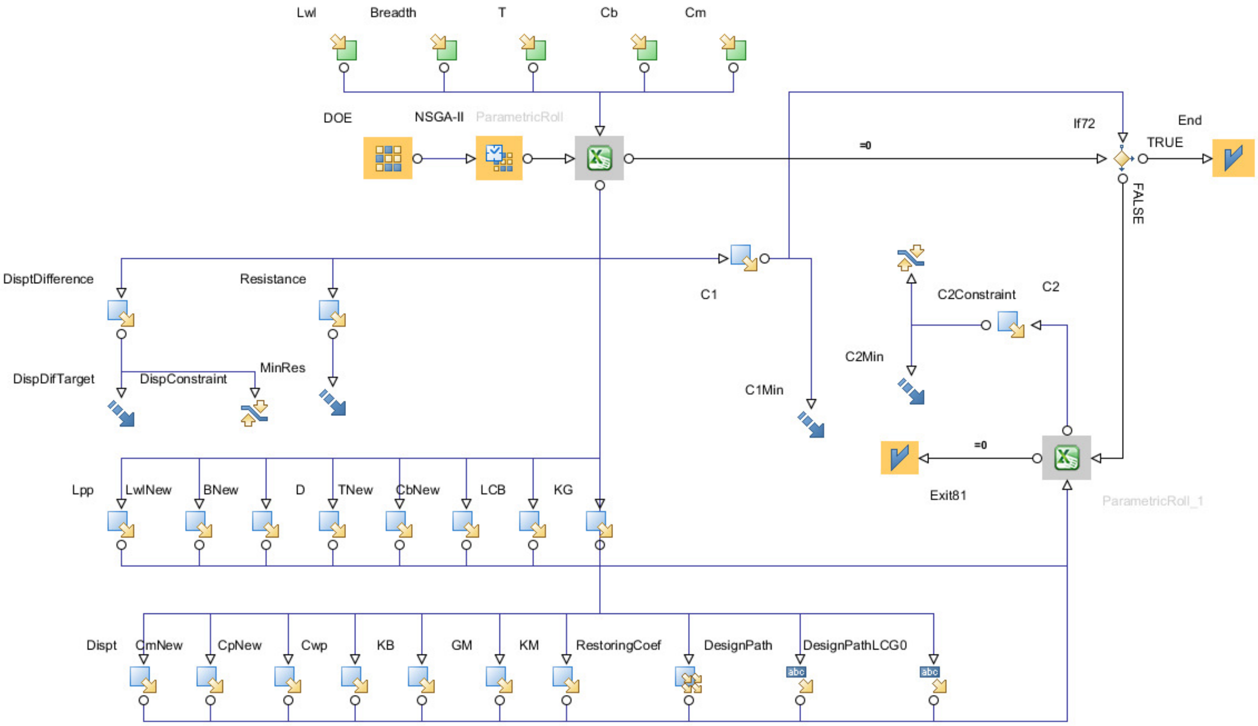


Figure 4: Work Flow in modeFRONTIER

