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COMPARATIVE STUDY ON CATAMARAN AND MONOHULL FOR THE HULL FORM DESIGN OF LIVESTOCK CARRIER

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Abstract

The process of transporting cattle (livestock transportation) between islands takes a long sailing time, therefore the vessel should be arranged to provide the reliable services for the animal welfare even under severe condition during sea transport. The aim of the research is to compare the performance of catamaran and monohull technology for the hull form design of the livestock carrier as a vessel that transport the commodities such as cows, goats, and sheep. The investigation of resistance, intact stability and seakeeping performance of the both hull forms type will be discussed. Based on this study, it might be concluded that the catamaran design has better resistance performance in the high service speed than the monohull. On stability review, the initial stability of catamaran has enabled the larger transversal weight shifts than the monohull, which means the Catamaran has better safety level for livestock carrier. On motion review, the catamaran has better performances notably at roll motion. However, it is indicated that the operability should be limited to the significant wave height below 3 meters to avoid deck-wetness.

Keywords: Catamaran, Livestock carrier, Monohull.

1. Introduction

In 2010, the population in Java and Sumatera is about 186.7 million people or 78.8 percent of the total population of Indonesia. By the assumption of beef consumption of 2.2 kg per capita (Ministry of Commerce), it is predicted that the demand for the beef in Java and Sumatra is estimated at 410 million kg per year, equivalent to 2.98 million numbers of cows. Regarding the amount of the beef consumption compared with the population data of the cows in Java and Sumatera, which is around 8.6 million cows, the need of beef consumption in both locations, should be able to be fulfilled. However, the number of existing cattle population might not be used entirely for consumption, since the many of livestock nurturing in Java Island is a family saving with an average cattle ownership rate of 1-2 heads per household. According to the condition, it might be identified that the local supply is not able to fulfil the beef consumption need in Java Island.

An effort to achieve these needs is done by transporting the cows from the production central areas such as Bali and Nusa Tenggara to the Java Island. The islands of Bali and Nusa Tenggara inhabited by 5.5% of Indonesia's population have 14.18% of the national population. The transportation of cows to Java Island should be supported by transportation mode, which is equipped with the system to ensure animal welfare.

The process of transporting cattle (livestock transportation) between islands takes a long sailing time, therefore the vessel should be arranged to provide the reliable services for the animal welfare even under severe condition during sea transport. In the meantime, many vehicles such as ships, trucks, and trains, which are used as cattle transportation facilities are not specially designed to support livestock transportation, see Fig. 1. Different from the crew and occupants that have the ability to abandon the ship while the accident occurs, the live animals are absolutely depending on the vessel and its system. Therefore, livestock carrier should be designed by adopting an innovative hull form that maintains the ship motion, which is animal, will not drop their foothold. The bunching animal to one side of the ship generates undesirable influence to the roll motion.

Fig. 1. Livestock transportation using truck and general cargo ship.

The aim of the research is to compare the performance of catamaran and monohull technology for the hull form design of the livestock carrier in achieving animal transport operability under Indonesia Waterway conditions. The hull form designs made for the livestock carrier were designed according to monohull non-bulbous bow type, mono hull with bulbous bow type and catamaran type. Subsequently, the three hull form designs were analysed for their calm water resistance, intact stability and the vessels behaviour in beam sea, quartering sea and head sea using numerical analyses. In this study, the articles reviewed mostly deal with ro-ro (Roll on Roll off) ship technology, since the livestock carrier has similar characteristics with the ro-ro ship, especially on the ramp door system and the subdivision of the compartment, which eliminates the transverse bulkhead. Santos et al. [1] studied transient asymmetric flooding on ro-ro liners in theory and experiment. Experimental results show that transient asymmetric flooding can cause a capsizing vessel for the type of ro-ro barge. Internal arrangements on ro-ro ships should be carefully reviewed and detailed at the design stage to avoid the occurrence of capsizing phenomena.

Ravn [2] investigates the probability of damage stability on ro-ro ships by considering the division of compartments based on the probability concept of damage stability. The study parameters indicate that the main contributor in determining the Attained Subdivision Index is the position of the ro-ro deck, the KG position, the existence of the side casing and the number of the transverse bulkheads. Otto et al. [3] studied the effects of collision damage and aggravation. The consequences of collisions and flooding are estimated using damage criteria connected to the distribution of damage sizes and location of the damage. The results of the study show that the annual risks to ro-ro boats are caused by vessel capsize after severe damage. Chan et al. [4] predicts the dynamic global wave load on ro-ro vessels at zero speed under regular oblique wave conditions. The results show that the non-linear time domain simulation method is very good in predicting vertical and dynamic horizontal bending moments. Dynamic global vertical wave loads in damage conditions (hull damage) are larger than intact conditions (whole hull). Korkut et al. [5, 6] conducted an experimental study on the behaviour of ro-ro ship movements on damage and intact conditions. Testing of the six degrees freedom movement response on the ro-ro model has been performed on regular waves for damage and intact conditions.

