A parametric study on the initial transverse stability of suspension ships

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Abstract. Suspension ships are a novel type of ships that utilize a suspension system as an integral part of their structure. One critical aspect of a suspension ship is its stability characteristics. The parameters that affect the initial transverse stability of these ships include the ship's mass ratio, loaded height of suspension, placement location height of suspension, and beam. It is found that designing a suspension ship in monohull configuration is more difficult than in a catamaran configuration. Special attention is required when the static mass ratio is below 2 for both monohulls and catamarans.

1. Introduction

Suspensions employed in land vehicles are known for their ability to improve traction and isolate shocks, thereby improving ride comfort. Similarly, adoption of suspension systems in ships aims to achieve similar objectives. However, due to the more complex ocean wave surface compared to land road profiles, designing of ship suspensions presents considerable challenges.

A suspension ship, which differs from conventional ships having rigid-body structures, comprises of a suspended body, a suspension system, and a hull unit. A suspended body, also known as a cabin or an upper deck, rests on a suspension system consisting of mechanical linkages, springs, and dampers. This system guides the relative movement between the suspended body and the hull unit. The hull unit provides buoyancy force and may consist of one or multiple hulls. From this point forward, these elements will be referred to as the cabin, suspension, and hull.

In the past two decades, several suspension ships have been developed as illustrated in Fig.1. Suspension controllers are employed to minimize the motion of the cabin. There are variations in the suspension systems and control methods.

A. Nauti-craft 2 play. The hydro-pneumatic system of the Nauti-craft 2 enables active counteraction of heave, pitch and roll movements by shifting fluids between cylinders [1].

B. Martini 1.5. The servo-yachts, previously known as Velodyne-Marine, utilized air suspensions and developed the suspension ship Martini 1.5. The cabin remained stable while advancing at a speed up to 30 knots [2].

C. Proteus. The first 100-ft long technology demonstrator of wave adaptive modular vehicle (WAM-V) developed and tested by Marine Advanced Research in 2009 [3]. The suspension linkages make use of leaf springs, slider, and rocker arms.

Figure 1. Different designs of suspension ships.

D. WAM-V 16. Autonomous surface vehicles incorporating suspension technology utilize air springs, hinges, and ball joints to operate on the water's surface and adapt to various sea conditions [4].

E. Wave Harmonizer 7. The ship's suspension adopted helical springs, pangtograph, and Watt's linkage. Direct Current (DC) motors are utilized to provided the desired force to suppress the motion of the cabin [5].

F. Wave Harmonizer 6. The suspension design was similar to Wave Harmonizer 7. The control system comprised a wave energy harvesting mode [6] and a motion reduction mode [7].

2. Design principle of suspension ships

Typically, a floating rigid body possesses six degrees of freedom (DOF). When it is joined to another rigid body, the total DOF can increase up to twelve. Suspension linkages of ships should be designed to constrain motions that could endanger the ship while allowing for other motions to be manipulated to enhance the ship's ride comfort.

2.1. Concept of suspension ships

A nine DOF suspension ship is examined in this research. The relative surge, sway, and yaw motions between the cabin and the hull should be constrained by the suspension linkages, while the heave, pitch, and roll motions of the cabin should be separated from those of the hull. Therefore, the surge, sway, and yaw motions depict the motions of the entire ship, while the heave, pitch, and roll motions relate to both the cabin and the hull.

A two-dimensional dynamic sketch of this suspension ship is presented in Fig.2. The cabin pitches around the center of gravity of the sprung mass G_s, while the hull pitches about the center of gravity of the unsprung mass G_u. Typically, the mass supported by the suspension and the mass below the suspension are termed as sprung mass M_s and unsprung mass M_u, respectively. The center of gravity of the entire ship is denoted as CoG, and the center of buoyancy is represented by CoB. K indicates an imaginary point on the baseline. In an initial state of static equilibrium, these five points align in a hypothetical vertical line. The initial trim angle and heel angle are both considered zero.

