AN OPTIMIZATION MODEL FOR PRELIMINARY STABILITY AND CONFIGURATION ANALYSES OF SEMI-SUBMERSIBLES

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G D Gosain, Oceaneering Subsea Distribution Solutions, India, **R Sharma**, Design and Simulation Laboratory, Department of Ocean Engineering, IIT Madras, India and **Tae-wan Kim**, Department of Naval Architecture and Ocean Engineering, SNU, Republic of Korea

SUMMARY

In the modern era of design governed by economics and efficiency, the preliminary design of a semi-submersible is critically important because in an evolutionary design environment new designs evolve from the basic preliminary designs and the basic dimensions and configurations affect almost all the parameters related to the economics and efficiency (e.g. hydrodynamic response, stability, deck load and structural steel weight of the structure, etc.). The present paper is focused on exploring an optimum design method that aims not only at optimum motion characteristics but also optimum stability, manufacturing and operational efficiency. Our proposed method determines the most preferable optimum principal dimensions of a semi-submersible that satisfies the desired requirements for motion performance and stability at the preliminary stage of design. Our proposed design approach interlinks the mathematical design model with the global optimization techniques and this paper presents the preliminary design approach, the mathematical model of optimization. Finally, a real world design example of a semi-submersible is presented to show the applicability and efficiency of the proposed design optimization model at the preliminary stage of design.

1. INTRODUCTION

In the design of engineering structures, a normal design approach is to maximize the safety and operational performance and minimize the cost. It is well known that from the design point of view some of these functional parameters (i.e. parameters that are minimized or maximized in the design process) are often either antagonistic or conflicting in nature or both. These can be treated with the application of 'Multiple Criteria Decision Making (MCDM)' optimization methods, for more details see Deb (2009), Papanikolaou *et al*. (2010), Coello *et al*. (2014). A simple and illustrative example relates the objectives like cost and safety, e.g. in general if cost (e.g. through less freeboard, less plate thickness, less coatings of paint, and lower size of stiffeners, etc.) is reduced then the safety is compromised and vice versa. There exists a critical demand from the industry to have a preliminary design model that is based on the advanced empirical techniques, is computationally efficient and allows the designer to compute optimal design solutions satisfying the requirements of the owner/order placing agency. This demand has motivated the present research.

Our primary aim is to investigate a preliminary design approach that interlinks the mathematical design model with global optimization techniques. We investigate the design and development of an optimization model for semi-submersibles and focus on exploring an optimum design method which aims not only at optimum motion characteristics but also optimum stability, weight and operational efficiency. The stability parameters are accounted through the GM in different 'Degrees of Freedoms (dofs)', the manufacturing cost is accounted through the steel weight and operational efficiency is accounted through motion characteristics. The manufacturing efficiency is related to cost which is directly related to steel weight, and high motion responses adversely affect the comfort levels and operational requirements (of station keeping through dynamic positioning system, and mooring lines, etc.). However, these parameters are indirect parameters and that is a limitation in our current research. In the future, we shall be interested in incorporating more direct functional parameters related to manufacturing and operational efficiency. Through optimization studies the aim is to determine the most preferable principal dimensions of a semi-submersible that satisfies the desired requirements for motion performance and stability at the preliminary stage of design. We present a preliminary design approach, the mathematical model of optimization and a semi-submersible design example to show the application of the proposed design optimization model.

In the present paper, the use of 'Genetic Algorithm (GA)' to solve the MCDM optimization problem has been inspired from Deb (2009) and Papanikolaou *et al*. (2010). Papanikolaou *et al*. (2010) compared the 'Non-linear Goal Programming (NLGP)' and the GA methods to solve MCDM optimization problems and reported that although the NGLP is faster as compared to the GA, it does not efficiently compute the desired broader spectrum of the feasible design solutions. As in the design, it is highly desired that the design agency offers maximum range of possible feasible design solutions to the owner/order placing agency, the application of GA is preferable in our opinion. Our application of the GA allows us a complete investigation of the possible feasible design solutions at a higher computational cost and it is justified in our opinion. Furthermore, the GA based method is applicable for ill-defined problems also where computation of derivatives is difficult or derivatives do not exist. The GA based methods search primarily randomly, though can be in some pre-defined manner, and are likely to miss local minima/maxima. Even with these limitations, the GA based methods are attractive for optimization because of their inherent strength in working with ill-defined problems that do not admit a continuous solution, e.g. semi-submersible dimensions cannot vary continuously because requirements of stability, safety, and motion are conflicting and admit only discrete solutions.

We use an empirical approach for the estimation of responses of semi-submersible and the approach is derived from the earlier works. Possibly, starting with Burke (1970), Ochi and Vuolo (1971), and Hooft (1970 and 1971) have developed simple empirical approaches for the computation of hydrodynamic motion responses and validated their results against model scale experimental data. Oo and Miller (1977) discussed a method to compute the wave induced heave motion response of a variety of semi-submersible hull configurations. Natvig and Pendered (1977) presented a sophisticated approach to compute the hydrodynamic motion responses. Santen (1985) presented some approximate methods to be used in the determination of heave motions of semi-submersibles. Later, the approximate method of Santen (1985) was found to be in good agreement with more sophisticated and detailed computations reported by other researchers, e.g. Barltrop (1998).

There are three emerging directions in the field of design and analysis of offshore structures: 1) design for complete life cycle - from conception to design to manufacture to decommissioning; 2) modularization of design - to reduce the design cycle lead time and unit cost of design; and 3) optimization covering the entire life cycle and at each of the stages in lifecycle in the environment of integration, e.g. for more details see Goldan (1985), Sharma and Kim (2010), Gallala (2013), and Misra (2015). In this regard, we present a 'Multiple Criteria Decision Making (MCDM)' driven optimization method for the semi-submersible design applicable at the early stage of design. The unique feature of proposed optimization method is that it deals with conflicting requirements and offers the designer a wider spectrum of design selections (based upon the chosen function/s and level of compromise). Also, the presented method is simple and is useful for small and medium scale shipyards that do not have financial resources to buy costly software solutions. Our presented method is simple, efficient and implementable with a general purpose computing software, Matlab*™. Also, the present method is integrable in the complete life cycle and other advanced stages of design.

As we focus on the application of optimization method for developing a design method to be applicable at the preliminary stage of design, we prefer to use simple, efficient and fairly accurate empirical methods for the estimation of hydrodynamic characteristics, e.g. Hooft (1970 and 1971).

The remaining of this paper is organized: Section 2 describes the basics of semi-submersible optimization problem, Section 3 presents the semi-submersible optimization design process, Section 4 discusses the proposed semi-submersible optimization model with a design example and Section 5 presents the conclusions and future scope of research. A more detailed treatment of the results of this paper can be found in the thesis of first author (Gosain, 2013).

2. SEMI-SUBMERSIBLE OPTIMIZATION PROBLEM

2.1. THEORETICAL DETAILS

In the proposed empirical model, we use Morison equations (Morison *et al.*, 1950) and Hooft's approach (Hooft, 1971) for the computation of motion analysis and forces acting on the structure with the added mass coefficient C_m that is selected from the DNV codes, i.e. DNV (1987 and 2011) recommendations.

Following Lewandowski (2003), the equation of heave motion of semi-submersible platform in regular waves can be written as:

$$m\ddot{z}+C_z\dot{z}+\left(\rho g A_w\right)z = F_o\cos\left(\omega t+\sigma\right) \quad (1)$$

where,

$$m = m_s + m_a \quad (2)$$

and

m = total mass of the platform,
m_s = structural mass of the platform,
m_a = added mass of entrained water of the platform,
C_z = equivalent damping coefficient assuming damping proportional to velocity,
$\left(\rho g A_w\right)$ = restoring coefficient or spring constant for A_w being the water plane area,
z = linear vertical displacement of the platform from its calm-water position,
$\dot{z} = \frac{dz}{dt}$ = heaving velocity of the platform,
$\ddot{z} = \frac{d^2z}{dt^2}$ = heaving acceleration of the platform,
F_o = amplitude of wave exciting force,
ω = circular frequency of wave
t = time, and
σ = phase angle by which exciting force leads wave elevation when its value is positive.

The solution to equation of heaving motion is:

$$z = z_a\cos\left(\omega t-\epsilon\right) \quad (3)$$

where, $z_a = \dfrac{F_o}{\sqrt{\left(\rho g A_w - m\omega^2\right)^2 + \left(C_z \omega\right)^2}}$, and (4)

ϵ = phase angle by which heaving motion lags wave elevation when its value is positive.

Since the natural frequency of heaving motion of the platform is:

$$\omega_n = \sqrt{\frac{\rho g A_w}{m}}, \tag{5}$$

the amplitude of heaving motion of the platform can be re-written:

$$z_a = \frac{F_o / \rho g A_w}{\sqrt{\left\{1-\left(\frac{\omega}{\omega_n}\right)^2\right\}^2 + (2\gamma)^2\left(\frac{\omega}{\omega_n}\right)^2}}, \tag{6}$$

where,

$$\gamma = \frac{actual\,damping}{critical\,damping} = \frac{C_z}{2m\omega_n}. \tag{7}$$

We can observe from Equation (6) that the heave amplitude is directly proportional to the amplitude of exciting force F_o and to the magnification factor that is:

$$\frac{1}{\sqrt{\left\{1-\left(\frac{\omega}{\omega_n}\right)^2\right\}^2 + (2\gamma)^2\left(\frac{\omega}{\omega_n}\right)^2}}, \tag{8}$$

and it is inversely proportional to the water plane area A_w. The responses of semi-submersible towards the motions of surge, heave and pitch are computed by multiplication of the wave energy spectrum with the square of the 'Response Amplitude Operator (RAO)' function to evaluate the response spectrum value at particular frequency. The expression of motion-response spectrum is written in the following forms:

$$S_z(\omega) = \left[RAO(\omega)\right]^2 S_\zeta(\omega), \tag{9}$$

and

$$S_z(\omega) = \left[\frac{F_0/\zeta_a}{[\left(K-m\omega^2\right)^2 + \left(C_z\omega\right)^2]^{2}}\right]^2 (\omega)., \tag{10}$$

where the RAO is amplitude of response per unit of the wave amplitude, F_0 is the force, K is the stiffness of the structure associated with different type of motion, m is the summation of mass and added mass of the structure associated with different type of motion, C_z is the structural damping ratio, ζ_a is the wave amplitude corresponding to particular frequency, ω is the natural frequency corresponding to particular frequency, and $S_\zeta(\omega)$ is the wave spectrum.