The results of the analysis show that the damage has a bad influence on the movement response that depends on the direction of the wave and wave frequency range. Surendran et al. [7] studied the dynamics of non-linear roll movements on ro-ro ships in wave conditions. Parametric investigations were performed to identify and quantify the effects of several key parameters including wave slope, wave frequency at capsizing condition of ro-ro vessel. The nonlinear ship response is specified in the frequency domain. Santos and Soares [8] conducted a numerical assessment of factors affecting survivability in ro-ro damage vessels in wave conditions. Survivability of ships in irregular waves is calculated based on the variation of parameters, namely: vertical centre of gravity location, spectral description on shipping lane, roll-damping factor, discharged coefficient, main deck height, double hull on the main deck and initial heel angle.

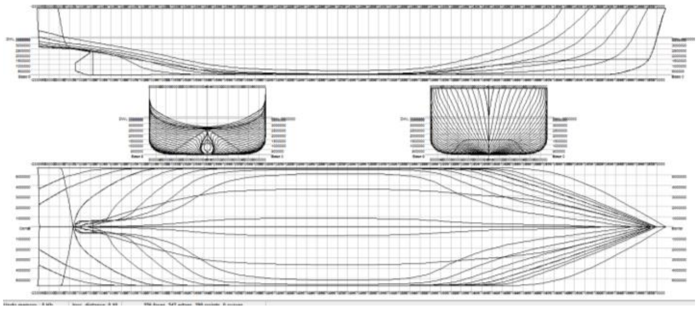
2. Material and Method

2.1. Hull form designs

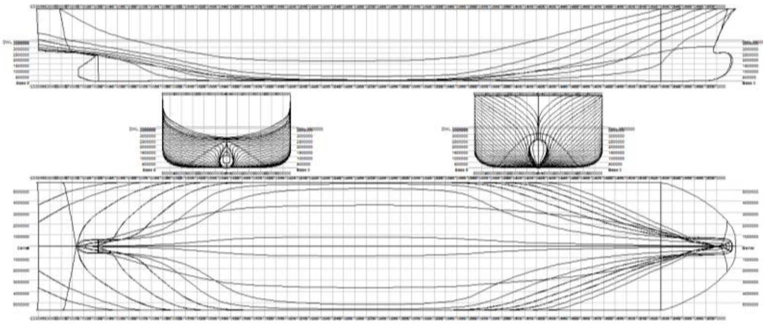
The new designs are generated with a starting point from the parent models, which is modified to have the same displacement for all of hull forms type. Considering the mission requirement such as sailing time, service speed and load capacity the principal dimension was determined by a linear regression method. Subsequently, the modification of the parent model was made to create the new hull shape, which can be seen in Fig. 2, and the principal dimension can be seen in Table 1.

Table 1. Principal dimension of hull forms.

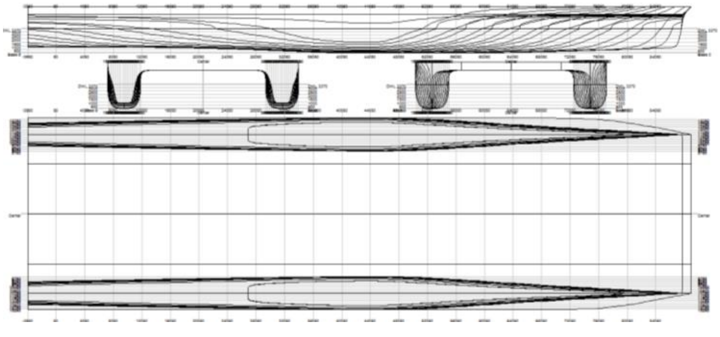
Hullform type	**Principal dimension**						
	Lpp [m]	**B [m]**	**H [m]**	**T [m]**	**Cb**	**LWT (ton)**	**Area/cattle (m^2)**
Monohull non-bulb	57.7	11.3	6.4	3.55	0.64	533	2.88
Monohull with bulb	57.7	11.3	6.43	3.55	0.64	563	3.59
Catamaran	88	26.75	6.48	2.82	0.55	773	7.27



(a) Monohull non-bulbous bow concept design.