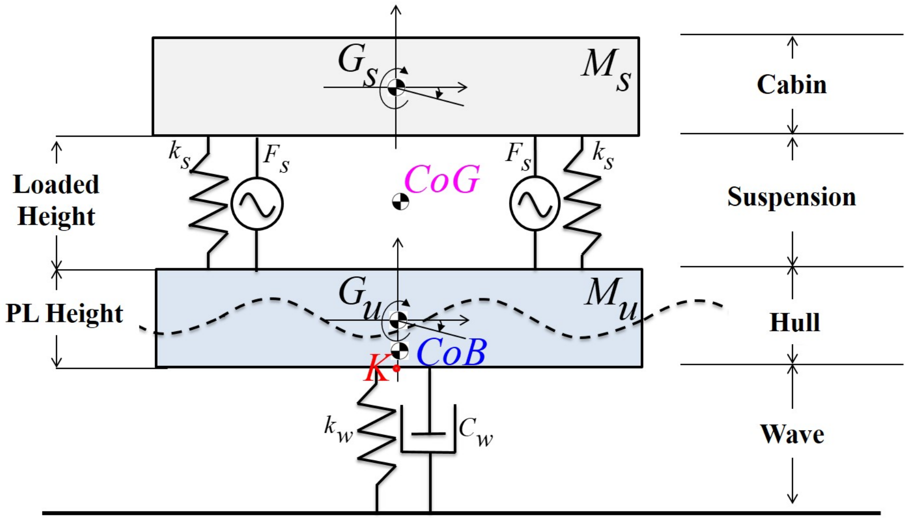


Figure 2. Dynamic sketch of suspension ships.

2.2. Initial transverse stability

The primary requirement in ship design is the initial transverse stability of a ship, which determines its ability to resist capsizing or heeling to one side when subjected to external forces.

Transverse stability is evaluated by examining the ship's metacentric height (GM). CoG denotes an imaginary point through which the entirety of the ship's weight presumably concentrates. The metacenter (M) is a theoretical point where the vertical line, which crosses CoG and CoB, intersects with the vertical line of buoyant force acting when the ship is inclined. If the GM value is positive, indicating that the point M is above CoG, the ship will tend to return to its upright position when tilted, which is considered a stable condition. However, if the GM value is negative, the ship will tend to continue tilting, which is unstable and can result in the ship capsizing.

Designing a suspension ship with appropriate initial transverse stability is essential for ensuring its safety at sea. The factors to consider are the ship's mass ratio of the unsprung mass and sprung mass, the loaded height of the suspension, the placement location of the suspension, and the beam of the ship. It is important to ensure the ship adheres to proper stability requirements to prevent accidents and maintain crew safety.

2.2.1. Mass ratio The mass ratio, q, is defined as the ratio of the sprung mass to the unsprung mass. It is expressed as

$$q = \frac{M_s}{M_u} \tag{1}$$

The distribution of mass across the cabin, the suspension, and the hull determines the CoG's location. When examining land vehicles, the suspension's mass is considered not as a single parameter but an additional mass to both the suspended body and the hull. The suspension system is represented by springs and dampers, which are massless.

Accurately determining the sprung and unsprung masses is crucial for modeling and simulating the ship's motion responses. In physical models, suspension linkages are either connected to the cabin or the hull. While it is possible to measure the mass of each suspension component, determining to which amount that the sprung mass or the unsprung mass should account for the suspension's mass remains challenging. The sprung mass of a physical model can be estimated through a free decay test [7]. The sprung mass can be estimated by utilizing the dampened natural frequency. This results in a dynamic mass ratio, which is differentiated from the static mass ratio.

The cabin-to-hull mass ratio, referred as the static mass ratio, is defined as

$$p' = \frac{M_{cabin}}{M_{hull}} \tag{2}$$

whereas the M_{cabin} and M_{hull} represent the overall measured mass of the cabin and hull, respectively.

The mass ratio inevitably changes during the cargo loading and offloading, as well as during passenger boarding and alighting. In this study, it is assumed that the fluctuations in mass ratio will not lead to alterations in the trim and heel of either the cabin or the hull.

2.2.2. Loaded height The loaded height, H_L, as depicted in Fig.2, indicates the vertical distance between the cabin and the hull when the suspension is stationary, and the ship attains static equilibrium.

The loaded height encompasses the allowable travel distance and the solid height of the suspension. The peak-to-peak vertical distance of the suspended cabin can travel when the hull is at rest represents the allowable travel distance. It determines the maximum motion amplitude that can be compensated by the suspension system. The solid height is the vertical distance between cabin and the hull while the cabin remains at its lowest point and the hull is stationary.

When the suspension is fully compressed, suspension bottom out happens, causing the cabin to hit the hull. The impacts of suspension bottom out on suspension ships is similar to the hard landings on aircraft by resulting in significant vertical acceleration spikes on the cabin which can cause damage and injuries.

The parameters affecting the loaded height vary among suspension designs. For this study, the considered parameter is the spring stiffness k_s. At a certain M_s and free length L_f of the spring, the height under loads varies according to changes in k_s, while the solid height is assumed constant.