We use the 'Bretschneider (B-S)' wave spectrum model to define $S_\zeta(\omega)$ for the motion response analysis using Equations (9-10) in our semi-submersible optimization model. The B-S spectrum replaced the Pierson-Moskowitz spectrum as a standard in the 'International Towing Tank Conference (ITTC)' recommendations. It is usually employed to describe tropical storm waves, such as those generated by hurricanes in the Gulf of Mexico or typhoons in South China Sea. Also, the B-S allows the user to specify the modal frequency and significant wave height and that means that the B-S can be used for sea states of varying severity from developing to decaying. In general, the B-S spectrum has a greater frequency bandwidth than the JONSWAP spectrum.

There exists different forms of definition for B-S wave spectrum and they are:

- Following Chakrabarti (2003), the B-S wave spectrum in terms of significant wave height H_s and significant wave frequency ω_s is:

$$S_\zeta(\omega) = 0.1687\left(\frac{\omega_s^4}{\omega^5}\right) H_s^2 exp\left(-0.675*\left[\frac{\omega_s^4}{\omega^4}\right]\right).$$

in m²/(rad/s), (11a)

where,

ω_s = significant wave frequency defined as the average frequency corresponding to the significant waves in the short-term record, in rad/s, and ω_s = (1/0.946)* ω_m ;

H_s = significant wave height defined as the average height of the highest one third waves in a short-term record, in meters; and

ω = frequency of the wave, in rad/s.

- Following Michel (1999 and 1968), Tucker and Pitt (2001), Techet (2005), ABS (2010) and OBS (2017), the B-S wave spectrum in terms of significant wave height H_s and modal frequency ω_m is:

$$S_\zeta(\omega) = \frac{5}{16}\left(\frac{\omega_m^4}{\omega^5}\right) H_s^2 exp\left(-1.25*\frac{\omega_m^4}{\omega^4}\right) \text{ in}$$

m²/(rad/s), (11b)

where,

ω_m = modal (peak) frequency corresponding to the highest peak of the spectrum, in rad/s,

H_s = significant wave height, in meters, and
ω = circular frequency of the wave or encountering wave, in rad/s.

We use Equation (11b) and for the B-S, relationship between the peak frequency and the significant height for the wave is:

$$\omega_m = 0.161g / H_s . \quad (12)$$

Following Hooft (1970 and 1971), the wave excited hydrodynamic forces on a semi-submersible platform are approximated by the sum of the following three forces:

- The undisturbed pressure force F_P arising from the pressure change over the hull in a wave that is not disturbed by the presence of the hull, i.e. Froude-Krylov force.
- The inertia force F_I arising from the acceleration of the water particles in a wave, which is not disturbed by the presence of the hull.
- The damping force F_C arising from the damping due to hull, of the velocity of the water particles in a wave that is not disturbed by the presence of the hull.

Now, the total wave excited force on the semi-submersible platform is:

$$F_z = \sqrt{\left(F_P + F_I\right)^2 + \left(F_C\right)^2} . \quad (13)$$

The F_C is most important in the evaluation of motion amplitudes near the resonance. However, outside the region of resonance the F_C shows a little effect on the amplitude. Since, the F_C on a semi-submersible platform is much less than the undisturbed pressure force and the inertia force, it can be treated as small except near the resonance. Also, since the semi-submersible platforms have very low natural frequencies (i.e. of the order of 0.314 radian per second or a natural period of 20 seconds and higher), the frequencies of most of the encountering waves will be much greater than the natural frequencies and will be outside the region of resonance.

Utilizing this and simplifying Equation (13) results into neglecting the damping force and the total wave excited force is:

$$F_z = F_P + F_I \quad (14)$$

where the F_P and F_I are computed for a hull cross-section as given by Faltinsen (1993):

$$F_I = \left(1 + C_a\right)\rho BH\zeta_a \left(\frac{\omega^2}{k}\right) e^{-k\left(h_1 + \frac{H}{2}\right)} \left(2sin\left(k\frac{L}{2}\right)sin\left(\omega t\right)\right) \quad (15)$$

$$F_P = -A_w\zeta_a \rho g e^{-kh_1}\left(2cos\left(k\frac{3L}{8}\right)sin\left(\omega t\right)\right), \quad (16)$$

and

$$\zeta_a = \sqrt{2 * S_\zeta\left(\omega\right) * \Delta\omega} . \quad (17)$$

The F_0 in Equation (10) is a force and this is replaced with the F_z for computing heave response spectrum. The area under heave response spectrum is one of the objective functions that are minimized. Following, Penny (1984) the structural steel weight distribution for semi-submersible is:

$$W_{col} = 0.286 d_1^{1.612} h_{tcol} , \quad (18)$$

$$W_{pont} = 9.4\times10^{-3}\left(S_p T_{op}\right)^{1.05} , \quad (19)$$

$$S_p = 2L\left(B + H\right), \quad (20)$$

$$W_{deck} = 0.218\times d\times A - 0.082\times10^{-4}\left(d\cdot A\right), \quad (21)$$

and

$$\text{Total structural steel weight} = W_{col} + W_{pont} + W_{deck} . \quad (22)$$

In Equations (18-22), the parameters are:

L, B, H = Pontoon section length, width and height,
d = Deck height,
A = Deck area,
d_1 = Column diameter,
h_{tcol} = Column height,
S_p = Pontoon area, and
T_{op} = Operational draft.

Following Moore (2010), the stability parameters for roll and pitch are defined:

$$GMr = KB + BMr - KG , \quad (23)$$

$$BMr = \frac{I_{xx}}{\nabla} , \quad (24)$$

$$GMp = KB + BMp - KG , \text{ and} \quad (25)$$

$$BMp = \frac{I_{yy}}{\nabla} \quad (26)$$

where,

GMr	= Metacentric height in roll,
GMp	= Metacentric height in pitch,
BMr	= Distance from the center of buoyancy to the meta-center in roll,
BMp	= Distance from the center of buoyancy to the meta-center in pitch,
KB	= Distance from keel to the center of buoyancy,
KG	= Distance from keel to the center of gravity,
I_{xx}	= Moment of inertia about the length wise longitudinal x-axis,
I_{yy}	= Moment of inertia about the breadth/width wise y-axis, and
∇	= Displaced volume.

3. SEMI-SUBMERSIBLE OPTIMIZATION DESIGN PROCESS

As mentioned previously, we consider the semi-submersible design problem as a multi-objective optimization problem. A multi-objective optimization problem (i.e. multi-objective programming, vector optimization, multi-criteria optimization, multi-attribute optimization or Pareto optimization) is primarily an area of multiple criteria decision making and it concerns with mathematical optimization problems involving more than one objective function to be optimized simultaneously. In the multi-objective optimization, optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objective functions, e.g. minimizing structural steel weight while minimizing the motion response and maximizing stability for a semi-submersible in roll and pitch.

From Deb (2009) and Coello *et al*. (2014), it is well known that for a non-trivial multi-objective optimization problem a single solution does not exist which simultaneously optimizes each of the defined objective functions. Furthermore, since the objective functions are conflicting in nature, there exists (possibly infinite number of) Pareto optimal solutions. A solution is called non-dominated (i.e. Pareto optimal, Pareto efficient or non-inferior), if none of the objective functions can be improved in value without impairment in some of the other objective values. In the absence of any other additional preferential information, all Pareto optimal solutions are considered mathematically equally good because the vectors cannot be ordered completely. In the present paper, our aim is to find a representative set of Pareto optimal solutions and quantifying the trade-offs in satisfying the different objectives.

Again from Deb (2009) and Coello *et al*. (2014), the evolutionary algorithms (under the class of a posteriori methods) are popular approaches to generating Pareto optimal solutions to the multi-objective optimization problems. At present, the ‘Evolutionary Multi-objective Optimization (EMO)’ algorithms apply Pareto-based ranking schemes, and the evolutionary algorithms (e.g. ‘Non-dominated Sorting Genetic Algorithm (NSGA)’ and strength Pareto evolutionary algorithm) are considered standard approaches now. The important advantage of evolutionary algorithms, for the efficient solution of multi-objective optimization problems, is that they ideally generate sets of solutions and allow computation of an approximation of the entire Pareto front. However, they also have limitations, e.g. low computational efficiency, higher computational time and the Pareto optimality of the solutions cannot be guaranteed. In the EMO, it is known that none of the generated solutions dominates the others even though optimality of the solutions cannot be guaranteed.

In our opinion, in the real world design practices, even with their limitations the EMO are useful because they generate sets of solutions that are essential at the preliminary design stage of a semi-submersible design. And, because of this reason, in the present work the evolutionary algorithm (i.e. NSGA) is used. We use NSGA-II as proposed by Deb *et al*. (2002) and our proposed design optimization model for the semi-submersibles is shown in Figure. 1. The optimization model is implemented in a general purpose computing software (i.e. Matlab*TM) and various interfaces have been written in the C++ computing language utilizing its object oriented features, Quarteroni *et al*. (2010) and Prata (2011).

Our main objective is to obtain optimized principal dimensions of a semi-submersible at the preliminary stage of design while satisfying the desired requirements for motion performance, structural steel weight and stability. Our scope is to give the designer a set of optimal solutions (Pareto front-best design alternatives) without costly and time-consuming model experiments and these optimal solutions will offer the designer and owner/order placing agency a well informed choice of selection.

In an optimization problem, it is important that the parameters and variables affecting the objective function are accounted accurately and efficiently, and for this first we conduct a sensitivity analysis to account for each of the variables affecting motion response or forces acting on the semi-submersible in beam and head sea conditions. For the sake of completeness and full and complete reproducibility, we show all the results. Figures. 2 to 13 show the effect of various dimensional parameters on motion response of semi-submersible in two different wave conditions i.e. beam sea and head sea conditions.

We observe from Figures. 2 (a) and 2 (b) that the forces become zero at three sets of wave frequency and the heave response become zero at the frequencies of zero forces for both the beam-sea and head-sea conditions (in the range of frequencies considered). The reason for this is that at very low frequencies (long waves) the forces on the columns predominate and are in-phase with the waves. As the frequency increases the forces on the hulls predominate so that for all the designs there is a frequency when the force on the columns is exactly equal and opposite to the forces on the hulls and above this frequency the force on the hulls predominates and is anti-phase to the wave. At much higher frequencies there are some numbers of zero or near zero force positions which are primarily due to the dimensions of the platform relative to the wave lengths.