(b) Monohull with bulbous bow concept design.



(c) Catamaran concept design.

Fig. 2. Lines plan of new hull form design.

The vessels were designed for carrying 500 cattle, a sailing period of 7 days with 21 crews. The service speed was 80% of the operational time at 14 knots. However, the maximum speed should be able to reach 18 knots. The maximum attainable speed is depending on the hull form resistance profile. Therefore, the optimum shape will be able to have a larger maximum speed than the others.

Theoretically, monohull is the simplest hull form concepts than the others. It also offers a low cost and low-risk solution compare than multihull. Monohull has been evolved through a lot of modification to accomplish the design requirements. The modification of monohull as a planning hull able to decrease the hull resistance by generating the significant lift force, which is, reduced the immersed body. Otherwise, the length to displacement ratio (slenderness ration) could be set higher than the conventional hull to have the minimum hydrodynamic pressure drag. However, an extreme extension of the hull length may cause an increase in the frictional drag to offset the low wave drag behaviour. The slenderness ratio usually misinterpreted with length to beam ratio. Although length to beam ratio generally increases the length to displacement ratio, however, the latter has a significant effect on the ship resistance than the former. The increase of beam for a given length and displacement might improve the static stability problem that might be occurred on the slender monohull. The other effort can be made through the additional bulbous bow appendage that may reduce the wave making resistance.

The catamaran is one of the multihull configurations that overcome the stability problem of the slender monohull, which has low drag characteristics. It consists of two hulls, which are separated with the box construction known as the cross deck at a certain distance. The basic dimensions are defined with some parameters namely *B* for an overall beam of the ship, *b* for a beam of each hull, *Sc* for hull separation distance, *ST* for the tunnel width, *HT* for the tunnel height and *HB* for the depth of cross-deck, see Fig. 3.

The twin hulls give the buoyancy and space for the propulsion machinery, whilst the cross deck structure provides the transverse strength of the ship. Instead of the reduced resistance, catamarans have a larger deck area and increase the safety level.

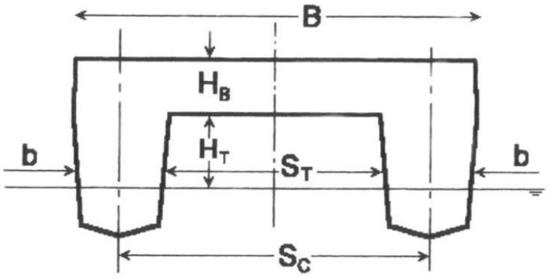


Fig. 3. Basic dimensions of catamaran [9].

2.2. Still water resistance

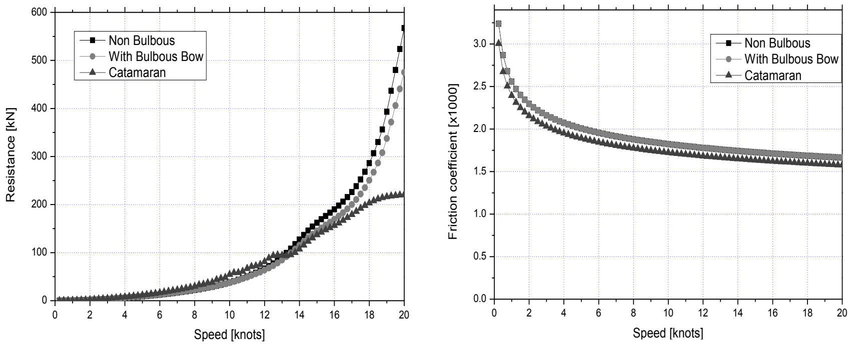
The total resistance of the ship is made up of a number of different resistance components. Four main resistance components namely frictional resistance, eddy resistance wave making resistance and air resistance are considered for analysing the hull form resistance in still water. Frictional resistance is observed due to the motion of a body through the viscous fluid. Eddy resistance is the resistance, which is occurred due to the energy, is taken away by eddy shed from the hull. It is usually occurred at the ship stern where the water unable to follow the curvature and then separate from the body, which is rising to eddies resistance [10]. Wave making resistance is caused by energy, which is delivered continuously to the wave system on the free surface [11]. Finally, the air resistance occurs on the moving body, which is located on the above waterline and superstructure through the air. The wave making resistance and eddy resistance usually are considered together known as the residuary resistance.

