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A Practical Estimation of Static Stability of a Hovercraft

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Abstract

The static stability of a high-speed hovercraft is estimated by model tests, simplified restoring moment equations and CFD. Well-known methods to increase the stability of hovercrafts are introduced. Roll and pitch moments of a scaled model with a skirt system are measured over inclination angles. The tests are performed on cushion at zero speed both on-land and over-water. To predict the static stability performance, simple restoring moment equations and CFD approach are introduced. Both shows a quantitative difference from the model test results, however, could be used as a design tool for relative comparison prior to model tests.

Keywords: hovercraft, static stability, model test, CFD

1 Introduction

Hovercraft is operated in hovering condition on-land and over-water using vertical supporting force by generating a pressure in a cushion space. Hovercraft is composed of lift fans, bow thrusters, propellers, skirt, hull and so on. Lift fans supply air to skirt and bow thrusters respectively. Bow thrusters, mounted on the upper part of the lift fans, are used to maneuver the craft. Skirt, attached to the hull, holds air in a cushion space. Propellers, mounted on the hull as far backward as practical, contribute main propulsion.

Hovercrafts have been developed with experimental, theoretical and computational methods since Sir Cockerell invented an idea in 1959(Mantle 1980). Hovercraft technology has relied on experimental ways, such as model tests or full scale trials. However, the recent advancement of computational methods enables designers to investigate hydrodynamic performance of hovercrafts.

Havelock(1913)'s theoretical study has been widely used in CFD analysis on hovercrafts. Kohara and Nakato(1992), Na and Lee(1996) distributed a pressure field on the cushion area and investigated wave patterns and wave resistance. Nikseresht et al.(2005) also employed pressure distributions with VOF method. Recently, other applications to hovercrafts by CFD have been introduced. Park and Yu(2004) computed unsteady flows from a lift fan to a bow thruster. Lavis and Forstell(2005) performed computations on a lift fan and a ducted propeller.

The present study first describes the stability of hovercrafts and some basic methods to increase it. The static stability of a hovercraft is investigated by model tests. Simple restoring moment equations and CFD computation to predict the static stability are introduced. The predicted values are compared with the model test results.

2 Stability of Hovercraft

The stability of hovercrafts can be divided into static and dynamic characteristics. Like aircrafts or surface ships, a hovercraft is operated in six degrees of freedom but, due to its proximity to the surface, is restricted in its pitch and roll attitudes.

The mechanism of the static stability of hovercrafts is similar to surface ships, except that the restoring moment is generated by pressure gradient in cushion chamber. The restoring moment mainly depends on the shape of skirt employed in the hovercraft as that of the surface ship is characterized by its hullform. The cushion pressure and its distribution in the cushion chamber are the main parameters of the restoring moment of static stability.

The dynamic stability of hovercrafts can be considered mainly by plow-in phenomenon. Plow-in is an unstable characteristic that can be occurred while running in the trim by bow at high speed. Plow-in decreases the performance of hovercrafts and even causes capsizing.

The static stability for roll and pitch motions is generally expressed in stiffness, which is defined as follows.

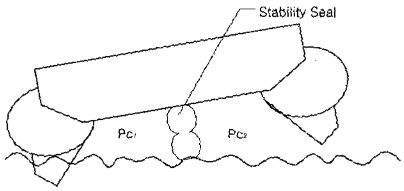
$$\%CP = \frac{M}{WL} \times 100 \tag{1}$$

Where $\%CP$: percent cushion pressure shift
M: pitch (or roll) moment
W: Hovercraft weight
L: cushion reference length (or beam)

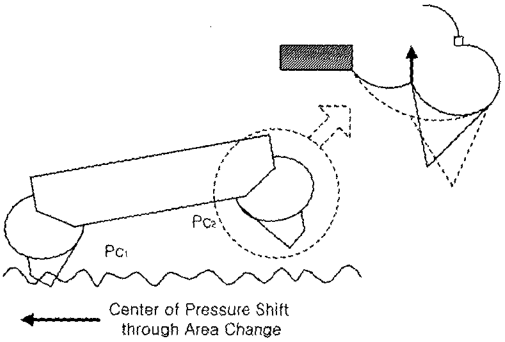
The roll or pitch stiffness means the percentage shift in the center of cushion pressure which results from a change in roll or pitch angle.

