PITCH AND ROLL HYDRODYNAMICS OF A PERICELL HOVERCRAFT

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ABSTRACT

Pitch and roll responses of hovercraft have been extremely difficult to predict due to the complexity of hydrodynamic analyses on one hand and the difficulties of appropriate cushion scale modeling on the other. The paper presents comparisons of pitch and roll stiffness coefficients for overwater and overland operations. Data are presented from model-scale and full-scale trials and analytic-numerical modeling. The effects of model-scale on the cushion dynamics relative to rotational responses are presented and the important characteristics of overwater and overland responses are discussed.

INTRODUCTION

The hovercraft has come of age in the defense forces of the United States through the adoption of air cushion support for the U.S. Navy's Landing Craft Air Cushion (LCAC) program and the U.S. Army's air-cushion-supported logistics program[1]. As Eames[2] recently noted, hovercraft "offer unique capabilities for amphibious warfare which are already being exploited in assault landing craft. There is no shortage of special applications for small ACV's. They have already proved themselves in riverine warfare and for various duties in the Arctic." These recent U.S. successes coupled with the decades of international experience demonstrate that hovercraft applications are assured for the future. Successful hovercraft applications are usually special in nature but normally the mission needs cannot be easily met without the unique capabilities of an air-cushion-supported vehicle. Amphibious assault and mine countermeasure missions are typical examples of excellent hovercraft applications.

Technological developments have kept pace on an international scale with the construction and deployment of new hovercraft designs. The most challenging problems faced by hovercraft designers have been analytical modeling, model scaling and full-scale evaluations. Analytical models of hovercraft dynamics must include all detailed aspects of cushion dynamics, fan performance, flexible skirts and compliant free surfaces. The complexities of the nonlinear interactions among these (and other) components of the hovercraft have limited the development of fully validated nonlinear time domain motion analysis routines. In the second area of scaling of model-scale motions to full-scale performance, the laws of thermodynamics prohibit the direct use of model-scale results. Since air is normally the working fluid for both model-scale and full-scale craft (and therefore its compressibility cannot be appropriately scaled[3]), designers are forced to apply empirical considerations and design experience to seakeeping evaluations. Full-scale seakeeping performance assessments constitute a third problem area. The difficulties of making accurate measurements are found both in shipborne motions and in the equally important area of sea state measurement. A foolproof method of measuring wave profiles in short crested directional seas in situ is still not within our grasp.

This paper is concerned with the various aspects of the evaluation of pitch and roll hydrodynamic response of a pericell hovercraft. Specific analytic predictions, model-scale results and full-scale trials are briefly summarized. Details of specific studies and complete performance results are referenced but not exhaustively covered in this survey. This summary is not intended to cover the complete body of nationally and internationally developed technology. This presentation concentrates rather on a few specific accomplishments which all relate to the same issue of pitch and roll response of a specific hovercraft design.

MOTION PREDICTION AND MEASUREMENT

Analytic Modeling

Hovercraft which are supported on peripheral cells (pericells) obtain their vertical plane stability from subtle changes in under cell flow conditions, modified discharge coefficients and changes in pressure with cell contact area and flexible geometry. The combined effect is a change in the spatial distribution and the support pressure which generates equilibrium restoring motion for the vehicle. The specific phenomenon of spatial pressure distribution has been examined in detail by Moran and Schechter[4].

The pericell design is simple in concept and effective in practice but difficult to model analytically due to the subtlety of the stability mechanisms. An advanced modeling of the dynamic restoring and damping mechanisms and their many complex interactions for a pericell hovercraft has been presented by Moran and Kim[5]. This analytical model provides a prediction in the nonlinear regime of the dynamic motion of a pericell hovercraft over a noncompliant surface in four degrees of freedom: pitch, heave, surge, and roll. The designation of noncompliance implies no greater restriction than