3. Result and Discussion

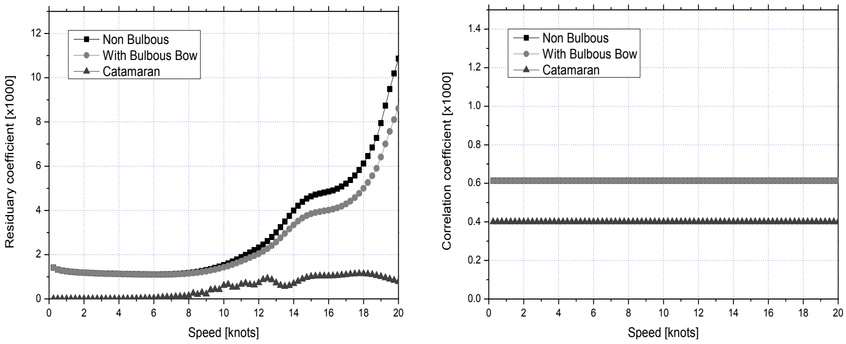
3.1. Still water resistance calculation result

The still water resistance of the three hull form designs has been evaluated using the Holtrop and Mennen method [12, 13] for the monohull. The Holtrop method is selected to evaluate the monohull because the hull form characteristics fit into applicability criteria and its proven accuracy as a well-known method for resistance prediction. However, the Holtrop method not appropriate for catamaran hull form, therefore, the slender body method is adopted to evaluate the catamaran resistance. The slender body method calculates the wave resistance of the ship through the analytical computation of energy in the free surface wave pattern, which is generated, by the ship. The total resistance is calculated by adding the viscous resistance component, which is estimated using ITTC'57 friction coefficient calculation method and the specified form factor [12].

The result of total resistance can be seen in Fig. 4. As shown in the figure the differences in the still water resistance between the three hull forms are dependent on the speed range and the type of the hull form. Approximately, below 13 knots, the catamaran has a larger resistance than the monohull. Above 13 knots, the two monohulls show a significant increase in the total resistance. According to the resistance coefficient, it might be seen that catamaran characteristics have shown a significant improvement than the two monohulls. However, the total resistance of the catamaran below 13 knots is similar to the monohulls. It might be explained that the catamaran wetted surface area of 1475 m^2 is significantly larger compared with the monohulls wetted surface area of 834 m^2. Otherwise, the catamaran shows better resistance on the speed above 13 knots.



(a) Total resistance. **(b) Friction coefficient (C_F).**



(c) Residuary coefficient (C_R). **(d) Correlation coefficient (ΔC_T).**

Fig. 4. Total resistance and resistance coefficients of three hull form.

3.2. Intact stability behaviour

In the monohull ship, the stability scope is at the defined position of the centre of gravity that is influenced by the transversal weight shift and the centre of buoyancy shift, which is occurred because of heel motion.

The possible maximum shift of the centre of buoyancy could achieve a quarter of the width of the ship. It is indicated that the hull form limits the righting moment. Catamaran hull form enables a greater transversal shift of the centre of buoyancy that increases the righting moment at the small heeling angles.

The inertial moment of the catamaran is equal to the combined inertia of each hull. It is indicated that the hull spacing has a significant influence on the stability performance of catamaran.

The three hull forms have to apply to the general intact stability criteria for all ships [14] and the standard stability criteria for livestock carrier [15]. The stability criteria for livestock carrier are adopted from Marine Orders Part 43 as additional stability assessment criteria. Table 2 and Fig. 5 show the intact stability criteria that are peculiar to livestock carrier.

According to the MO43, the intact stability of livestock carriers has to consider some factors, which generate heeling arm that contribute a negative effect to the vessel stability, namely the effect of livestock shift, fodder shift and wind.

The heeling arm due to the shift of livestock, the shift of fodder and the wind load at zero degree is determined as follow:

Livestock heeling arm at 0°: $\frac{m\times c}{f\times D} = LF$ (1)

Fodder heeling arm at 0°: $\frac{F}{S\times D} = WL$ (2)

Wind heeling arm at 0°: $\frac{0.05\times A\times H}{D} = OW$ (3)

Table 2. Intact stability criteria for livestock carrier.