We note that for the beam seas, the zero force at around $\omega_n = 0.4 rad/sec$ is due to the pressure and inertia forces cancelling one another while the zeros at $\omega = 0.717$ and 1.242 rad/sec are due to the cos (k$\frac{b}{2}$) term which appears in F_z. We observe from Figures. 3 (a) and 3 (b) that the vertical forces and the heave response of the platform in the head seas are greater than those of the beam seas. In general, theese observations apply to all the other cases too. Furthermore, we note that for the beam sea, the variation of the number of columns has very little effect on the vertical forces and on the heave response. And, for the head sea, the maximum force and the maximum heave response of the platform decrease as the number of columns increases. The maximum response is reduced by around 15 % when the number of columns is increased from 2 to 6.

We observe from Figures. 4 (a), 4 (b), 5 (a) and 5 (b) that for both the beam and head sea conditions as the volume ratio increases the froces and heave responses of the platform reduce. This effect is mainly due to the increased draught with increasing volume ratios since the pressure and water particle acceleration in waves decrease exponentially with increasing depth from the mean sea level. Also, the results show that the maximum heave response is reduced by around 55 % in the head seas and by around 54 % in the beam seas as the volume ratio is increased from 0.2 to 0.4. Thus, the change in volume ratio does lead to a reduced response apart from the draught effect.

We observe from Figures. 6 (a), 6 (b), 7 (a) and 7 (b) that for both the beam and head sea conditions the vertical forces on the platform increase as the displaced volume increases but the heave response of the platform decreases. The reduction in response is mainly due to the increase in waterplane area, i.e. spring stifffness effect increases with increasing displacement. For the head sea condition, the maximum heave response is reduced by around 15% and for the beam sea condition the maximum response is reduced by around 14 % when the displacement volume is increased from 20, 000 m^3 to 40, 000 m^3.

We observe from Figures. 8 (a), 8 (b), 9 (a) and 9 (b) that for the beam sea condition the maximum heave response of the platform is reduced by around 10 % as the pontoon spacing is incresased from 40 meters to 60 meters; and for the head sea condition the maximum force decreases slightly but the maximum heave response is increased by 14 %. In the beam sea condition the heave response reduces as the pontoon spacing increases, but in the head sea condition the response increases.

We observe from Figures. 10 (a), 10 (b), 11 (a) and 11 (b) that for both the beam and head sea conditions as the natural heave frequency increases while keeping the draft as constant; the maximum wave excited heave force and heave response reduce. For the head sea condition, the maximum response is reduced by 45% and for the beam sea condition it reduces by 31%. Furthermore, the frequency of maximum response moves toward a higher frequency as the natural frequency is increased from 0.258 to 0.314 rad/sec. Although, the response can be reduced by increasing the natural frequency, it can be noted that at a higher frequency there is a risk of synchronism or resonance with high wave frequencies commonly encountered at sea and there can be extremely severe response due to the synchronism. Because of this the option of high natural frequency is not implementable in the design practices.

From Figures. 2 to 11, we can observe that the heave response reduces with: Higher number of vertical columns; larger volume ratio or deeper draught; larger displacement volume; smaller pontoon spacing or length; and larger natural heave frequency at a constant draught.

We observe from Figure. 12 (a) that the vertical elliptical cross-section results into low heave and the difference between the circular and square cross-sections is negligibly small. Figure. 12 (b) shows that the vertical wave-excited force is considerably low for the vertical elliptical section because of its lower added mass at wave frequencies higher than 0.5 rad/sec. The horizontal elliptical section experiences the highest wave forces due to its high added mass. However, for the wave frequencies smaller than 0.35 rad/sec, it experiences a low wave force. Thus, for the waves with frequencies larger than 0.5 rad/sec, the heave force is highest for the horizontal elliptical section and smallest for the vertical elliptical section. And, for the wave frequencies lower than 0.35 rad/sec, the heave response is highest for the vertical elliptical section and is lowest for the horizontal elliptical section.

The number of columns that we use in our formulation is the number per pontoon, e.g. 2 columns per pontoon and two pontoons (minimum number of the pontoons). As we report in Figures. 2 and 3, a detailed study is done to study the effect of number of columns (per pontoon) in both the head and beam sea conditions. Although, our results of Figures 2 and 3 show that the number of columns (per pontoon) affects the response, in practice the manufacturing cost associated with it actually rules the application, e.g. higher number means higher cost. Because of this, in our application too, the number is fixed to 2 considering cost and manufacturing impacts.

After, the sensitivity analysis, now we focus on the objective functions. As mentioned previously, in order to use the design objectives indicative of desired platform behavior in waves, we consider the following objective functions:

- Minimizing the heave motion: This is implemented through the area under heave response curve as has been implemented by other researchers, e.g. Birk and Clauss (2008). We first compute the RAOs to check the effect of different design parameters on response of the structure and then these are incorporated in the optimization model. They also help in understanding whether the particular parameter is worth considering in the optimization model or not? In the final optimization model the B-S wave spectrum is used the heave response spectrum and the area of response spectrum are used to compare the structural responses for different designs.

- Minimizing the structural steel weight of structure: This is implemented through the structural steel structural steel weight as computed by the empirical approach.

- Maximize stability in roll: This is implemented through the GM_r (meta-centric height in roll).

- Maximize stability in pitch: This is implemented through the GM_p (meta-centric height in pitch).

Our model emphasizes on maximizing the GM in roll and pitch degrees of freedom. However an upper constraint can be placed on the roll and pitch accelerations as per the operational requirements put up by the client. Also, the optimized solution sets obtained from the use of GA in our model are in the form of pareto-front and they give us different options to choose the rolling and pitching parameters from the optimized solution sets, as per the preferences of client.

The minimization of heave motion and structural steel weight of structure and the maximization of stability in roll and pitch are subjected to the constraints. We use three constraints: Geometric inequality constraint (i.e. pontoon length, pontoon width, pontoon height, column diameter, column height, pontoon spacing, B/H, deck_area, $D \leq B$, L-2*B, and displacement); equality constraints (i.e. air gap and deck height); and stability parameters (i.e. GMr, GMp, and heave natural period). The detailed listing is reported in Table 1. These constraints are specified either by the shipbuilding yards (i.e. as per availability or limitations or both of the manufacturing facilities) or the owner/order placing agency or the classification societies or all. The basic geometry of semi-submersible platform is shown in Fig. 13. The design characteristics associated with the platform geometric properties are listed in Table 2.

The specification of deck area is one of the design characteristics selected early in the preliminary stage of design of semi-submersible. In the proposed formulation, minimum deck area is assumed to be 6000 m^2 and the reference system for vertical measurement is the base line (keel). The computed results show that the deck area is higher than the minimum required and the displacement or total structural steel weight of the structure achieves the required feasible range and gives broad optimal design choices.

4. SEMI-SUBMERSIBLE OPTIMIZATION MODEL WITH A DESIGN EXAMPLE

The feasible solution space sets searched by the proposed optimization algorithm model are shown in Figure. 14. The optimum results obtained from semi-submersible optimization model in the form of 'Pareto Optimal Front (POF)' are shown in Figures. 15 to 17. In Figures 15 - 17, the blue color shows the '*feasible space*' and the red color shows the '*Pareto frontier*'.

The dimensions of offshore platform have impact on the stability and response. A too high GM value results into a large righting moment and thus into the increased accelerations in the pitch and roll degrees of freedom. In this regard, a stiff platform tends to respond to the wave profile more quickly and tends to assume the slope of the passing wave. This increases the responses in pitch and rolls degrees of freedom and creates shorter pitching and rolling periods that are uncomfortable for the crew.

On the reverse side, a lower GM value results into platform becoming vulnerable to large heeling moments. Hence, in a balanced design, there needs to be a compromise between the stability and motion response of the platform. This is reflected in the results reported in Figures. 15 (a) and 15 (b). In our opinion, a higher emphasis on stability is expected to compromise adversely on the response of platform and vice-versa also. This emphasis on stability can be quantified through the use of weights. The use of weights as preferences is important and can be implemented also in our model. However, we have not implemented this because of: Quantification of weights is as per the client's preferences, specifications and requirements and clients do not allow that to be reported; and current implementation emphasizes on equal weights to all design parameters as we focus on a preliminary detailed study.

Since, the area under the heave response curve and total structural steel weight are objectives that are conflicting in nature, Figure. 15a indicates the feasible designs and the POF between the area under heave response curve and structural steel weight. Figure. 15 (b) shows the feasible designs and the POF between the area under heave response curve and meta-centric height in pitch. Since, the total structural steel weight and pitch meta-centric height are the objectives that are conflicting in nature, Figure. 16 (a) shows feasible designs and the

Pareto frontier between total structural steel weight and meta-centric height in pitch. Figure. 16 (b) shows feasible designs and the Pareto frontier between area under heave response curve and meta-centric height in roll. Since, the total structural steel weight and roll meta-centric height are the objectives that are conflicting in nature, Figure. 17 (a) shows feasible designs and the Pareto frontier between structural steel weight and meta-centric height in roll.

Now, from Figures. 15-17, we select the optimized results in the form of Pareto-optimal solution sets and list them in Table 3. In our results the units are in SI system unless stated otherwise. An offshore platform like semi-submersible is a moored structure and the mooring system on semi-submersible usually offers restoring forces predominantly in the horizontal plane and very little in the vertical plane. Although, the motions in pitch and roll degrees of freedom have an adverse effect on the drilling operation, they are not as significant as the heave motions. From the analysis of available field data it has been found that the operations are halted by excessive heave motion rather than excessive roll or pitch motions. Hence, our focus is on the stability in horizontal plane and because of this we report heave time periods in Table 3.

In Table 3, there are 9 designs, and they are chosen taking into consideration the objective of minimum structural steel weight, maximum KM (in roll and pitch degrees of freedom) and minimum response area in each of the graphs. The minimum and maximum objectives are colored in red and underlined to indicate the best in each of the stated goals.

As we mentioned previously, the primary motivation of the present research is to offer the designer a wider spectrum of possible design solutions and in this regard from Table 3, a designer can select the best design from the options available depending upon the specific choice/s of selection. Additionally, a designer can use structural steel weight to each of the objectives to select the best compromised choice.

From the design point of view, we observe the following key designs from Table 3:

- Design 1 is best in context of its minimum total structural steel weight of the structure.
- Design 2 is best for its minimum response area.
- Designs 3 and 4 have the advantage of having maximum meta-centric height in roll and pitch respectively.