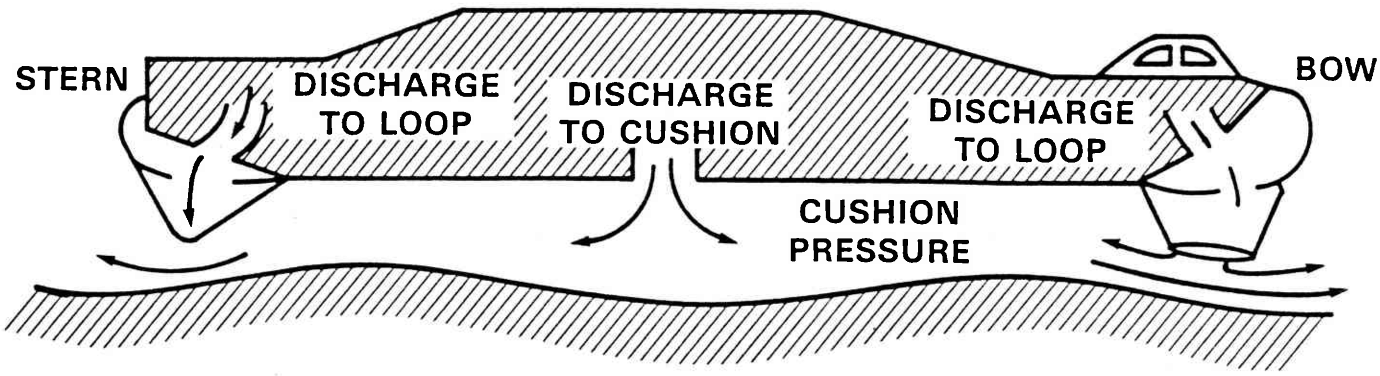

Fig. 1 Schematic flow diagram for a pericell hovercraft

normally accepted in seakeeping models but is an indication of the exact free surface condition. The analytic modeling of sway and yaw necessary to complete the full six-degrees-of-freedom characterization has been presented previously by Moran[6] in a model which contains a different analytical model for vertical plane response.

The cushion flow system modeled by Moran and Kim[5] is shown schematically in Figure 1. The major concern in this model is the design of the skirt and cushion air supply systems which provide hovercraft lift and stability. The pericell system consists of a series of peripheral cells attached to a flexible supporting air distribution loop which extends around the craft perimeter. The lift system does not have any internal cushion subdivision or stability keel. Each pericell is a complete loop. Air is supplied by two separate systems as shown in Figure 1. The physical characteristics of the system have been analytically modeled in the detail necessary to accurately represent the complete nonlinear behavior of the hovercraft to operate over any terrain or wave surface.

Damping

Velocity-dependent damping is one of the most difficult phenomena to analytically model. The damping characteristics can be examined only from the motion of the craft which results from the complex interactions between the system discharges and the pressure distributions. The major source of damping for a pericell hovercraft is in the nonlinear behavior of the air flow escaping through the gap between the cell and the ground or free water surface. The second most important damping mechanism is the characteristic function of the fan which generates air for the craft lift system.

The fan function is subject to an unsteady back pressure which normally is a time-dependent function itself. Most fans operating under dynamic conditions develop hysteresis pressure/discharge relationships with the function dependent upon the maximum pressure, minimum pressure, oscillation frequency and the harmonic content of the time-dependent back pressure. For normal variations in back pressure, the fan characteristic function is nonlinear (without hysteresis and may be adequately represented by a quadratic polynomial which allows a parametric evaluation of the fan characteristic on vehicle damping. These results and modeling characteristics have been previously presented by Moran and Jennings[7].

Hovercraft damping in pitch or roll is quantified by the coefficient, β, in the exponential function which characterizes the decay in a declining oscillation. The pitch response, for example, may be represented as:

$$\dot{\theta} = \dot{\theta}_0 \exp[-\beta(\dot{\theta})t]\cos[\omega(\dot{\theta})t]$$

in which the pitch rate ($\dot{\theta}$) is found to be a function of amplitude ($\dot{\theta}_0$), amplitude dependent damping (β) and amplitude dependent frequency (ω). The empirical results of a declining oscillation experiment on a 7/100 scale model of a pericell hovercraft are shown in Table 1 by Murray and Moran[8]. The table shows the pitch and roll, natural frequencies, and damping coefficients with and without heaving motion at zero speed over a solid surface. Heave oscillation alone could not be obtained since the damping characteristic of the hovercraft is so large that less than one full cycle of motion was measurable. The roll natural period and roll damping were obtained from the heave reading. This was possible since the characteristic motion of the pericell hovercraft in roll is such that the craft sinks as the roll angle is increased. The roll decay coefficient given in the table therefore represents a coupled roll/heave motion. As expected the natural frequency in roll is significantly higher than the corresponding frequency in pitch.