Parameter	Criterion	Unit
Area under GZ curve up to 30 degrees	3.151	m deg
Area under GZ curve up to 40 degrees	5.156	m deg
Area under GZ between to 30 and 40 degrees	1.718	m deg
Max GZ at 30 degrees or greater	0.20	m
Angle of maximum GZ	25	deg
Angle of maximum GZ (catamaran)	10	deg
Initial metacentric height GM	0.15	m
Angle of hell due to wind effect	10	deg
Area A is not less than [1.03 m deg + 0.2 area (A+B)]		

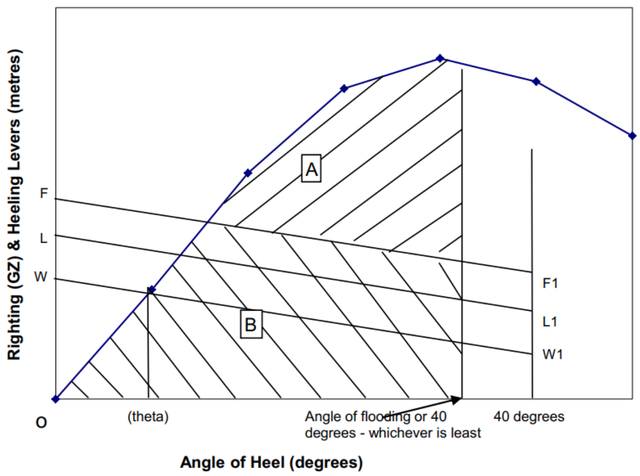


Fig. 5. Illustration of intact stability requirement for livestock carrier [15].

The stability calculations are made with the stability calculation program. The calculation procedures require the load case definition, which is, described the mass distribution of the loaded vessel such as lightweight, consumables weight, and payload weight. The full load condition is determined as the loading condition on the computation. The initial condition is assumed even keel condition with no heel and no trim on the draught. The result of the analysis might be seen in the Figs. 6-8. The result presented the heeling angle only to down flooding angle. This is in accordance with AMSA MO43, which implies that the stability graph for livestock carrier should be displayed until the down flooding angle [15].

According to the analysis results it can be seen that catamaran have better intact stability than the monohulls. The separated twin hulls have increased the length of the righting arm (GZ) substantially. The large righting arm will contribute positively to the magnitude of the righting moment. Therefore, the catamaran has a significant area under the GZ curve to achieve the stability criteria. Instead of the GZ length, the initial metacentric height also obtained to be larger than the monohulls. In the other case, the catamaran is observed not comply with the requirement of the angle of maximum GZ, nevertheless, the catamaran still has the better righting arm than a monohull on the heeling angle more than 25 degrees.

The intact stability of monohulls is also obtained comply with all of intact stability criteria. The bulbous bow monohull shows better performance than the non-bulbous bow design. The comparison of the intact stability behaviour can be seen in Table 3.

Table 3. Comparison of intact stability behaviour of three hull forms.

Parameter	Criterion	Non-bulbous	Bulbous	Catamaran	Status
Area under the GZ curve up to 30 degrees	3.151 m deg	10.628	12.249	200.557	Pass
Area under the GZ curve up to 40 degrees	5.156 m deg	17.891	20.606	261.359	Pass
Area under the GZ between to 30 and 40 degrees	1.718 m deg	7.262	8.357	60.802	Pass
Max GZ at 30 degrees or greater	0.2 m	0.737	0.848	6.938	Pass
Angle of maximum GZ	25 deg	36.5	36.9	-	Pass
Angle of maximum GZ (Cat)	10 deg	-	-	16	Pass
Initial metacentric height GM	0.15 m	1.284	1.469	46.826	Pass
Angle of hell due to wind effect	10 deg	1.0	0.9	0.02	Pass
Area A is not less than [1.03 m deg +0.2 area (A+B)]	4.606 m deg	14.162	-	-	Pass
Area A is not less than [1.03 m deg +0.2 area (A+B)]	5.150 m deg	-	16.876	-	Pass
Area A is not less than [1.03 m deg +0.2 area (A+B)]	54.254 m deg	-	-	261.4	Pass

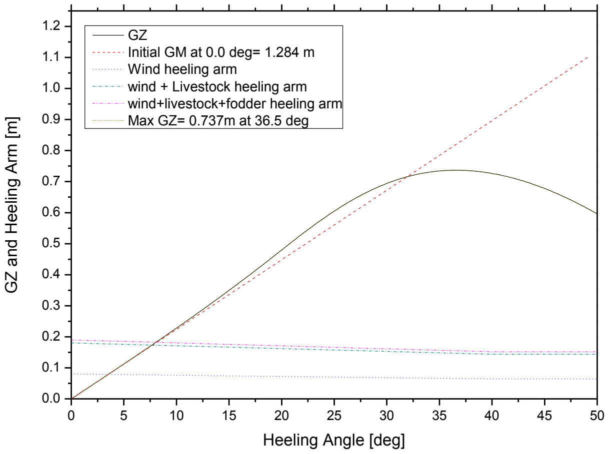


Fig. 6. GZ curve and heeling arm of monohull non-bulbous bow.