However, the 'Designs 1 to 4' pay some penalty to achieve these minimum or maximum objectives. 'Designs 5 to 9' show a compromised solution with paying minimum penalty to achieve the objectives mentioned to arrive at the optimum design of semi-submersible. Since the objective functions are conflicting one can assign systematically structural steel weight attributes to each of the objective functions to choose the best design according to the requirements. In the field of offshore and ship structures, although the material cost is much less than the system and machinery costs, the material cost is 'only' the cost that is reducible through the design directly. Other costs can be reduced through design indirectly, e.g. design for less motion will reduce power consumption by the position control systems and thereby reducing cost. This material cost is related to the structural steel weight and we think that a correlation can be found between each of the objective functions and structural steel weight. Furthermore, there are ongoing investigations focusing on the exploration of lighter structural configurations other than steel plate and sections that can be applied to the offshore platforms, e.g. corrugated shell plating, Ringsberg *et al*. (2014). Once, a suitable structural steel weight is assigned to each of the objectives then it will be easy to select the best compromised choice in terms of less material cost. However, these ideas are at the nascent stage only and we do not have any results in these directions. In future, we shall focus on detailed exploration of these ideas.

A closer analysis of the results show that the 'Design 1' weighs 25% lesser and costs 6.34 million Euros lesser when compared to the 'Design 2', i.e. one ton of steel costs 800 Euros, adapted from Ringsberg (2011). Also, for the 'Design 1' maximum heave response is 21% greater than the 'Design 2' for the same sea conditions. So a compromise solution, i.e. 'Design 5' between structural steel weight/cost and response can be selected from the Pareto optimal front which weighs 3% more than the 'Design 1' and 23% lesser than the 'Design 2' with cost of 5.89 million Euros lesser than the 'Design 2' with maximum heave response of 7% greater than the 'Design 1'. This is shown in Figure. 17b. Similarly, the 'Designs 6 to 9' represent compromise design solutions for different design requirements.

Based upon the above analysis, we state that essentially, the proposed optimization model offers a broad spectrum of the design choices at the preliminary stage of design, where the design can be selected according to the requirements placed by either the owner/order placing agency or the classification societies or all.

5. CONCLUSIONS

This paper has presented a critical parameter (from sensitivity analysis) driven optimum design model for semi-submersible platform. The design has been carried to optimize the parameters of structural steel weight, stability and motion performance. The presented optimization model for design of semi-submersible takes all design variables into considerations, reveals compromised solution set with broad design choices where minimum penalty is paid in terms of cost (manufacturing and operational); with an emphasis on increasing motion performance and stability. The optimized design obtained in terms of Pareto optimal front can be investigated further for detailed analysis accounting for the non-linearities followed by model experiments.

Since the proposed design model is based upon a highly iterative process, the dimensions are refined in step wise manner, and the proposed model can be efficiently used in practice. The proposed model meets applicable operational requirements while minimizing costs/structural steel weight. The model is based upon some chosen parameters which can be used by the user depending upon variable set of requirements placed by either the owner/order placing agency or the classification societies or all.

However, the proposed design model is based upon simple empirical models and that is useful only at the preliminary stage of design. For a detailed motion analysis one needs to consider the moments of the response spectrum along with a probability distribution (e.g. Raleigh distribution), and then these moments of the response spectrum can be used to compute probabilities of exceedance. The moments of response spectrum and probabilities of exceedance are useful in the advance stage of design. Furthermore, in the later advanced stages of design with more detailed design available an integration with the 'Computational Fluid Dynamics (CFD', 'Finite Element Analysis (FEA)', 'Computer Aided Design/Engineering (CAD/E)' software solutions will be highly desired to arrive at design solution set that can be used for the selection of 'Final Design' at the contract signing and production stages. Our future work shall go in this direction and currently this is under investigation.

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6. ACKNOWLEDGEMENTS

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APPENDICES

Table 1: Constraints for semi-submersible optimization problem

Geometric inequality constraints	(i) 90 < Pontoon Length (L in m) < 110, (ii) 10 < Pontoon Width (B in m) < 15, (iii) 5 < Pontoon Height (H in m) < 15, (iv) 5 < Column Diameter (d_1 in m) < 15, (v) 9 < Column Height (ht_{col} in m) < 31, (vi) 60 < Pontoon Spacing (in m) < 75, (vii) B/H > 1 and B/H < 2, (viii) deck_area (A=L**b*, in m^2) > 6000 m^2, (ix) D ≤ B, both in m, (x) L-2*B > 10, both in m, and (xi) Displacement (in tons)* < 50000.
Equality constraints	(i) Air gap (in m) = 9, and (ii) Deck height (*d* in m) = 7.
Stability parameters	(i) GMr (in m) > 0, (ii) GMp (in m) > 0, and (iii) Heave natural period** (in s) > 18.

*Note that the displacement as given in Equation (22) is dependent upon the d_1 , ht_{col} , L, B and H, etc. These values have the upper and lower bounds associate with them. Using the lower bounds of parameters will result into lower bound for the displacement. Hence, because of this, the displacement is given in terms of upper bound with constraints on dimensions.
**The natural period in heave degree of freedom less than 18 seconds is of serious concern for the semi-submersibles. Furthermore, the downtime of semi-submersibles is mainly governed by the heave motions. Because of this our focus is on the heave motion.

Table 2: Basic dimensions related properties/characteristics of the semi-submersible platform

S. no.	Design parameters	Governing equation
1	Water line area (in m^2)	$A_{wl} = \sum_{i=1}^{ncol} \frac{\pi d_1^2}{4}$
2	Equivalent diameter (in m)	$D_{equi} = \sqrt{\frac{4BH}{\pi}}$
3	Transversal moment of inertia (in m^4)	$I_{xx} = \sum_{i=1}^{ncol} I_{xx}(i) + y^2(i) \cdot A_{wl}(i)$
4	Longitudinal moment of inertia (in m^4)	$I_{yy} = \sum_{i=1}^{ncol} I_{yy}(i) + x^2(i) \cdot A_{wl}(i)$
5	Volume of the columns (in m^3)	$V_c = \sum_{i=1}^{ncol} A_{wl} h_{tcol}$
6	Submerged volume of the columns (in m^3)	$V_{mc} = \sum_{i=1}^{ncol} A_{wl} h_1$
7	Volume of the pontoons (in m^3)	$V_p = \sum_{i=1}^{npont} \frac{\pi D_{equi}^2}{4} l_i$ or $V_p = \sum_{i=1}^{npont} LBH$
8	Displacement (in tons)	$\Delta = (V_{mc} + V_p) \cdot \gamma$

Nomenclature: γ = Water specific density; B, H = Width and height of the cross section, in m; d_1 = Column diameter, in m; x, y = Column distances from the length wise and breadth/width wise axes respectively, in m; h_1 = Submerged columns height, in m; L = Pontoon length, in m; $ncol$ = Number of columns; $npont$ = Number of pontoons; and h_{tcol} = Total column height in m.

Table 3: List of the optimized results in the form of Pareto-optimal solution sets.

Design parameter	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**	**Design 6**	**Design 7**	**Design 8**	**Design 9**
Pontoon length - L (in m)	90.51721	109.474	90.1065	108.8142	90.0957	91.60072	94.08344	106.5726	107.6659
Pontoon breadth - B (in m)	12.72714	11.9236	11.9236	14.75612	12.12217	11.9003	11.72224	13.78383	13.70918
Pontoon height - H (in m)	6.434266	7.40971	6.2204	7.849512	6.847735	5.953942	6.150722	7.310521	6.966525
Column diameter - d_1 (in m)	12.54891	11.747	11.747	14.73967	11.7413	11.77601	11.69111	13.78308	13.67346
Height of column - ht_{col} (in m)	24.9767	35.0487	35.2332	9.74136	28.20123	35.65414	37.37359	14.50501	18.09055
Pontoon spacing - pont_spc (in m)	66.39504	74.8975	74.8975	60.816	67.1399	73.45316	74.93374	60.56642	64.4107
Total structural weight - total_wt (in tons)	***22710.79***	30636.1	24741	25683.96	***23264.47***	***24602.11***	25752.73	***24772.12***	25897.01
Deck area - deck_area (A in m^2)	6009.894	8199.36	6748.76	6617.645	6049.017	6728.363	7050.023	6454.719	6934.834
Submerged height of column - h_1 (in m)	15.94008	26.0475	26.2386	0.698022	19.18033	26.67594	28.37886	5.519492	9.077317
Metacentric height in roll - GMr (in m)	4.266614	0.01875	4.20019	5.871289	2.013876	3.665777	3.150674	3.655063	4.093915
Metacentric height in pitch - GMp (in m)	13.67998	9.83783	6.83426	36.02517	9.176403	7.787396	7.249893	28.95267	26.49012
KMr (in m)	23.00161	24.0219	***28.0947***	18.45936	22.31862	***27.61035***	***28.04324***	17.97657	19.97586
KMp (in m)	32.41497	33.841	30.7288	***48.61325***	29.48115	31.73197	32.14246	***43.27418***	***42.37207***
KG (in m)	18.73499	24.0031	23.8945	12.58807	20.30475	23.94457	24.89256	14.32151	15.88194
KB (in m)	4.530233	5.83523	5.95731	3.944855	5.010462	5.960839	6.241283	3.892149	3.971547
Heave time period - heave_tim_pd (in s)	18.02623	22.2024	19.3123	18.05805	19.43407	19.12065	19.69884	18.35079	18.49834
Area under heave response spectrum curve - Aera_und_curv (in $unit^2$)	3.927717	***3.15544***	3.5999	4.428898	***3.676167***	3.613926	***3.501146***	4.086634	***3.91233***
Area moment of inertia about the X axis - Ixx (in m^4)	1.97E+10	3.80E+10	3.02E+10	1.50E+10	2.19E+10	2.93E+10	3.25E+10	1.55E+10	1.90E+10
Area moment of inertia about the Y axis -Iyy (in m^4)	2.30E+10	4.70E+10	2.89E+10	3.03E+10	2.46E+10	2.95E+10	3.29E+10	2.93E+10	3.21E+10
Area moment of inertia about the Z axis -Izz (in m^4)	3.11E+10	5.83E+10	3.85E+10	3.97E+10	3.23E+10	3.81E+10	4.19E+10	3.77E+10	4.18E+10
Radius of gyration in roll - Rr (in m)	29.431	35.2162	34.9456	24.188	30.6726	34.5023	35.5384	25.0374	27.0642
Radius of gyration in pitch - Rp (in m)	31.8484	39.1657	34.1797	34.3353	32.4969	34.6301	35.7294	34.3801	35.2195
Radius of gyration in yaw - Ry (in m)	36.9949	43.6161	39.4551	39.3268	37.2395	39.3719	40.3534	38.9901	40.1727
Parametric choice of selection	**Min weight**	**Min area**	**Max KM_r**	**Max KM_p**	**Com Awt**	**Com WKM_r**	**Com AKM_r**	**Com WKM_p**	**Com AKM_p**

Nomenclature: Min weight - Minimum weight; Min area - Minimum area under the response curve; Max KM_r - Maximum KM_r; Max KM_p - Maximum KM_p; Com Awt - Compromise between area under the response curve and weight; Com WKM_r - Compromise between the weight and KM_r; Com AKM_r - Compromise between area under the response curve and KM_r; Com WKM_p - Compromise between the weight and KM_p; and Com AKM_p - Compromise between area under the response curve and KM_p.