2.2.3. Placement location height The height of the suspension's placement location, H_{PL}, shown as PL Height in Fig.2, indicates the vertical distance from the baseline to the placement location of the suspension.

This parameter has a significant bearing on the suspension design and the selection of ship configurations. All current suspension ships, shown in Fig.1, are catamaran with entirely suspended cabins. The suspension is located on the top deck of the hull, with its placement height equal to that of the hull. However, for potential future designs, the suspension may be positioned lower than the top deck of the hull or even inside the hull, resulting in varying placement heights.

2.2.4. Beam of ship It is widely recognized that the beam of the hull and the overall beam of the ship play a crucial role in determining its initial transverse stability. Additionally, the shape of the hull is also a key factor. However, the hull's shape is not highly relevant to this study like other factors and will be explored in future research.

3. Parametric investigation on a suspension model

A suspension design, along with the proposed initial assembly, is presented. A parametric investigation into the initial transverse stability is carried out to identify feasible ship designs that possess a positive GM.

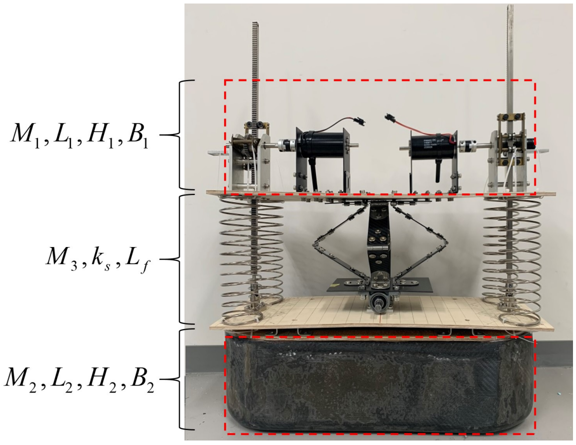


Figure 3. Initially assembly of a suspension model.

Table 1. Design specifications of a suspension model

Item	**Value**
mass of cabin M_1	2.5 kg
mass of suspension M_3	2.6 kg
mass of hull M_2	1.3 kg
spring stiffness k_s	235 N/m
free length of spring L_f	0.22 m
Diameter of spring	0.05 m
Dimension of cabin L_1, H_1, B_1	L0.5 m H0.20 m B0.15 m
Dimension of hull L_2, H_2, B_2	L0.5 m H0.15 m B0.15 m

3.1. Metacentric height GM

It is known that GM of a floating body can be calculated by

$$\mathrm{GM} = \mathrm{KB} + \mathrm{BM} - \mathrm{KG} \tag{3}$$

where, KB is the vertical distance from K to CoB, KG is the vertical distance from K to CoG, and BM is the distance from CoB to the metacenter M.

3.2. Suspension prototype

An initial assembly of a suspension design and its specification are presented in Fig.3 and Table 1, respectively. The cabin and hull are considered as blocks with the dimensions provided. The block's center of gravity is assumed to be at its geometric center, significantly simplifying the calculation the GM for the initial layout.

Let the water density ρ be 1025 kg/m^3, the draft of ship d can be obtained as

$$d = \frac{\frac{M_1+M_2+M_3}{\rho}}{L_1 \cdot B_1} = 0.0833\ \mathrm{m} \tag{4}$$

Then, KB is

$$\mathrm{KB} = \frac{d}{2} = 0.0416\ \mathrm{m} \tag{5}$$

The second moment of waterline area about longitudinal axis I_L is estimated by

$$I_L = \frac{1}{12} L_2 \cdot B_2^3 = 1.4062 \times 10^{-4}\ \mathrm{m}^4 \tag{6}$$

Then, BM is

$$\mathrm{BM} = \frac{I_L}{\frac{M_1+M_2+M_3}{\rho}} = 0.0225\ \mathrm{m} \tag{7}$$

The loaded height of the suspension is given as

$$H_L = L_f - \frac{M_1}{4k_s} = 0.2173\ \mathrm{m} \tag{8}$$

The vertical distance from the center of gravity of the hull, suspension, and cabin to the point K on the baseline can be obtained as

$$KG_1 = H_2 + H_L + \frac{H_1}{2} = 0.4673 \tag{9}$$

$$KG_3 = H_2 + \frac{H_L}{2} = 0.2587 \tag{10}$$

$$KG_2 = \frac{H_2}{2} = 0.0750 \tag{11}$$

Then, KG is

$$\mathrm{KG} = \frac{M_1 \cdot KG_1 + M_2 \cdot KG_2 + M_3 \cdot KG_3}{M_1 + M_2 + M_3} = 0.3029\ \mathrm{m} \tag{12}$$