General methods to increase pitch and roll stability were summarized by Mantle(1980). Conventional hovercrafts employ a combination of the following three basic methods, compartmentation method, center of pressure shift method, and pressure-rise method as shown in Figure 1. The Compartmentation method consists essentially of compartmentation of the cushion area by either downward-directed air jets or inflated flexible skirt keels. The pressure difference of the compartments generates a restoring moment. The center of pressure shift method employs skirts shaped so as to cause outward movement of cushion area of the down going side. The incurred center of pressure (C.P.) shift, with area change, gives the desired restoring moment. The pressure-rise method uses the multicushion design which provides pitch and roll stability from the basic stiffness in heave of the individual "jupes (folded shapes)" or conical cushions.

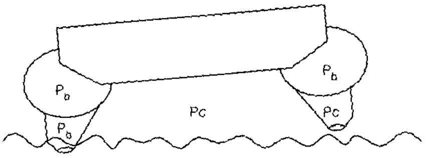
Plow-in, which can judge the dynamic stability of a hovercraft, occurs usually at trim by bow condition. An air cushion feed directly into the bow cushion from lift fans could increase the bow-up moment to prevent plow-in. Also many hovercrafts have horizontal stability seal located forward from the midship to make higher pressure in the fore cushion area.



(a) Compartmentation method



(b) Center of pressure shift method



(c) Pressure rise method

Figure 1: Static stability Improving Methods

3 Model Tests

3.1 Test Setup and Procedure

The model tests were conducted at the towing tank of David Taylor Model Basin (DTMB). A 1/12th scaled model is shown in Figure 2. The skirt of the model was made of ripstop nylon with approximately scaled flexural stiffness comparable to that of the full-scale skirt material. The hull-mounted fan system combined with the skirt system produces cushion characteristic corresponding to the full scale.

The model, initially hung above the free surface, is laid on the water after the cushion chamber is filled with the air. A weight on the deck generates a roll or pitch moment, and the inclination angle is measured. Figure 3 shows roll static stability tests. Changing the location of the weight, the inclination angles over various heeling moments can be measured.

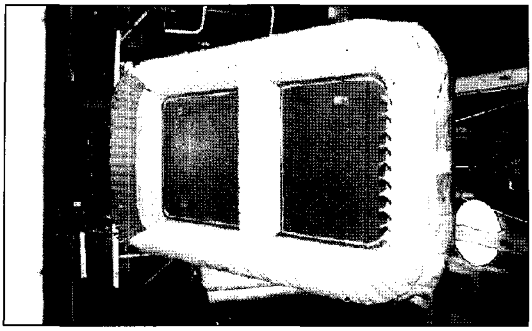


Figure 2: 1/12 scale model

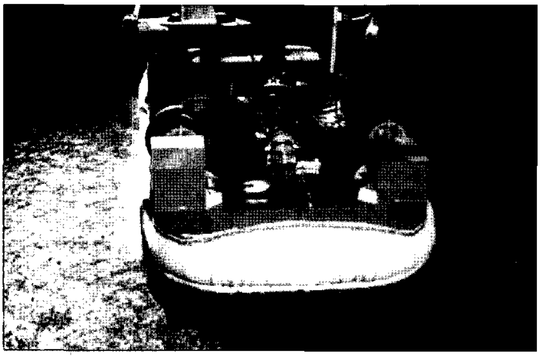


Figure 3: Roll static stability test

3.2 Model test results

Roll and pitch stability tests were performed both on-land and over-water conditions. Figure 4 shows the roll stability test results. The slope of the curves at 0 degree gives the roll stiffness of 1.24 and 1.01, for on-land and over-water, respectively. The moment of over-water condition at 0degree is higher than that of on-land condition due to the deflection of the free surface, even though the skirt system is symmetric shown in the Figure 2. The different bow and stern skirt shapes and the stability seal located forward cause longitudinal unsymmetry. Figure 5 compares the pitch stability test results. The on-land and over-water pitch stiffnesses are 3.44 and 2.54, respectively. The moment at 0 degree is not zero due to the unsymmetric skirt system.