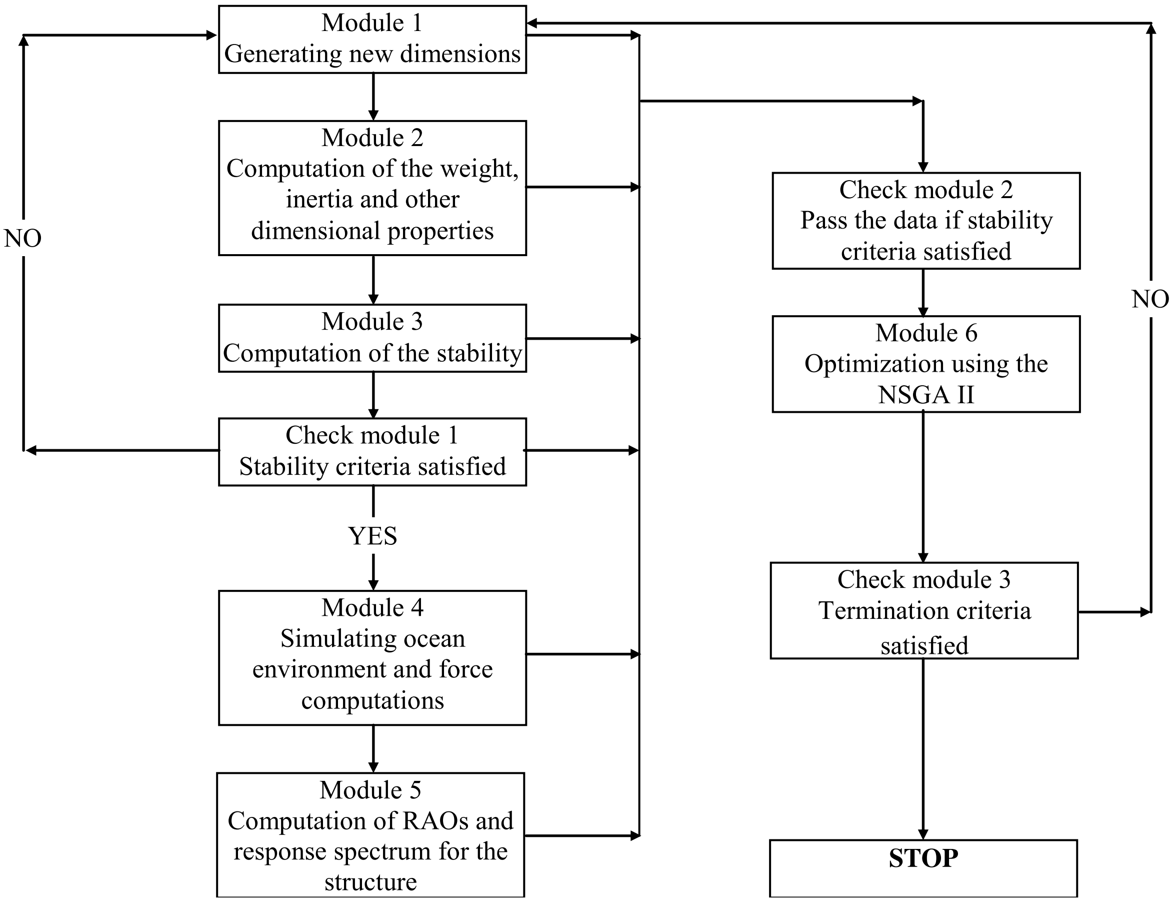
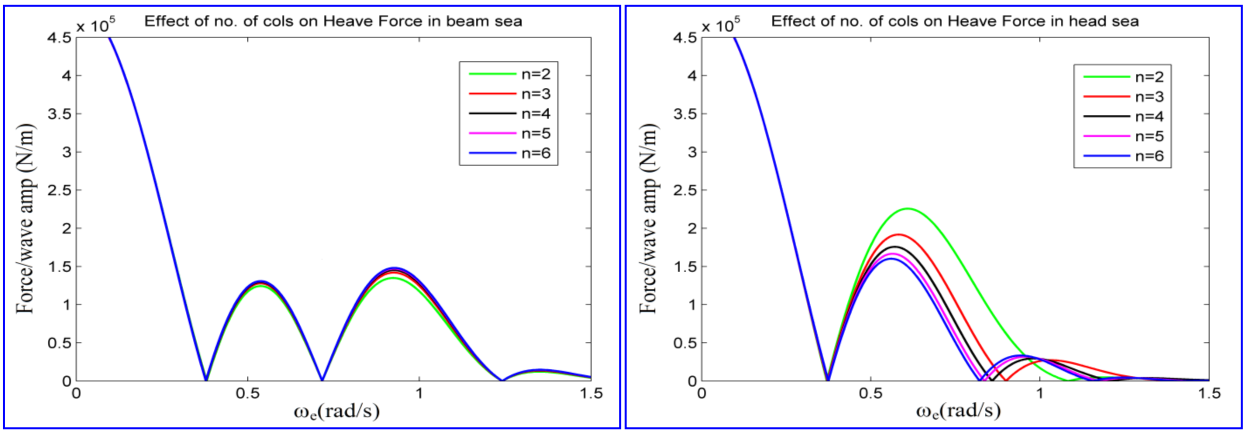
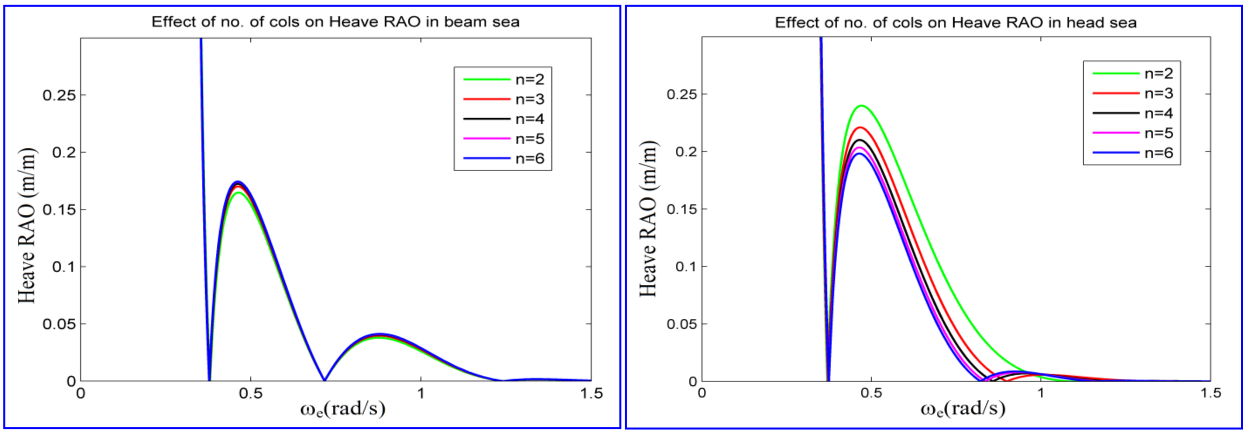


Figure 1: Optimization design model for the semi-submersibles.



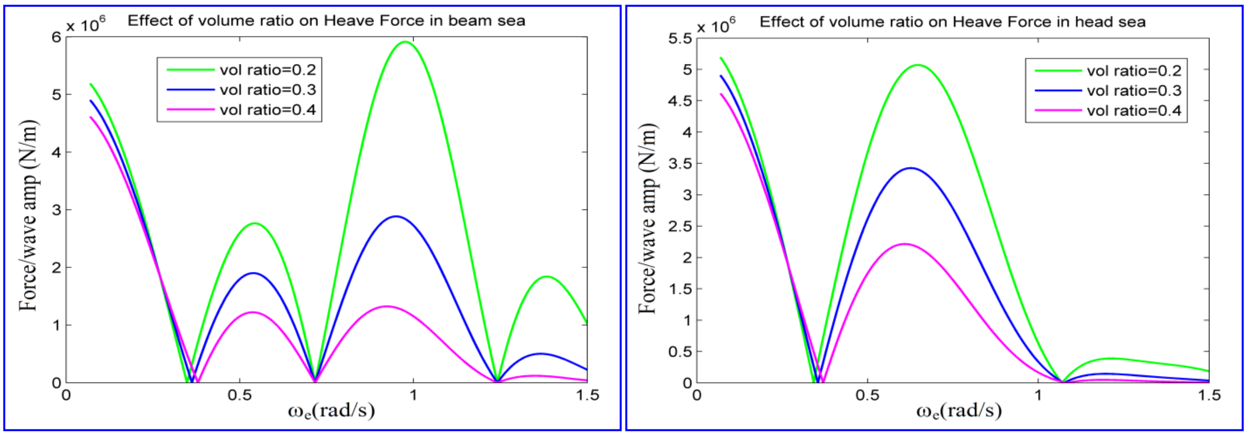
(a) Beam sea condition (b) Head sea condition

Figure 2: Effect of the number of columns on heave force in beam and head sea conditions.