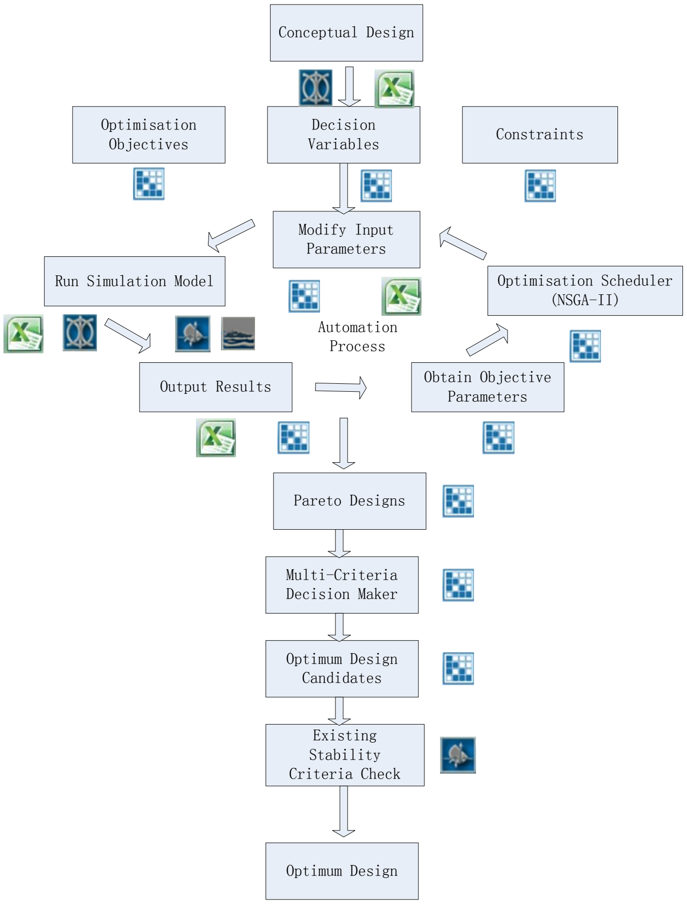
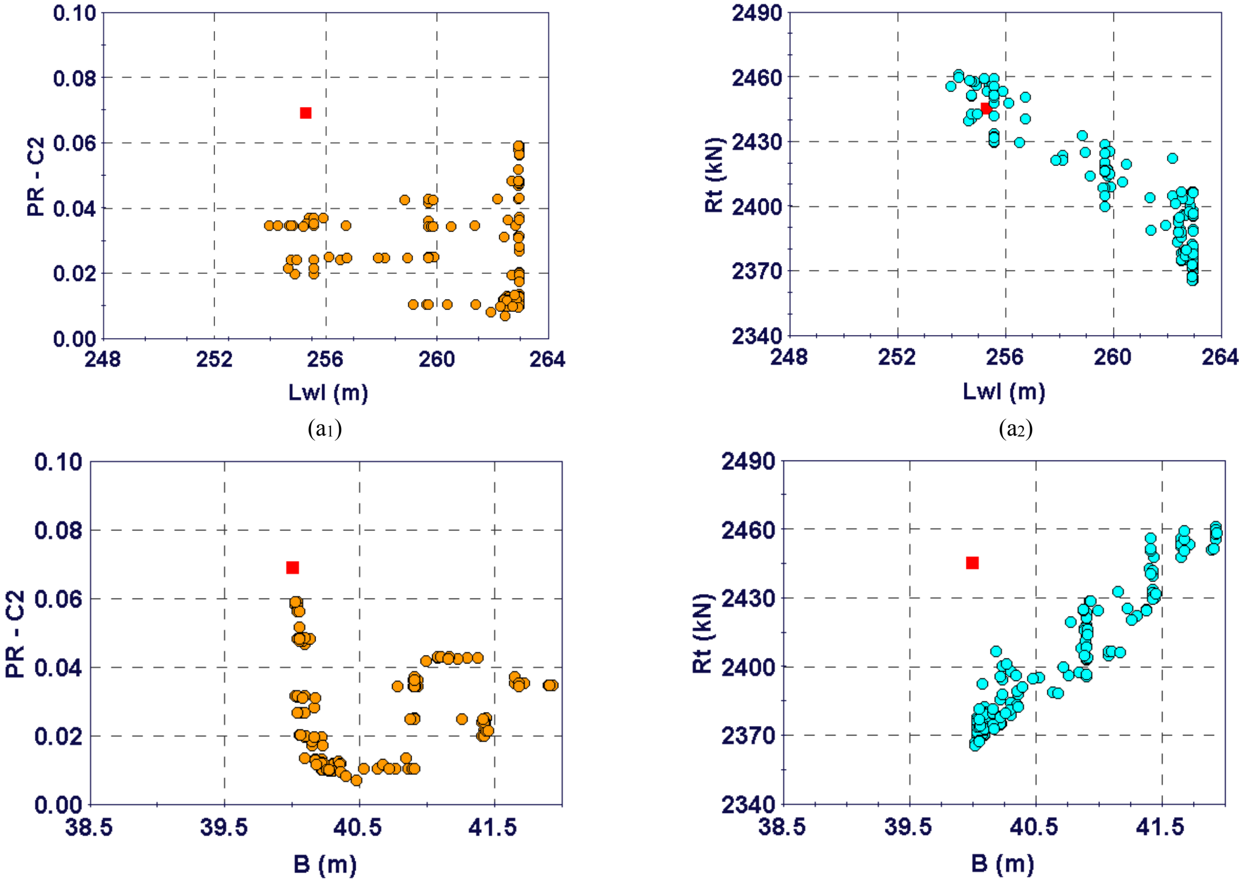