The characteristic amplitude dependence in pitch damping for a hovercraft is shown in Figure 2 from an experimental investigation by Moran[9]. The decay coefficient (β) is plotted here as a function of the average pitch rate over one decay cycle in a declining oscillation experiment. The peak responses in both frequency and decay coefficient with increasing oscillation amplitude coincide with the beginning of skirt contact with the surface. The magnitude of the pitch induced heave motion is indicated by the dashed curve with ordinate at the right of Figure 2. The initiation of pitch induced heave motion is also coincident with skirt contact with the surface.

Stiffness

The pitch and roll stiffnesses of a pericell hovercraft are characterized as angular moments which are functions of the pitch or roll angle, respectively. Moment coefficients are easily obtainable on full-scale hovercraft by moving weights on the deck and recording the resultant angular declination. The AALC JEFF(A) has undergone a series of such full-scale experiments at the Navy's Experimental Trials Unit. These trials also included experimental evaluations of the hovercraft lift fan and skirt system performance which were reported by Moran, Waters, and Jennings[10].

Tab. 1 Pitch and roll response coefficient for a pericell hovercraft at zero speed

Type of Oscillation	Natural Frequency ω_n 1/sec	Decay Coefficient β 1/sec
	MODEL-SCALE VALUES	
Pitch	8.6	2.8
Roll/Heave	16.5	3.5
	FULL-SCALE VALUES	
Pitch	2.3	0.7
Roll/Heave	4.4	0.9

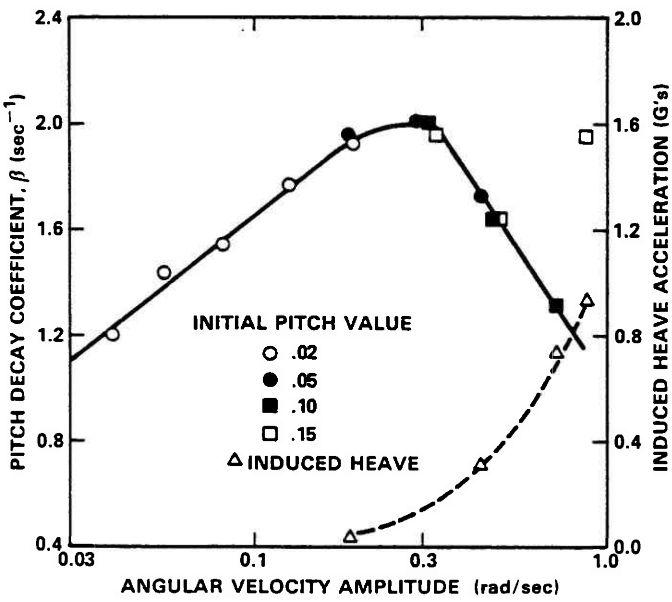

Fig. 2 Pitch decay coefficient as a function of angular velocity

The pitch and roll moment trials were performed overland in order to restrain and stabilize the vehicle during testing. Comparisons of the pitch and roll moment coefficients measured on the full-scale JEFF(A) and on a 7/100 scale model have been reported by Jennings and Waters[11] and are shown in Figures 3 and 4. There is extremely good correlation between the model- and full-scale pitch stiffness coefficients throughout the complete range of pitch angles. The roll response comparison is good for declinations less than 1.0 degree but deviates for larger angles.