Therefore, the GM of the initial assembly is

$$GM = -0.2387 < 0 \quad \text{unstable} \tag{13}$$

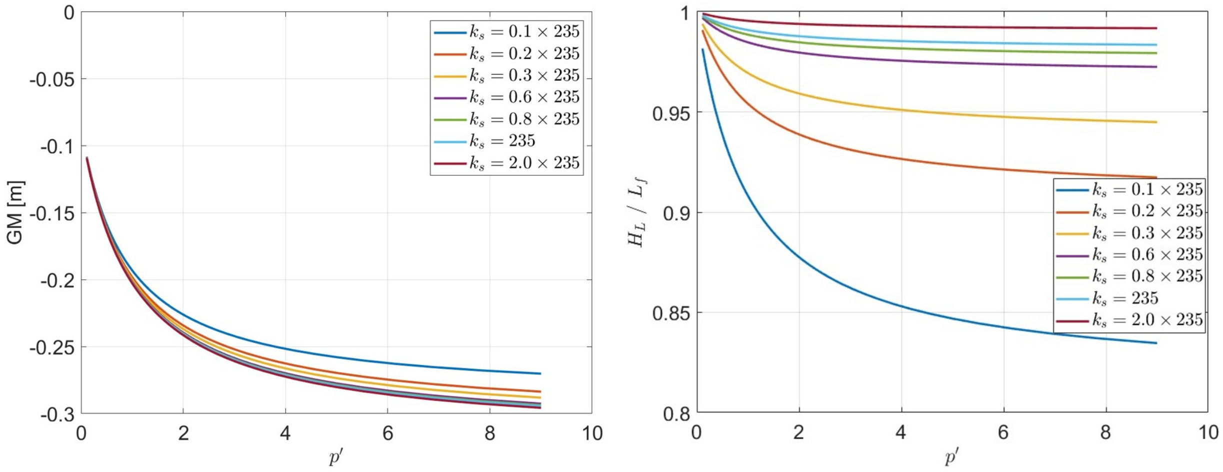
This demonstrates that the initial assembly of the prototype suspension ship is not stable. The main reasons are

- the mass of the cabin and the suspension components are substantial, leading to a high center of gravity and a large GM;
- the loaded height of the suspension is considerable, also contributing to a large KG;
- the placement location of the suspension is so high that causes a large KG;
- the beam of the hull are narrow, resulting in a small KB and BM.

3.3. Parameter tuning

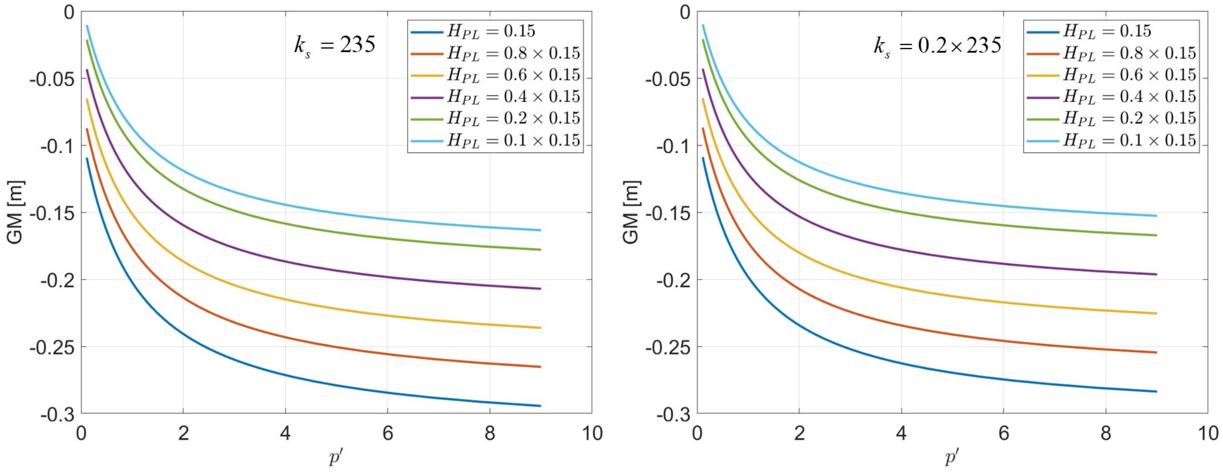
The aim of tuning the parameters is to identify design proposals that possess satisfactory initial transverse stability, and more importantly, to comprehend the impact of the parameters.