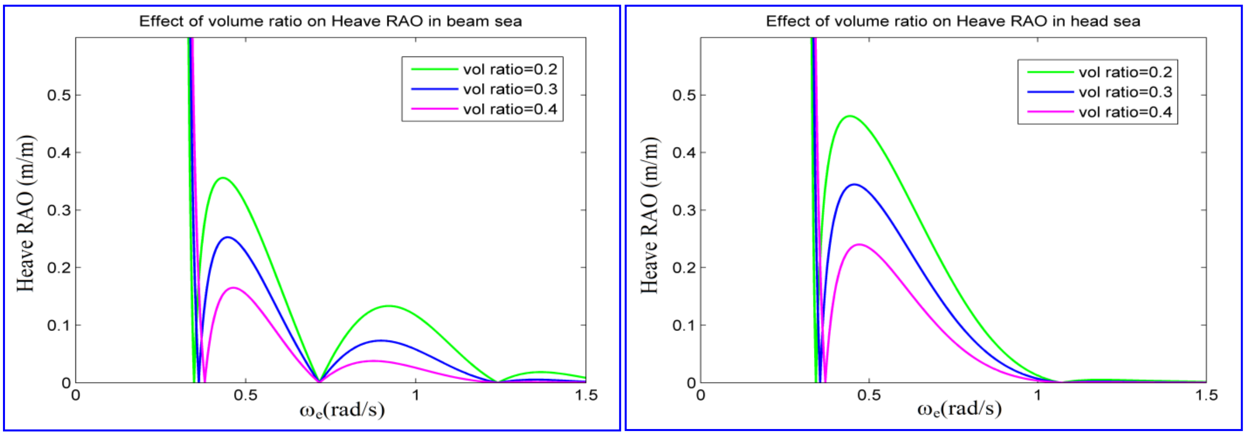
(a) Beam sea condition (b) Head sea condition

Figure 3: Effect of the number of columns on heave RAO in beam and head sea conditions.



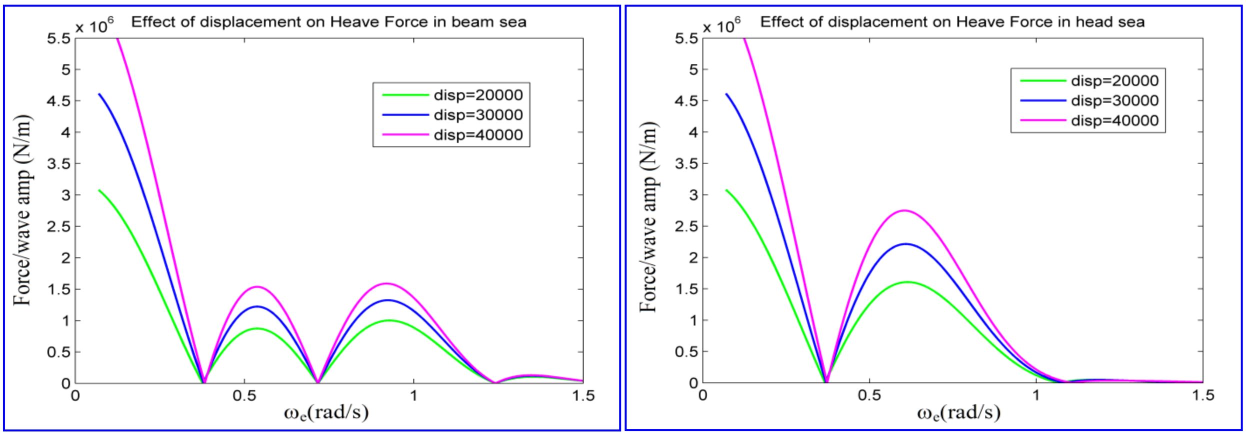
(a) Beam sea condition (b) Head sea condition

Figure 4: Effect of the volume ratio on heave force in beam and head sea conditions.



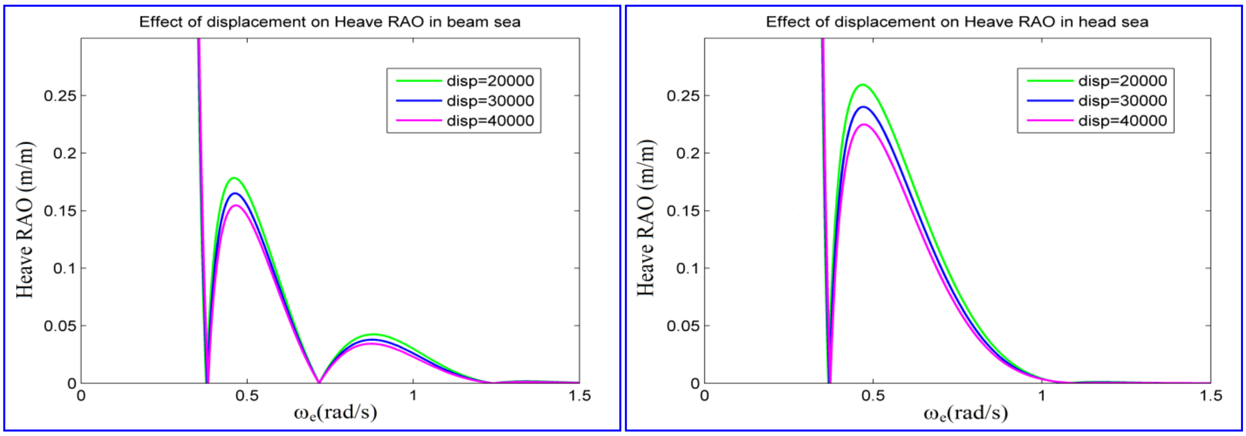
(a) Beam sea condition (b) Head sea condition

Figure 5: Effect of the volume ratio on heave RAO in beam and head sea conditions.



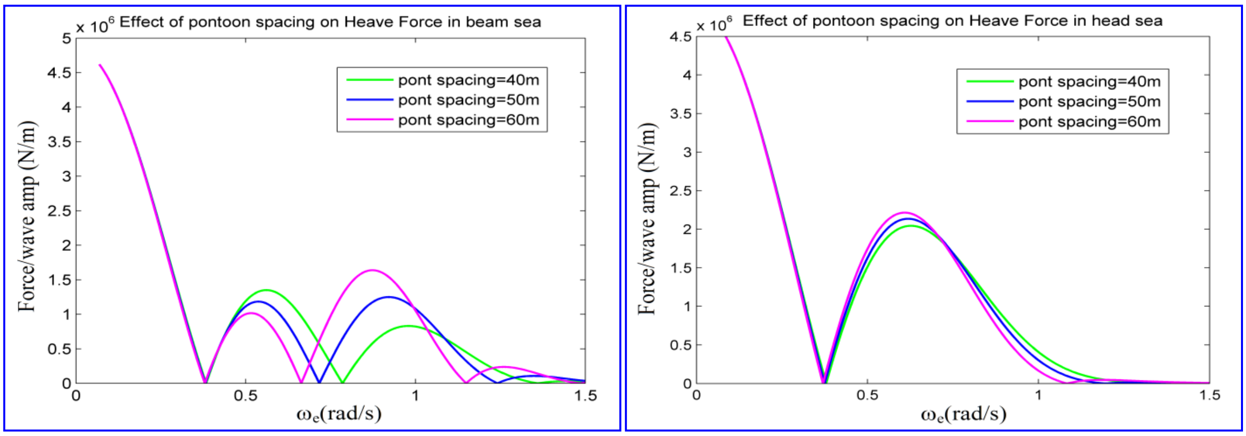
(a) Beam sea condition (b) Head sea condition

Figure 6: Effect of the displacement on heave force in beam and head sea conditions.



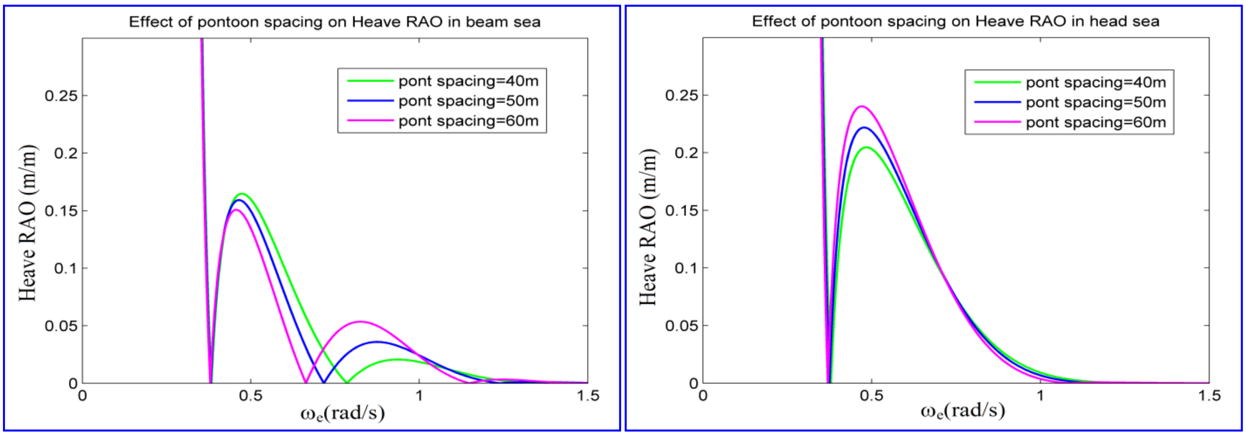
(a) Beam sea condition (b) Head sea condition

Figure 7: Effect of the displacement on heave RAO in beam and head sea condition.



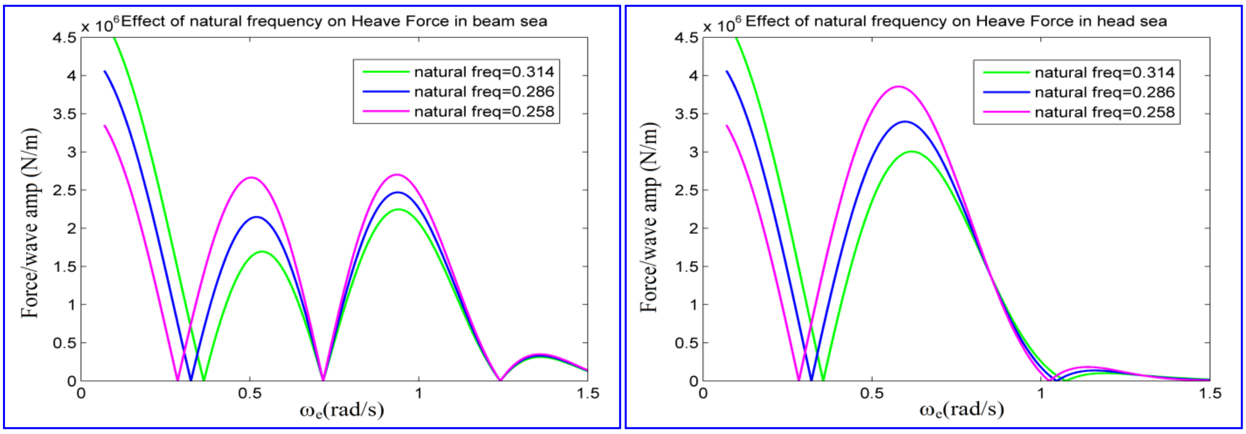
(a) Beam sea condition (b) Head sea condition

Figure 8: Effect of the pontoon spacing on heave force in beam and head sea conditions.