Several significant findings have been reported by Jennings and Waters[11]. The first is that both pitch and roll stiffness are greater when the vehicle is subjected to bow down trim than at even trim. The increase in cushion stiffness may be due to closing off the leakage path between the pericell and the cushion at the inner attachment point. In a cushion modification study, the installation of an inner attachment seal on the bow pericells increased pitch stiffness at large bow down pitch angles. Without the inner attachment seals, the bow pericells do not contribute significantly to favorable stability of the skirt system. Finally, it is clear that the use of model-scale experiments to predict overland cushion borne stiffness is adequate if the model represents the full-scale skirt configuration to sufficient accuracy.

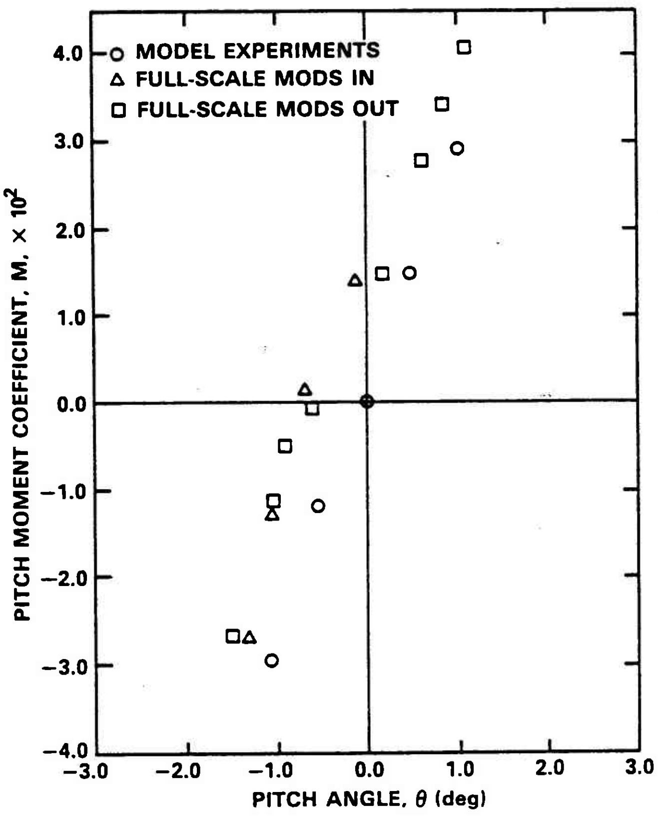

Fig. 3 A comparison of the pitch stiffness of the JEFF(A) with the 7/100 scale verification model

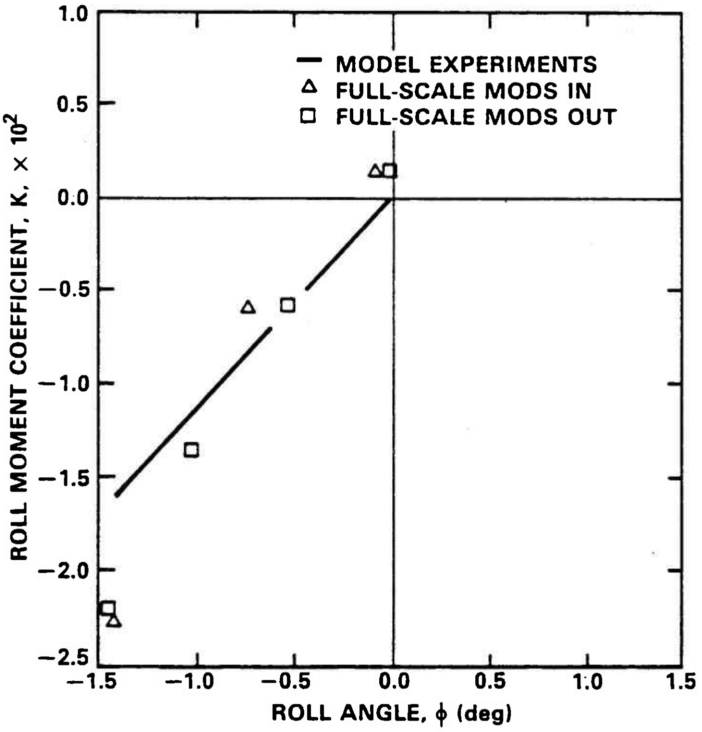

Fig. 4 A comparison of the roll stiffness of the JEFF(A) with the 7/100 scale verification model