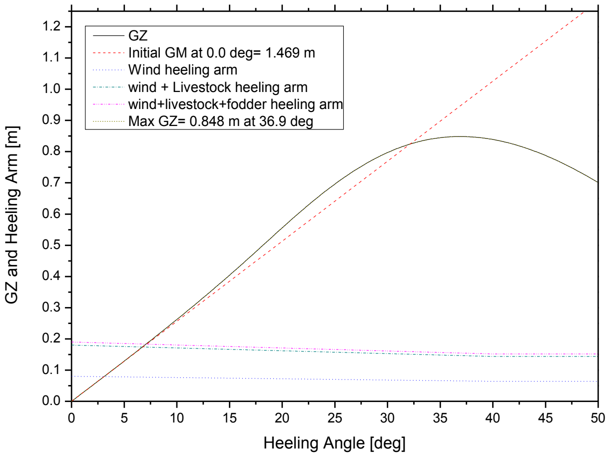


Fig. 7. GZ curve and heeling arm of monohull with-bulbous bow.

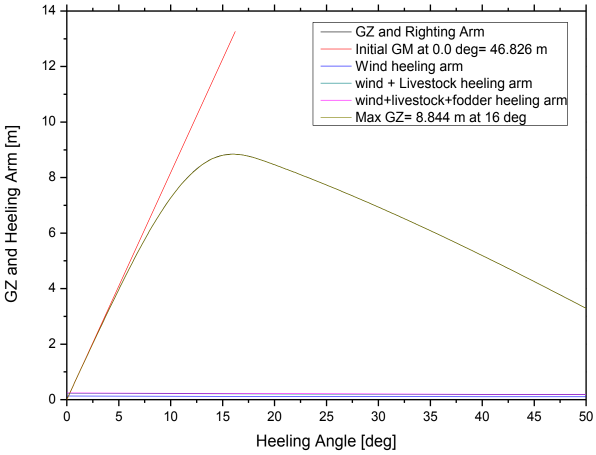


Fig. 8. GZ curve and heeling arm of catamaran hull form.

3.3. Seakeeping behaviour

Since the significant wave height of the Indonesia sea environment is 3.75-4 meters. Therefore, the simulation was made with the significant wave height range of 2-4 meters. The integral parameters of the adopted wave spectra are described in Table 4. For defining the limits of operability for each hull form among a controllable number of scenarios it was determined to use one spectrum profile with one particular peak period and with an increment of significant wave height.

The primary outcomes from the result of seakeeping analysis in head wave environment can be seen in Table 5 and briefly presented as follow:

- For the two monohulls show roughly similar characteristics for the significant amplitudes of the three (heave, roll, and pitch) motions and accelerations.
- All of the three hull forms are able to stay within the limit criteria.

- In the case of vertical acceleration, the maximum peak at the livestock pen showed significant differences among the monohulls and the catamaran. The bulbous bow had 2.3% lower magnitudes when compared with the non-bulbous bow. The catamaran showed more than 18.3% lower magnitudes when compared with the bulbous bow. Although the catamaran design shows an improvement on the maximum peak acceleration at the livestock pen, however, in the case of the vertical acceleration at the bow and the centre of gravity, the catamaran shows the larger magnitude of acceleration than the monohulls.
- The deck wetness of the three hull forms was quite similar. All of the designs show the deck wetness on the wave condition with 3.5 meters significant wave height. It is indicated that the operability criteria for the three hull forms should be limited to the sea environment with a significant wave height below 3.5 meters.

Table 4. Wave conditions in the seakeeping analysis.

Wave condition	Spectrum type	Significant wave height [m]	Zero crossing period [s]	Peak enhancement factor
1	JONSWAP	2.0	6	3.3
2	JONSWAP	2.5	6	3.3
3	JONSWAP	3.0	6	3.3
4	JONSWAP	3.5	6	3.3
5	JONSWAP	4.0	6	3.3

Table 5. Hull forms behaviour on head sea.