Hereafter, the suspension mass and the ship's total mass remain constant. The static mass ratio p' is adjusted within a range of $0.1 \sim 0.9$, while the spring stiffness is modified from soft to hard. The suspension is relocated from the bottom to the top deck of the hull. The free length of the spring is reduced to a certain value if permissible. The hull's beam is increased up to 2.5 times its original size. Catamaran configuration is taken into account with three transverse distances between the two hulls. Changes in GM along with adjustments to these parameters are illustrated from Fig.4 to Fig.7.



(A) (B)

Figure 4. GM and H_L vary against the static mass ratio p' and spring stiffness k_s.



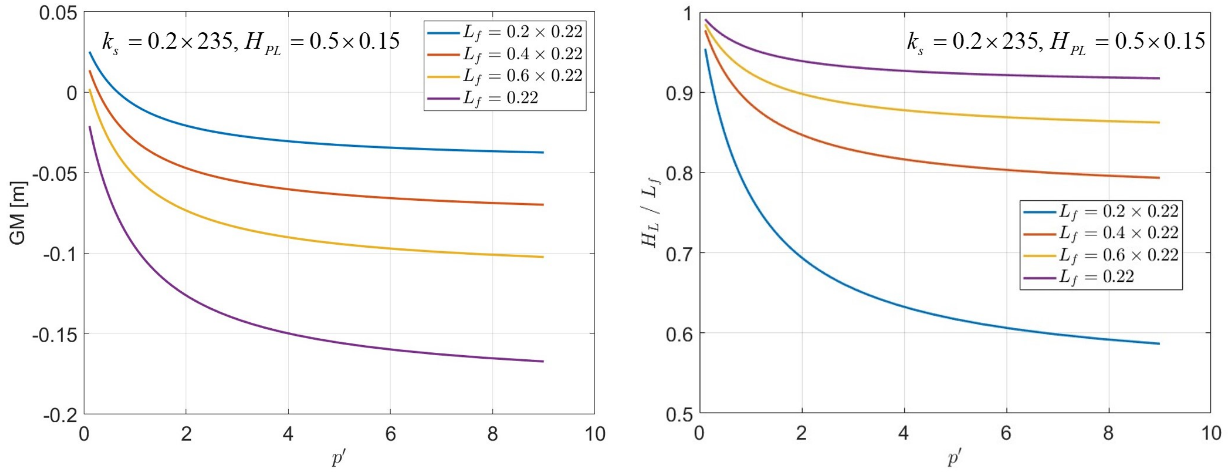
(A) (B)

Figure 5. GM vary against the static mass ratio p' and placement location height H_{PL}.

3.3.1. static mass ratio, spring stiffness The GM that changes along with spring stiffness at different static mass ratio p' is illustrated in Fig.4(A), with the corresponding loaded height shown in Fig.4(B). The dimensionless loaded height is acquired via dividing the free length of spring L_f.

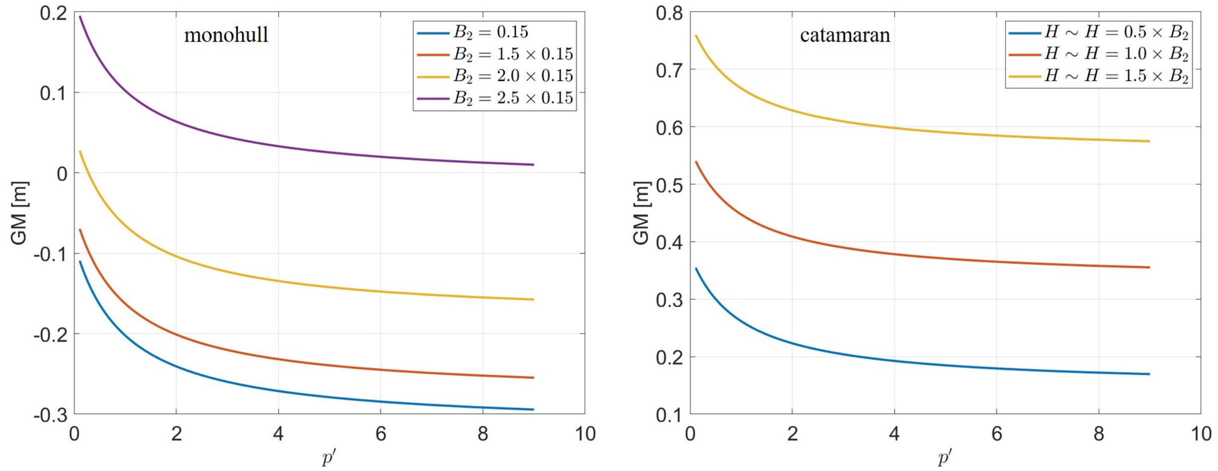
As shown in Fig.4(A), altering the mass distribution between the cabin and hull, as well as modifying the stiffness of the springs did not attain initial stability. A lighter cabin and softer springs are found effective in improving stability. In regions where the static mass ratio is less than 2, the GM increases sharply with a reduction in p'. The impact of changing spring stiffness, however, decreased.