Detailed pitch and roll stiffness derivations have been reported by Cavanagh, Ricci, and Hills[12]. The pitch stiffness derivative (M_θ) for the JEFF(A) shown in Figure 5 is compared with the observed constant model-scale derivative. Interestingly, the roll stiffness derivative (K_ϕ) shown in Figure 6 indicates a dramatic dissimilarity between model and full-scale results. One of the more interesting dynamic characteristics of pitch stiffness is the over-water speed dependence measured during a full-scale trial[12]. The effect of wind speed and sea state is clearly evident in the pitch derivatives shown in Figure 7 demonstrating that hovercraft stability is not an environmentally independent consideration.

Overland Response

The ultimate test of worth of an analytical simulation rests in the accuracy of prediction of known hovercraft behavior. Previous air-cushion-supported vehicle simulation models have suffered from a lack of validation or poor agreement with measurements. There are two major factors which seem to dominate good agreement between measured and computed motions. The first is that the most critical elements of the dynamic system must be carefully identified and second receive major detail in modeling. Identification is not a trivial task since it requires repeated iteration of a simulation model during development to determine the critical elements as accuracy is refined. The detailed modeling must also be a developmental process since excessive detail or complexity in the modeling of noncritical elements not only is unnecessary but may lead to unwarranted numerical error accumulation. For a pericell hovercraft, the critical element is the modeling of cell extremities in the proximity of the associated free surface or terrain which in turn determines the under-cell flow characteristics.

A single example[5] of the validation of the analytic model is shown in Figure 8 where the hovercraft pitch and heave responses to traversing a large overland gully are presented. It is clear that even under this severe excitation which exercises the full nonlinear character of the model, the predicted model-scale response is excellent. A general observation for both overland response and seakeping response to periodic wave forms is that the simulation predicts a slightly greater reaction to the initial disturbance than is experimentally observed. This effect remains in the subsequent motion in the form of a damped oscillation.

These simulation model results may be classified as untuned. Tuning of a simulation model may be accomplished by modifying various model characteristics with the objective of matching the computed results for operational conditions corresponding to available experimental data. For an air-cushion-supported vehicle, the major tuning parameters are the lift system discharge and the pressure ratios between the cushion, pericells, and the flow loop.