Speed [kn]	Wave height [m]	Vertical acceleration on livestock pen [mm/s^2]			Deck wetness appearance		
		No bulb	With bulb	Catamaran	No bulb	With bulb	Catamaran
14	2.0	1051	1034	970	No	No	No
	2.5	1314	1292	1212	No	No	No
	3.0	1577	1551	1455	No	No	No
	3.5	1840	1809	1697	Yes	Yes	Yes
	4.0	2103	2067	1939	Yes	Yes	Yes
16	2.0	1196	1172	1038	No	No	No
	2.5	1495	1465	1298	No	No	No
	3.0	1793	1758	1558	No	No	No
	3.5	2092	2051	1817	Yes	Yes	Yes
	4.0	2391	2344	2077	Yes	Yes	Yes
18	2.0	1324	1294	1057	No	No	No
	2.5	1655	1618	1322	No	No	No
	3.0	1986	1941	1586	No	No	No
	3.5	2317	2265	1850	Yes	Yes	Yes
	4.0	2648	2588	2114	Yes	Yes	Yes

The seakeeping analysis was carried out in the following wave to evaluate the sensitivity of the three hull forms relating to bow diving phenomenon. Simulation observations were made in presenting the behaviour of the designs. During the simulation, it was defined to model the following wave using the JONSWAP spectra and the same wave parameters as the head wave condition. The possible situations were met on the simulation analysis such as the ship was overtaking the wave, the ship was running at the wave speed and the wave was overtaking the ship. The wave height also was configured as the head wave condition.

The behaviour of the three hull forms in the following sea can be seen in Table 6. The principal findings from the result of the seakeeping analysis are described as follow:

- All of the three hull forms show a significant decrease in the vertical acceleration. The non-bulbous bow, the bulbous bow, and the catamaran have 77%, 75% and 96% lower of the maximum peak acceleration at the livestock pen than the head wave condition respectively. It is indicated that the following sea has a positive influence on the vertical acceleration of the three hull forms.
- Bow diving occurred on the three hull forms when the significant wave height is above 3 meters.
- The increased speed has the influence to reduce the bow diving because of the increased of running trim.
- The vertical acceleration was relatively linear with the wave height for all of the three hull forms.
- All of the designs show an optimum vertical acceleration on the speed of 16 knots. It is indicated that the vertical motion due to the speed of the ship able to reduce the vertical acceleration, which is generated by the following wave.

Table 6. Hull forms behaviour on following sea condition.

Speed [kn]	**Wave height [m]**	**Vertical acceleration on livestock pen [mm/s^2]**			**Bow diving occurrence**		
		No bulb	**With bulb**	**Catamaran**	**No bulb**	**With bulb**	**Catamaran**
14	2.0	193	199	27	No	No	No
	2.5	241	248	34	No	No	No
	3.0	289	299	40	No	No	No
	3.5	337	348	47	Yes	Yes	Yes
	4.0	385	398	54	Yes	Yes	Yes
16	2.0	164	161	25	No	No	No
	2.5	205	202	31	No	No	No
	3.0	246	242	38	No	No	No
	3.5	287	282	44	Yes	Yes	Yes
	4.0	328	323	50	Yes	Yes	Yes
18	2.0	308	325	39	No	No	No
	2.5	385	406	49	No	No	No
	3.0	462	487	58	No	No	No
	3.5	539	569	68	Yes	Yes	Yes
	4.0	617	650	78	Yes	Yes	Yes

Finally, the seakeeping analysis was made to investigate the behaviour of the ship in the stern quartering wave condition. The stern quartering wave condition is considered to evaluate the sensitivity of the hull designs regarding the couple rolling and pitch motion phenomenon and to identify the vertical acceleration response of the livestock pen on board. The models of the sea environment have the same parameters as the head and following wave conditions. The results of the simulation can be seen in Table 7.

The general outcomes from the simulation analysis of the stern quartering condition can be described as follow:

- The vertical acceleration of the three hull forms shows an increased magnitude compare with the following sea condition, especially in the ship speed of 14 knots and 16 knots, however, the vertical acceleration shows a decreased magnitude on the ship speed of 18 knots. It might be explained that the additional acceleration is generated due to the roll motion, which is induced by the stern quartering wave.
- The maximum roll angles are 9.45 degrees, 9.46 degrees and 1.08 degrees for no bulbous bow, with bulbous bow and catamaran respectively. It might be seen that catamaran design have roll motion amplitude significantly smaller than the monohulls. The bulbous bow design has the same roll motion amplitude with the non-bulbous bow design. It is indicated that the bulbous bow as additional appendages does not have any influence on the roll motion, but it effectively improves the resistance performance of the hull.
- The maximum speed of the ship able to reduce the vertical acceleration of the livestock pen. It is also might be seen that the increased ship speed has reduced the maximum of roll angles. It is indicated that the increased speed will reduce the influence of stern quartering wave to generate the roll motion, which is increased the vertical acceleration of the livestock pen. However, the excessive additional ship speed might increase the vertical acceleration.

Table 7. Hull forms behaviour on stern quartering sea.