Figure 5: Optimisation Process with Relevant Software

RESULT AND DISCUSSION

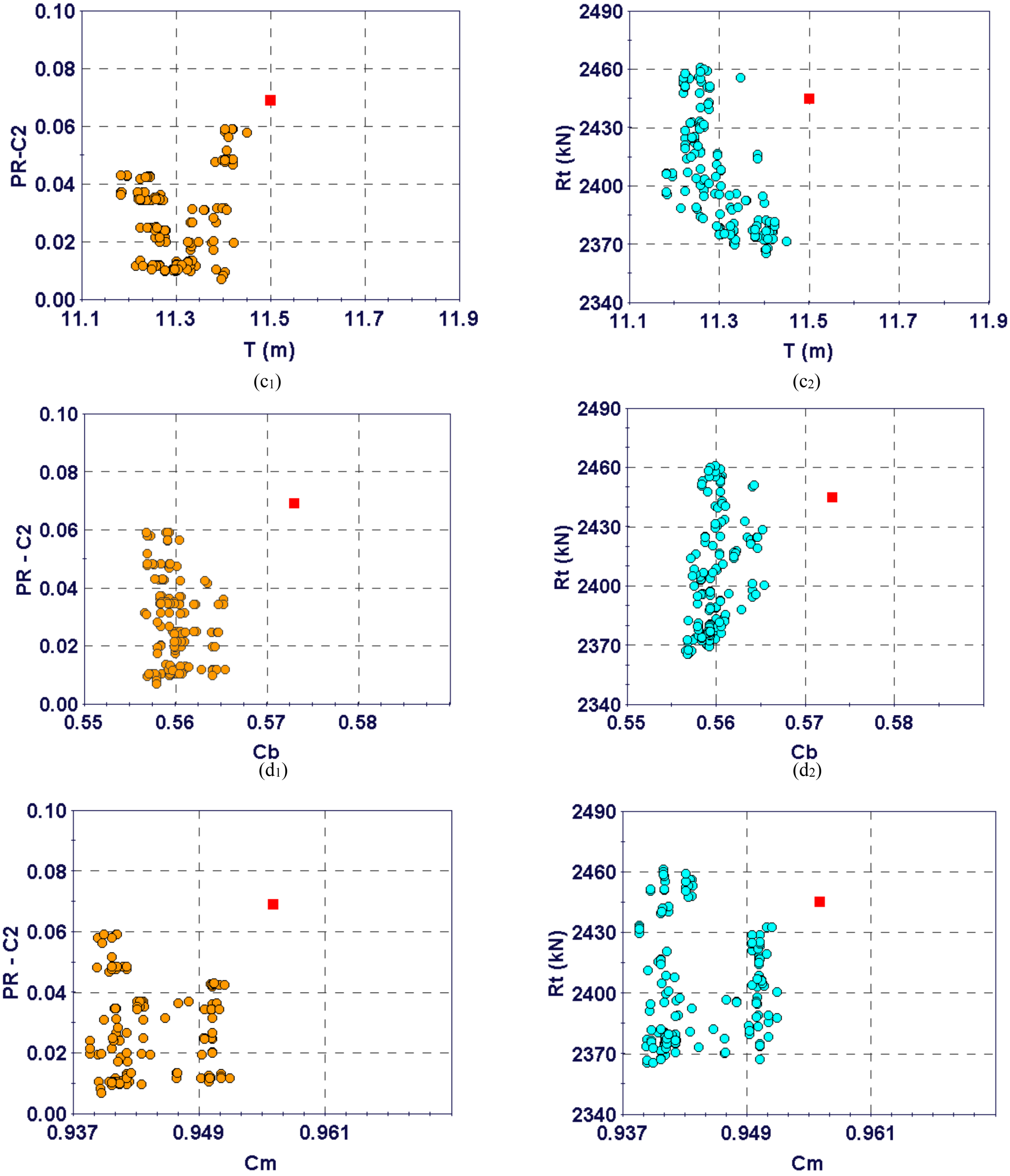
The main aim of this paper is to decrease parametric rolling performance and reduce the resistance through multi-objective optimisation. The objectives of hullform variation, parametric rolling performance and resistance were optimised by the NSGA II genetic algorithm. It is necessary to analyse the influence of each variable on the design objectives. Figure 6 shows the Pareto designs of this investigation with the five input variables on C_2 of parametric rolling (figure a_1 to figure a_5) and resistance R_t (figure b_1 to figure b_5). From the Pareto design distribution given in figure 6, compared to the original design no. 0 (shown in red point), the Pareto designs could be achieved by increasing length, increasing breadth, decreasing draft, decreasing C_b and decreasing C_m.

Although the minimisation of C_1 value is a design objective, all the C_1 values are larger than the standard R_{pr0} and all the designs are needed to be applied to second check. It was assumed that giving C_1 design objective a weight to 0 would be a valid scenario. For the other three objectives, it was assumed that all of them are equally important and therefore the weight was uniformly distributed to them. The designs were ranked according these weights. The 10 optimum designs are shown in table 5. The optimum design according to this ranking was the No.885 design. Additional calculations proved that it complied also with the existing intact stability criteria (2008 IS code). Its main particulars compared to those of the original design are listed in table 6. The resistance of the new design compared to that of original design is shown in figure 7. It is evident that the optimisation managed to keep the displacement the same, solve the parametric rolling problem and at the same time reduce the resistance by 2.5%.