Fig.4(B) demonstrates that although the static mass ratio increased by approximately 8 times, the loaded height of suspension H_L decreased by less than 20%. At static mass ratios lower than 2, H_L decreases significantly, particularly when k_s is below half of its original value. This suggests the need for a softer spring stiffness and potentially a shorter free length of spring.



(A) (B)

Figure 6. GM and H_L vary against the static mass ratio p' and free length of springs L_f.



(A) (B)

Figure 7. GM vary against the static mass ratio p' and beam.

3.3.2. placement location height The GM varies with the placement location height of suspension at different static mass ratios p' and spring stiffness is illustrated in Fig.5.

The initial transverse stability remains unobtained by lowering the placement location to one tenth of the hull height, even when the spring stiffness is reduced to one fifth of its original value.

It is observed that a lower placement location height results in increased stability. With smaller p', the increase in GM achieved by decreasing H_{PL} becomes less significant. It should be noted, however, that tuning H_{PL} has a greater impact than that of k_s.

3.3.3. free length of springs The GM at various free lengths of springs for different static mass ratios p' is depicted in Fig.6(A), and the associated loaded height is shown in Fig.6(B). The suspension's placement location is now halfway and the adopted spring stiffness is one fifth of the initial value.

The initial transverse stability, GM > 0, is achieved only within a narrow parameter range, where p' and L_f are both small. From a stability perspective, a shorter spring length is preferable. Nevertheless, it should be noted that the loaded height might changes significantly with variations in p', particularly for $p' < 2$. This could result in a high occurrence of suspension bottoming out. Therefore, it is essential to consider the trade-off between the free length and stiffness of the spring.

3.3.4. beam The GM that alters with changes in beam at varying static mass ratios p' is illustrated in Fig.7(A), and alterations based on the transverse distance between the two hulls of a catamaran can be observed in Fig.7(B). The monohull suspension ship is used as a half model to build the catamaran. The transverse distance between the two hulls is used as a tuning parameter. The decks of the two hulls are fixed by crossbeams, and so are the cabins. The mass of the crossbeams is neglected.

Monohull initial transverse stability, where GM > 0, is achieved when the beam is 2.5 times its original size. For a catamaran, the initial transverse stability can be achieved despite the fact that the transverse distance between the two hulls is only half of the beam of one hull. It demonstrated that the most dominating parameter that influences the initial transverse stability is the beam.

This suggests that implementing suspensions for a monohull is incredibly challenging. In addition, this explains why all the current suspension ships are in a catamaran configuration.

4. Conclusions

Initial transverse stability is a crucial factor in the design of suspension ships. Various parameters need to be considered when calculating GM, such as the mass ratio, loaded height of suspension, placement location height of suspension, and the ship's beam. A parametric investigation was carried out to analyze the impacts on GM. The following conclusions can be drawn from the analysis:

1. A reduced mass ratio results in a increased GM. The initial transverse stability displays significant variation when the mass ratio of the cabin and hull is less than 2. It is imperative to pay close attention if the static mass ratio falls within this range;
2. A shorter loaded height is preferable for a larger GM. However, the allowable travel distance must be taken into account to prevent bottom out. If springs are utilized, the spring stiffness and free length must be carefully balanced.
3. A lower placement location height results in a larger GM. Although, the impact becomes weaker with the reduced static mass ratio, it exerts more impact compared to the spring stiffness.
4. A larger beam produces a larger GM. The beam of the hull for a monohull and the overall beam of a catamaran are the dominating parameters that influence the initial transverse stability.

Achieving initial transverse stability for a monohull with a fully suspended cabin was found challenging. However, suspending only a portion of the cabin to improve ride comfort could be a more practical solution which could be one of the future studies.

Acknowledgments

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