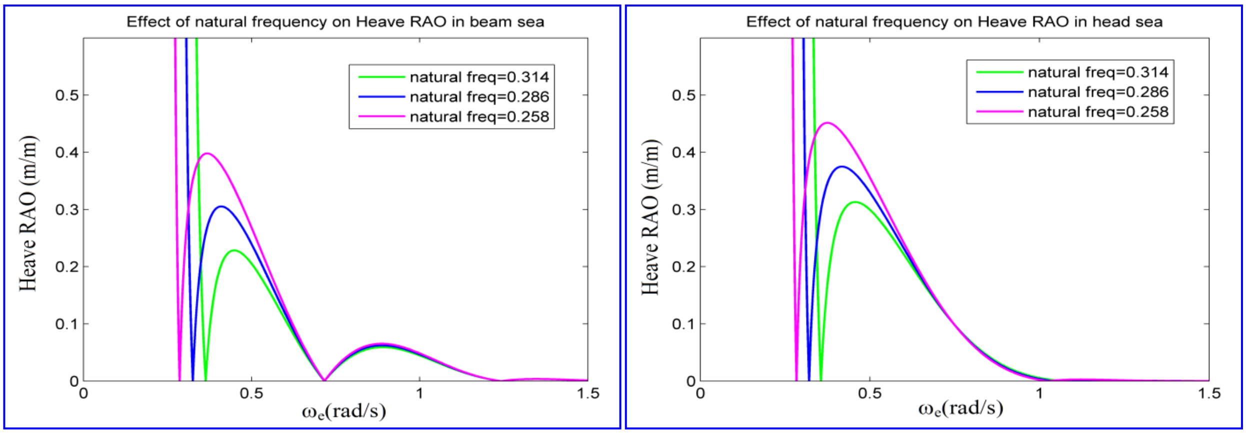
(a) Beam sea condition (b) Head sea condition

Figure 9: Effect of the pontoon spacing on heave RAO in beam and head sea conditions.



(a) Beam sea condition (b) Head sea condition

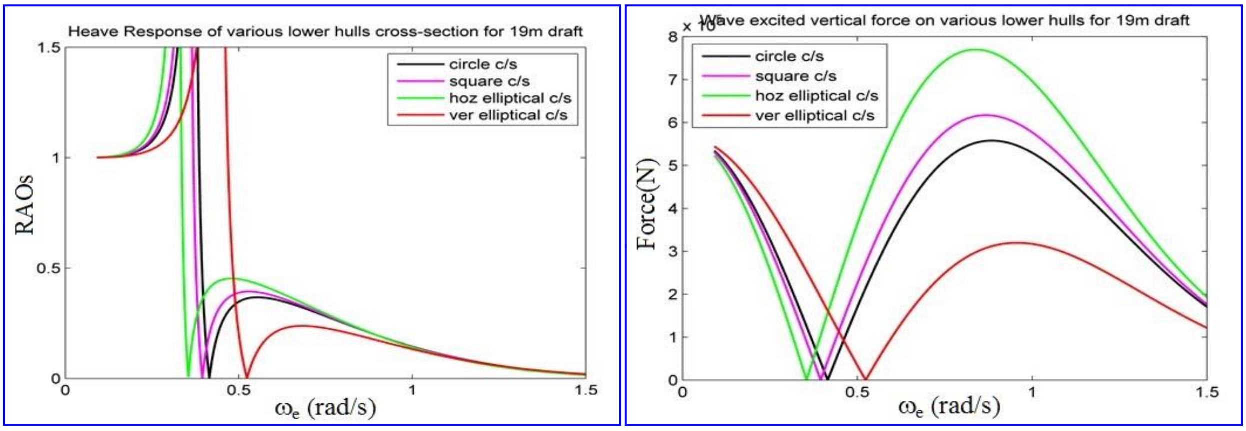
Figure 10: Effect of the natural frequency on heave force in beam and head sea conditions.



(a) Beam sea condition

(b) Head sea condition

Figure 11: Effect of the natural frequency on heave RAO in beam and head sea conditions.



(a) Heave response of various pontoon cross-sections.

(b) Force acting on lower hull of semi-submersible.

Figure 12: Heave response and force acting on lower hull of semi-submersible for different types of the pontoon cross-sections.

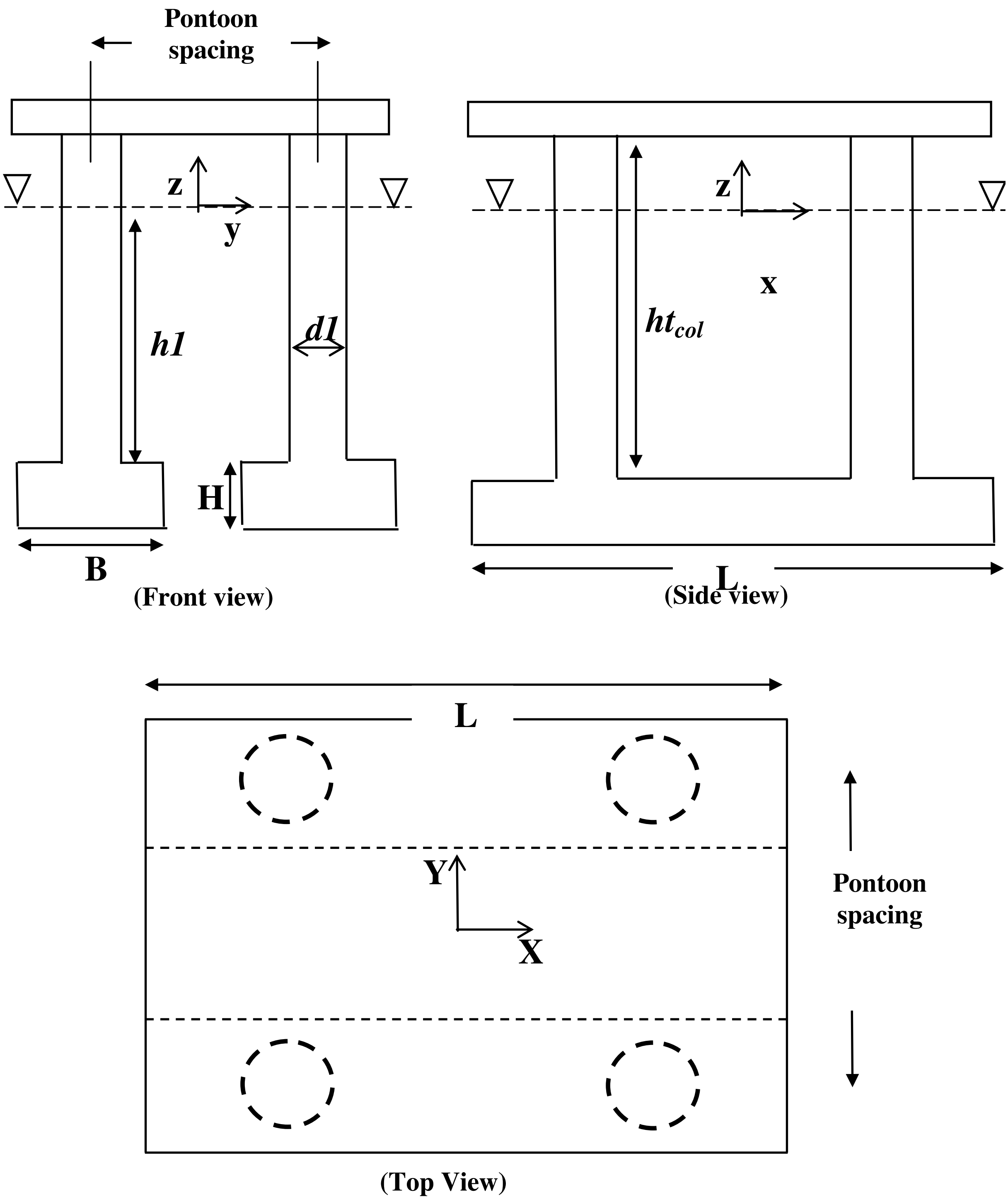


Figure 13: Description of the semi-submersible model for optimization.