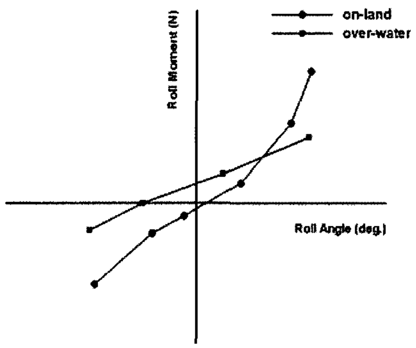


Figure 4: Roll moment curves

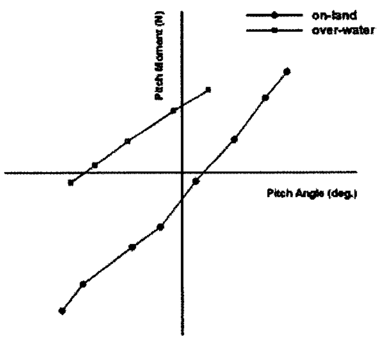


Figure 5: Pitch moment curves

The pitch stiffness is found much greater than the roll stiffness due to smaller cushion area of the forward compartment, location of the stability seal and air feeding system.

4 Simplified Restoring Moment Prediction

4.1 Roll Static Stability

Once the hovercraft heels one side as shown in Figure 6, the pressure gradient along the beam is generated. The pressure of the wetted side gets increased and decreased the other side. Simultaneously, the center of cushion pressure moves from C to C'. Assuming the pressure gradient in the cushion chamber is negligible to simplify the roll stability equation, the roll moment by the pressure difference in the skirts with double fingers can be calculated by equation (2).

$$M_\theta = P_b A l_1 - P_c A l_2 \tag{2}$$

Where M_θ: roll moment
A: area of skirt tip
Pb: bag pressure
Pc: cushion pressure

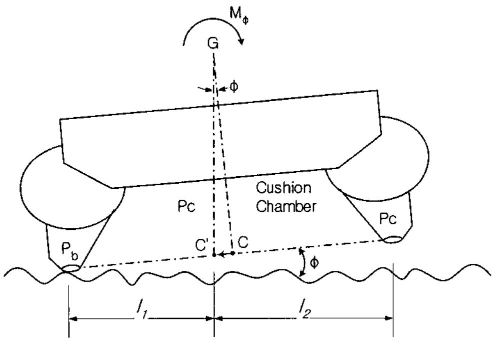


Figure 6: Pressure distribution in cushion

4.2 Pitch Static Stability

In a similar manner, equation (3) is derived for the pitch moment of the skirt system shown in Figure 1(a). It has single fingers in bow and stern, and a stability seal amid the craft. This assumption simplifies the equation as the pressure difference is offset each other.

$$\begin{aligned} M_\phi &= \frac{L}{2} B \cdot \frac{L}{4} (P_{C1} - P_{C2}) \\ &= \frac{L^2 B}{8} (P_c \frac{V}{V_{c1}} - P_c \frac{V}{V_{c2}}) \end{aligned} \tag{3}$$

Where M_ϕ: pitch moment
L: cushion length
B: cushion beam
V: chamber volume
V_{c1}: chamber volume of down going side
V_{c2}: chamber volume of up going side

Using the above equations (2) and (3), 0.7 %/deg and 3.0 %/deg are calculated for roll and pitch stiffness of the present hovercraft, respectively.

5 CFD Analysis

Numerical static stability tests were performed using a commercial CFD program, FLUENT ver. 6.2. As the roll stability is worse than the pitch stability, we computed only the roll stability. On-land and over-water conditions were investigated employing symmetry boundary condition and VOF method, respectively.

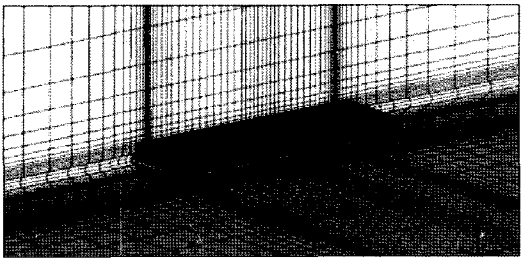


Figure 7: Computational grid system

The grid is shown in Figure 7 consist of 0.3 million hexahedral cells. The complex skirt shape and the compartment seal were neglected for the grid generation. The initial inclination angle is restricted to small values for the skirt not to touch the fixed or free surface. The hovercraft including the skirt is assumed rigid and fixed in its initial position and shape.

5.1 On-land condition

As the hovercraft in the computation can not move for the pressure change in the cushion chamber, the air gap from the tip of the skirt to the ground needs to be considered. That is, the initial air gap must not affect the stiffness. Two gap distances, 30 and 50 mm, were given, and steady state computation were carried out. It was found that the larger air gap gives smaller moment and lift force. However, the stiffness remains unchanged for the both cases, as the stiffness is nondimensionalized by the weight of the hovercraft, which, in this computation, is the obtained from the lift force. We set the size of the air gap of 50 mm for all computation.