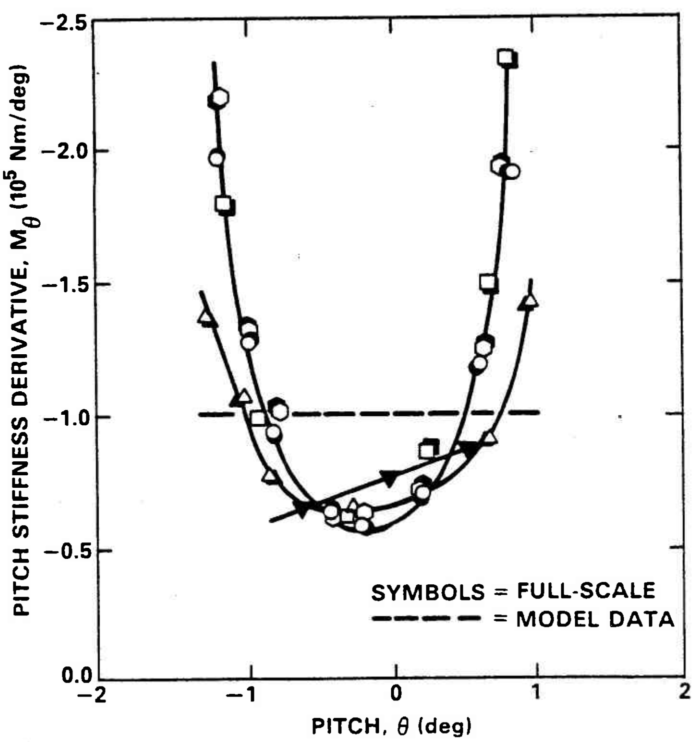

Fig. 5 Static pitch stiffness derivatives, full-scale

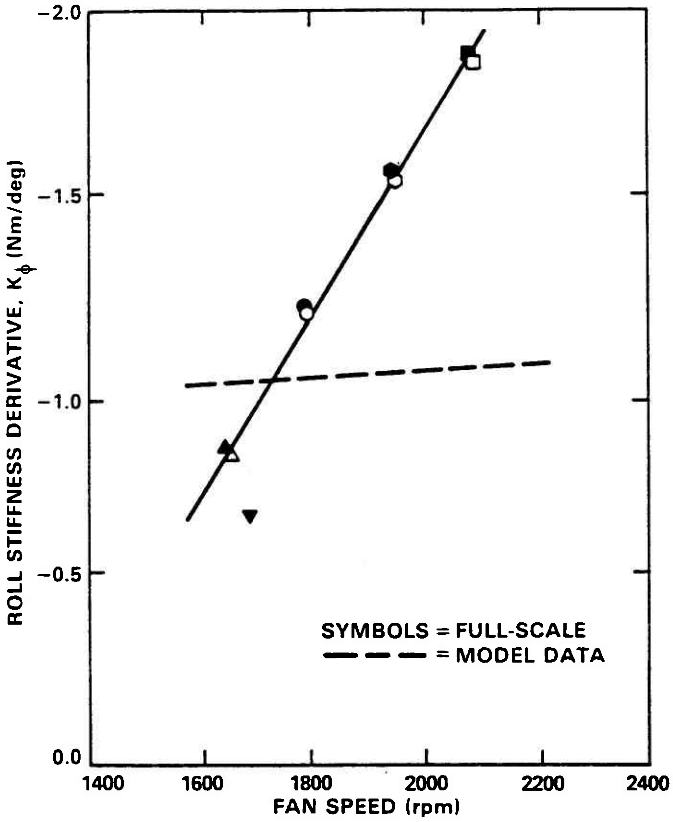

Fig. 6 Variation of static roll stiffness derivatives with fan speed

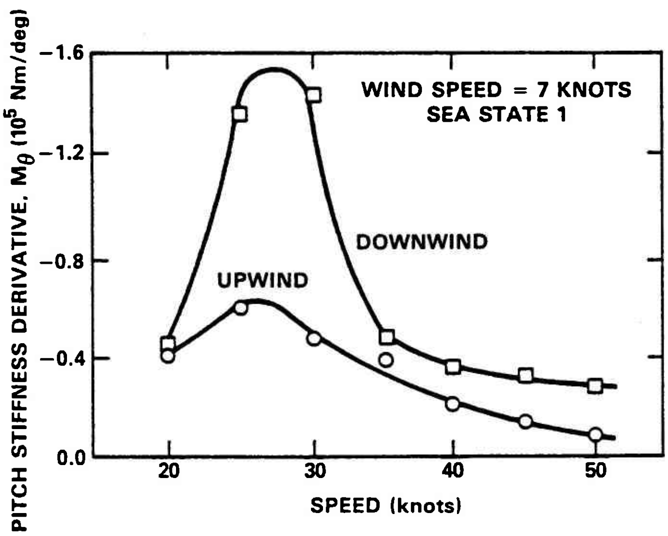

Fig. 7 Variation of the overwater pitch stiffness derivative with speed

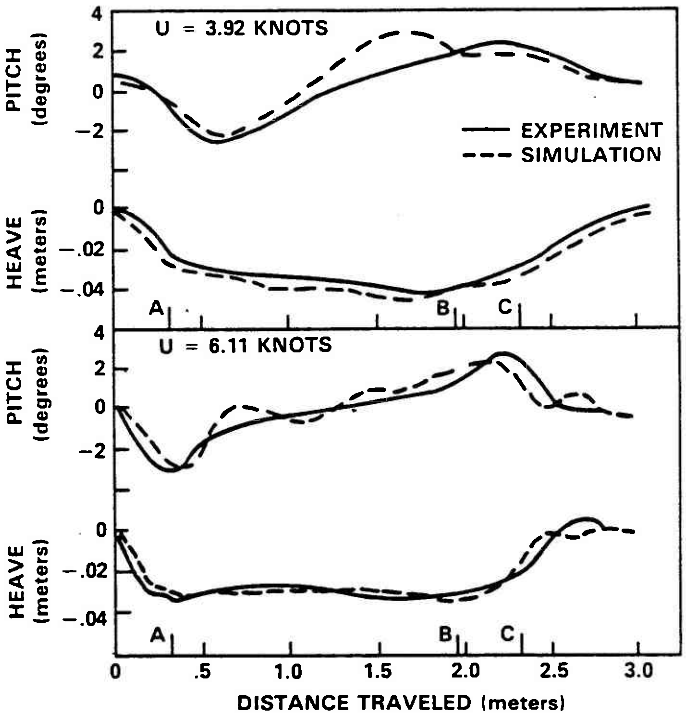

Fig. 8 Model pitch/heave response over gully terrain

It is possible through a tuning process to bring the natural oscillation frequencies and damping coefficients for pitch and heave into closer agreement with those experimentally observed. There are few data available to substantiate assumptions on the behavior of flexible feed holes under dynamic conditions and so modifications to static measurements may occasionally be justifiable under the present state of knowledge. We know that the numerical model behaves much more efficiently than the actual vehicle since there are no holes in, nor cracks between, the numerical pericells. Experience with hovercraft models proves that they always leak cushion air and usually in a most non-uniform and unpredictable manner. Setting a minimum flow area in the simulation model is therefore a justifiable way to account for such physical anomalies.

Seakeeping Response

The simulation program has been extended by Lin and Amato[13], and Kim and Lin[14] to account for the effects of a compliant free surface through a relaxation equation. The computed seakeeping response for the pericell hovercraft shows rational performance under reasonable wave conditions. Since the simulation method operates in the time domain, the hovercraft is subject to initial condition transients and it appears that several computational cycles are required to dissipate the effects of the initial conditions and achieve an equilibrium dynamic response.

SUMMARY