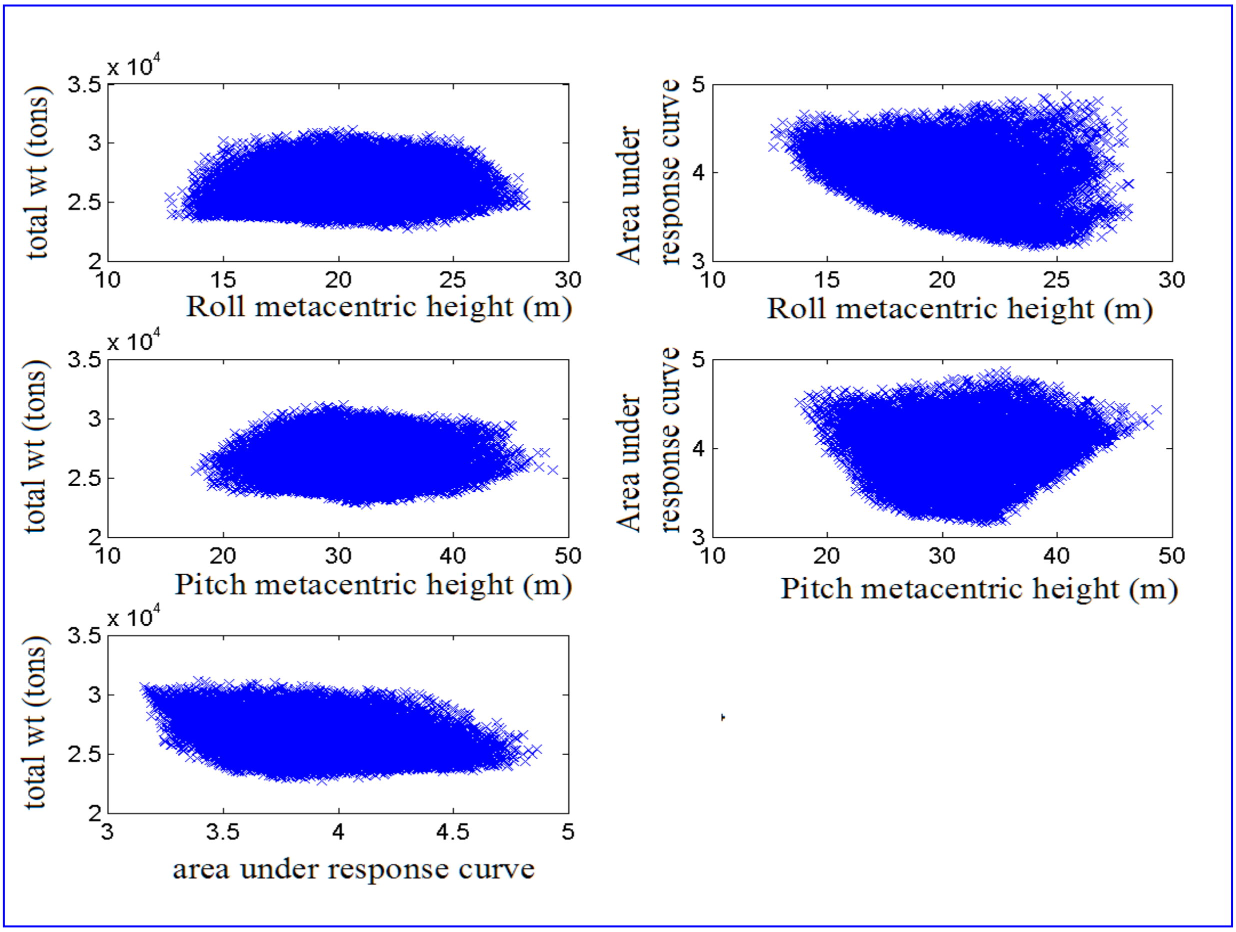
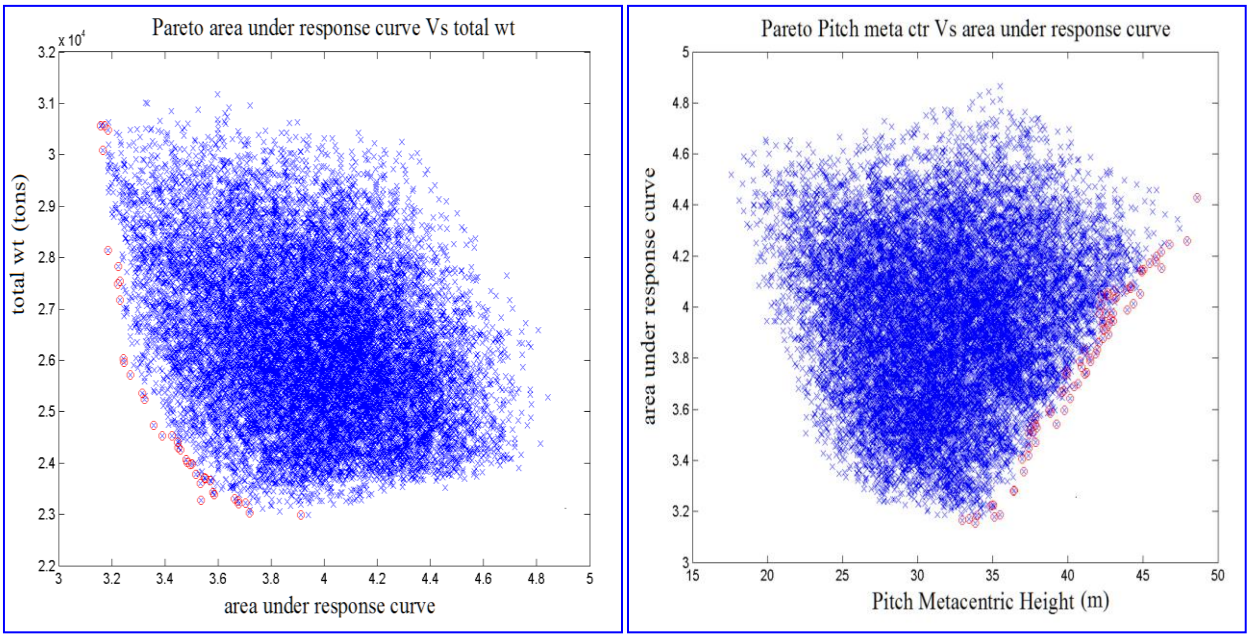


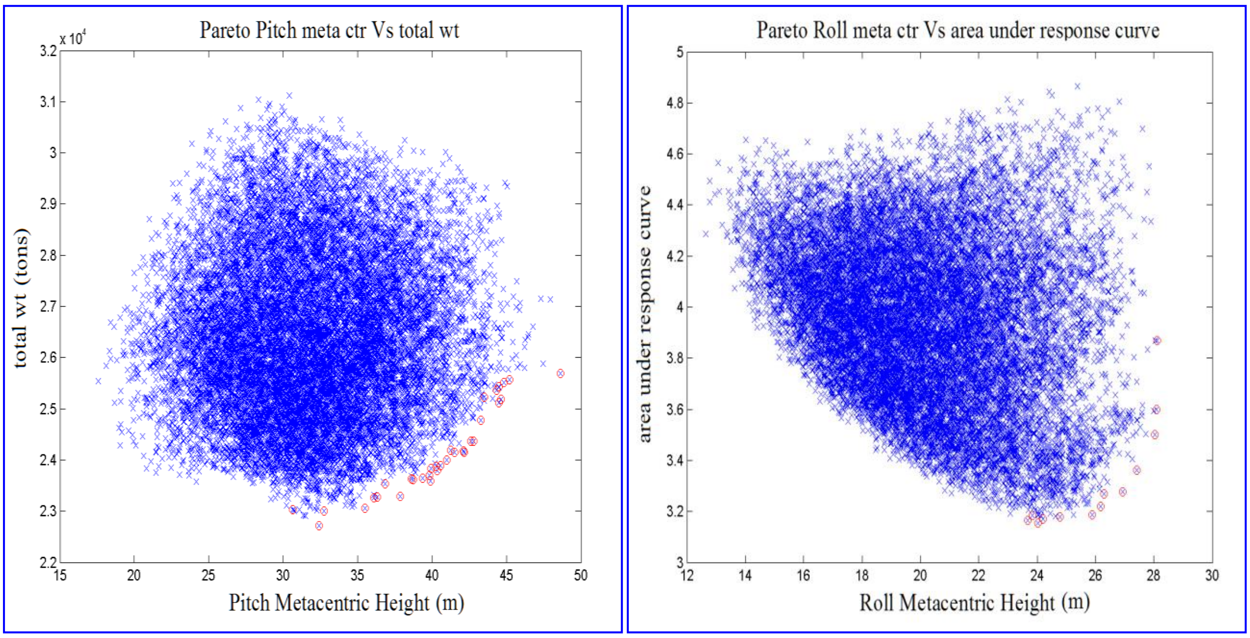
Figure 14: Feasible solution space sets computed by the NSGA-II.



(a) POF for area under the heave response curve and total weight.

(b) POF for area under heave response curve and pitch meta-centric height.

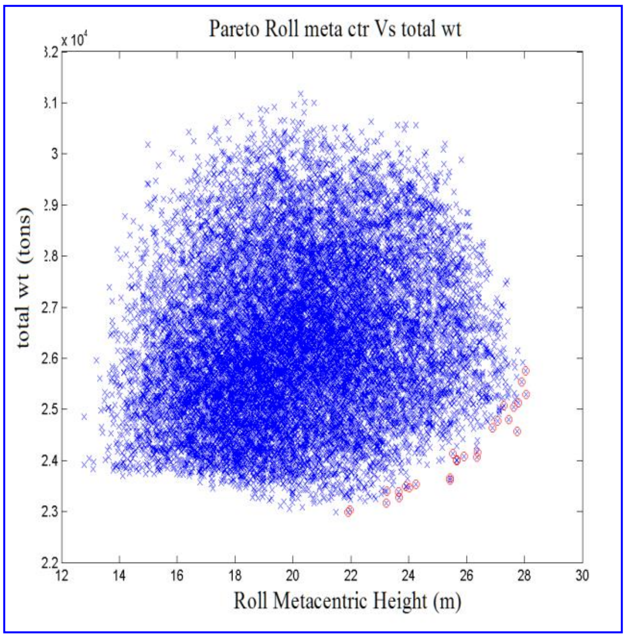
Figure 15: Computed POF for the area under heave response curve versus total structural steel weight and versus meta-centric height in pitch.



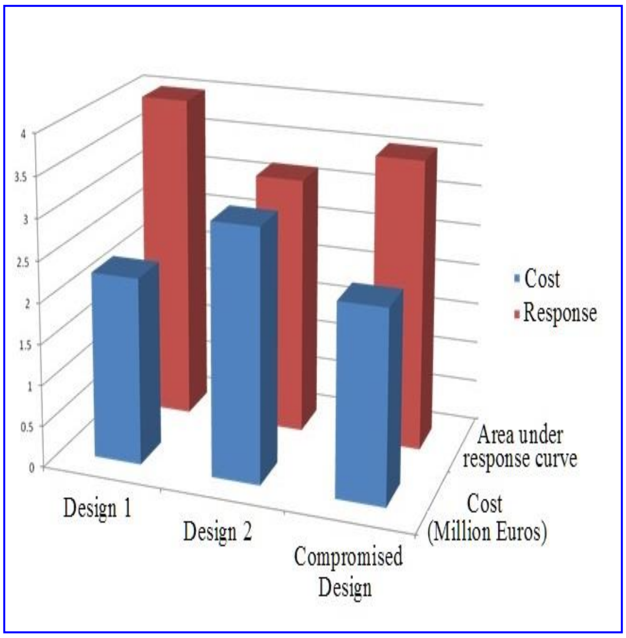
(a) POF for the total weight and pitch meta-centric height.

(b) POF for area under the heave response curve and roll meta-centric height.

Figure 16: Computed POF for the total structural steel weight versus meta-centric height in pitch and the area under heave response curve versus meta-centric height in roll.



(a) POF for the total weight and roll meta-centric height.



(b) Cost and response result analysis for the solutions obtained from POFs.

Figure 17: Computed POF for the total structural steel weight versus meta-centric height in roll and cost and response result analysis for the solutions obtained from POFs.