The roll stiffness is obtained from the slope in Figure 8, based on the computation results for two heeling angles, 0.1 and 0.3 degrees. The stiffness is computed 0.79, a little smaller than that by the model tests.

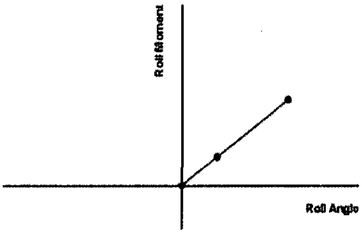


Figure 8: Roll moment curve of on land computation

5.2 Over-water condition

Unsteady state over-water computations were performed using VOF method to capture nonlinear free surface motions. The fans of the hovercraft were modeled as a velocity inlet. The velocity was given from fan model test results. However, we set for the velocity to increase gradually to prevent internal waves, up to 20 and 10 seconds for 0.1 deg. and 0.3 deg. heeling angles, respectively.

Figure 9 shows a captured free surface for 0.1 deg. heeling angle. Complex free surface elevation near the skirt is shown. Though the heeling angle is smaller than the model tests, the complex free surface behavior is similar to the model tests. However, internal waves are developed in the cushion area, which causes a pressure fluctuation.

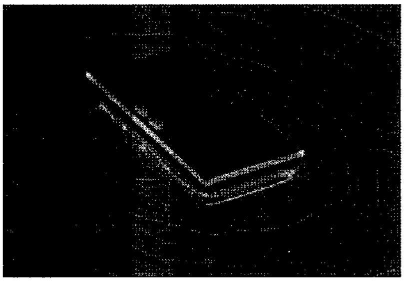


Figure 9: Wave height contours (roll angle: 0.1 deg., T: 58 sec)

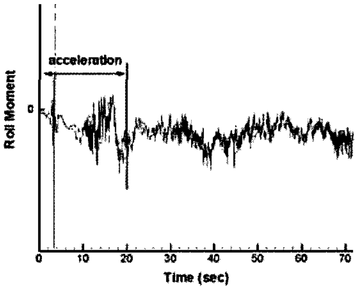


Figure 10: Time history of roll moment (roll angle: .1 deg.)

Table 1: Roll and pitch stiffness (%)

	Roll		Pitch	
	On-land	Over-water	On-land	Over-water
Model tests	1.24	1.01	3.44	2.54
CFD	0.79	1.66	-	
Simplified prediction	0.7		3.0	

Figure 10 shows time history of roll moment for the heeling angle of 0.1 degree. Even though we accelerated the velocity for 20 seconds, the moment history shows an oscillation due to the fluctuation of internal waves. To calculate the roll stiffness, moment and lift force are averaged from the end of the acceleration, 20 and 10 seconds for 0.1 and 0.3 degree, respectively, to the end of the computations, 72 and 43 seconds. Using the averaged moment and weight, roll stiffness of 1.66 is obtained.

The result of the over-water computation is quite different from the on-land condition. The fluctuation of the free surface and pressure might be a major source of the discrepancy.

Table 1 summarizes all the results obtained from model tests, simplified equations, and CFD computation. It is found that CFD and simplified prediction do not agree with the model tests. The simplified prediction does not exactly consider pressure gradient, center of cushion pressure and the effect of stability seal which might cause the difference. Though CFD could model all the assumption made in the simplified equation, both on-land and over-water computations showed different results from the model test results. The on-land computation, which showed numerically stable, needs more mesh to improve accuracy. The over-water computation should employ a numerical treatment to stabilize the internal waves.

6 Conclusions

This paper investigated three methods, model tests, the simplified equations, and CFD, to estimate the static stability performance of a hovercraft.

For the simplified restoring moment equations, the assumptions cause the error in which the pressure gradient in the cushion chamber is negligible in roll stability equation and a stability seal is amid the craft in pitch stability equation. However, as the equations need only main dimensions and pressures, they could be easily used when deciding main dimensions.

Contrast to the simplified prediction method, CFD requires a very tedious work. However, it can consider the complex shape and flow field. Though the over-water computation could not remove the free surface fluctuations, the on-land case was very stable and needed a short computation time. The difference between the on-land computation and the model tests might be primarily caused by the simplification of the skirt geometry. If the on-land computation guaranteed the consistency, it would be a powerful tool to design hovercrafts. Also, the over-water computation will be elevated if dynamic motion is considered according to free surface fluctuation.

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