Speed [kn]	Wave height [m]	Vertical Acceleration on the livestock pen [mm/s^2]			Maximum of roll angles in degrees		
		No bulb	With bulb	Catamaran	No bulb	With bulb	Catamaran
14	2	221	289	88	4.72	4.73	0.54
	2.5	277	362	110	5.9	5.91	0.68
	3	332	434	132	7.08	7.1	0.81
	3.5	388	506	154	8.27	8.28	0.95
	4	443	578	176	9.45	9.46	1.08
16	2	227	297	68	4.4	4.4	0.52
	2.5	283	371	85	5.51	5.5	0.65
	3	340	445	102	6.61	6.6	0.78
	3.5	396	519	119	7.71	7.7	0.92
	4	453	593	137	8.81	8.8	1.05
18	2	195	266	52	4.28	4.26	0.51
	2.5	243	332	66	5.35	5.32	0.63
	3	292	398	79	6.42	6.39	0.76
	3.5	341	465	92	7.49	7.45	0.89
	4	390	531	105	8.56	8.51	1.01

4. Conclusions

A comparative study has been made of the catamaran, with bulbous bow monohull and no bulbous bow monohull as an alternative hull form for livestock carrier. This study is made using strip theory method and empirical formula for evaluating the resistance, intact stability, and seakeeping performance. The conclusions of the observation from the investigation are presented as follow:

- The catamaran design has better resistance performance in the high service speed (above 13 knots) compared with the monohulls. The residuary resistance is significantly decreased, especially in the large service speed where the monohulls show an aggressive resistance escalation. However, in the case of the lower service speed (below 13 knots), the total resistance does not differ significantly among catamaran and monohulls.
- The separated twin hull has increased the height of metacentre of the hull form. Therefore, the initial stability of catamaran has enabled the larger transversal weight shifts than the monohulls. This characteristic is important to increase the ship safety level for the livestock carrier, which has dynamics cargo shift due to the livestock motion on the upper deck.
- In the head sea condition, the catamaran shows similar performance with the monohulls. All of the hull forms have experienced the deck wetness on the wave height above 3 meters. It is indicated that the operability of the three hull forms should be limited to the significant wave height below 3 meters.
- In the following and stern quartering sea condition, all of the three hull forms show a significant reduction on the vertical acceleration. The ship performance on following sea condition also can be indicated that the limit of ship operability is below 3 meters of the significant wave height. In the stern quartering sea condition, it might be seen that the catamaran have a smallest roll motion amplitude than the monohulls. Furthermore the increase of ship speed able to reduce the amplitude of roll motion due to the stern quartering wave for the entire hull forms.
- Although catamaran design has shown better performances than the monohulls, however, the significant improvement of resistance can be achieved only for the high service speed. Otherwise, the improved safety level through the significant increase in the metacentre height may produce a very large righting moment, which makes the higher acceleration of roll motion that has a negative influence on the welfare of the livestock cargo. Therefore, the adoption of catamaran design should be supported by a detailed analysis to determine the appropriate design parameters.

Nomenclatures

A	Area under GZ curve minus area under heeling arm curve (Fig. 5), m^2
A	Lateral area of the vessel above waterline (Eq. 3), m^2
B	An overall beam of the ship (Fig. 3), m
B	Area under GZ and heeling arm curve (Fig. 5), m^2
b	A beam of each hull in a catamaran (Fig. 3), m
C	Livestock shift constant
C_F	Friction resistance coefficient (Fig. 4)
C_R	Residuary resistance coefficient (Fig. 4)
D	Displacement, tonnes
F	Floor area per animal, m^2
F	Fodder heeling moment, tonnes m
FF_1	Heeling arm curve due to all factors

GM	Metacentre height, m
GZ	Righting arm, m
H	Vertical separation of centroid, m
H_B	Depth of cross-deck (Fig. 3), m
H_T	Tunnel height (Fig. 3), m
LF	Heeling arm at 0° due to the effect of fodder shift, m
LL_1	Heeling arm curve due to combined wind and livestock shift
M	Average mass of livestock per animal, tonnes
OW	Heeling arm at 0° due to wind, m
P	Wind pressure, tonnes/m^2
S	Stowage factor of fodder
S_T	Tunnel width (Fig. 3), m
WL	Heeling arm at 0° due to the shift of livestock, m
WW_1	Heeling arm curve due to wind, (Fig. 5)

Greek Symbols

ΔC_T	Correlation coefficient (Fig. 4)
Θ	Angle of heel due to wind, deg

Abbreviations

ITTC	International Towing Tank Conference
MO43	Marine Order 43 (cargo and cargo handling-livestock)

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