(a_1) (a_2)

(b_1) (b_2)



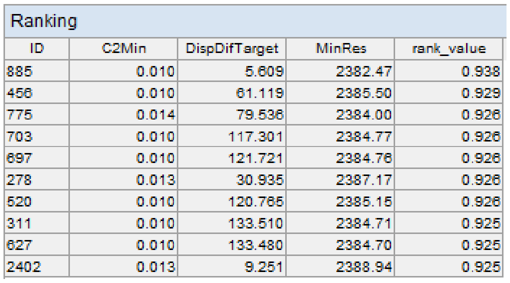
(c1) (c2)

(d1) (d2)

(e1) (e2)

Figure 6: Effects of Five Variables on C_2 of Parametric Rolling and Resistance R_t

Table 5: Top 10 Optimum Design Ranks



Ranking

ID	C2Min	DispDifTarget	MinRes	rank_value
885	0.010	5.609	2382.47	0.938
456	0.010	61.119	2385.50	0.929
775	0.014	79.536	2384.00	0.926
703	0.010	117.301	2384.77	0.926
697	0.010	121.721	2384.76	0.926
278	0.013	30.935	2387.17	0.926
520	0.010	120.765	2385.15	0.926
311	0.010	133.510	2384.71	0.925
627	0.010	133.480	2384.70	0.925
2402	0.013	9.251	2388.94	0.925

Table 6: Main Particulars of C11 and the No.885 Optimum Design

Item	C11	No.885	Unit
Length btw. waterline (L_{wl})	255.30	262.93	m
Breadth (B_{DWL})	40.00	40.36	m
Depth (D)	24.45	24.24	m
Draught (T)	11.500	11.403	m
Displacement (Δ)	69,034.40	69,040.00	tons
Block coefficient (C_B)	0.573	0.557	/
Midship Coefficient (C_m)	0.956	0.941	/
Transverse metacentric height (GM_T)	1.928	1.947	m
Vertical Centre of Gravity (VCG)	18.418	18.372	m
Service Speed (V_s)	12.86	12.86	m/s
Natural Roll period (T_Φ)	24.49	24.59	s
Bilge Length (L_{BK})	76.54	78.83	m
Bilge Breadth (B_{BK})	0.40	0. 40	m
Parametric Rolling - C_1	0.436	0.436	/
Parametric Rolling – C_2	0.068 (fail)	0.010 (pass)	/
Displacement Difference - DispDif	0.000	5.609	tons
Resistance at 25 knots – R_t	2444.96	2382.47	kN

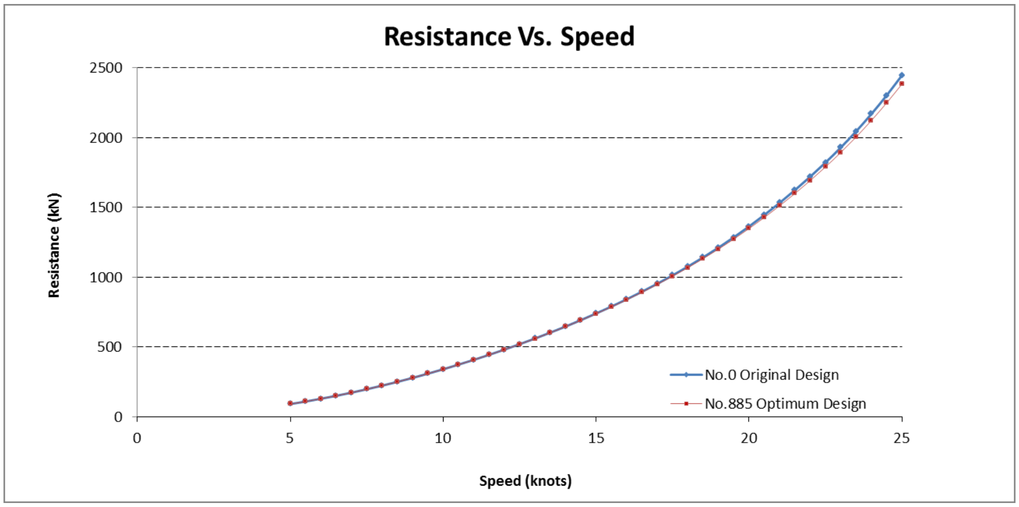


Figure 7: C11 and No.885 Optimum Design Comparison

CONCLUSION

In this paper, the procedure to check whether the vessel is vulnerable to the proposed draft vulnerability criteria of parametric rolling or not was presented. An optimisation process was developed to investigate the main impact of five design variables on parametric rolling performance and resistance. A tool was developed for the automation of the overall process with Visual Basic Application in Excel. A multi-objective optimisation process was integrated in *modeFRONTIER* and the NSGA II genetic algorithm was utilised to optimise the design objectives. Compared to the original design, increasing length, breadth, decreasing draft, block coefficient, midship coefficient could improve the ship safety to parametric rolling and reduce the resistance. The achieved optimum design passes the parametric rolling criteria while the resistance has also been reduced.

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