A large body of empirical information and several evaluation techniques currently exist for analyzing the pitch and roll dynamics of a pericell hovercraft. A mathematical model and adjunct computer simulation have been developed to predict the nonlinear dynamic motion of a pericell hovercraft in operation over large amplitude disturbances. Simulated results compare well with available measured responses from full-scale and model-scale studies. Full-scale pitch and roll stiffness derivatives compare extremely well with model-scale results for pericell designs. Rotational motion damping has been found to be a more difficult parameter to predict and dependable full-scale measurements are extremely rare.

The ultimate interest in pitch and roll dynamics stems from our need to dependably predict static and dynamic stability. "No widely accepted stability standards for amphibious ACV's exist for operation underway at high speed. Adequate stability, over the years, has been judged, for each craft principally from the experience of model- and full-scale testing[15]." This problem area will continue to command our attention in all future hovercraft design evaluations.

NOMENCLATURE

K_ϕ	Roll derivative coefficient, dk/dϕ
M_θ	Pitch derivative coefficient, dM/dθ
t	Time
β	Decay or damping coefficient
θ	Pitch angle, positive bow up
$\dot{\theta}$	Pitch rate, dθ/dt
ϕ	Roll angle, positive starboard down
$\dot{\phi}$	Roll, rate, dϕ/dt
ω	Frequency

ACKNOWLEDGMENTS

I am extremely grateful to the scores of scientists and engineers throughout the Navy who have contributed the major technical accomplishments which are only briefly summarized in this paper. Margaret Bullock was a steady and dependable long-term supporter in all technical areas. Nicholas Caracostas, Ki-Han Kim, Cheng-Wen Lin, and Amelio Amato carried the major burden of developing the analytic methods. Thomas Waters, Alan Jennings, Joseph Ricci, James Kallio, and Lawrence Murray have been making major contributions to this field for a decade and are responsible for the full-scale and model-scale experimental studies. Special acknowledgment must go to my friend James Fein who introduced me to hovercraft, and to Dorothy McLean who completed this manuscript.

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