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# Vision-aided Speed Modulation System to Enhance Seaworthiness of Autonomous Planing Crafts

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***Abstract*— The present study focuses on enhancing the operationability and seaworthiness of Autonomous Planing Crafts' (APC) in seaway by employing an autonomous speed setting mechanism as a response to the APC behavior when operating in real seaways. The mechanism, embedded in the craft's autonomous navigation system, employs a motion computation model termed Motion Assessment of Planing Craft (MAPC) where the sea state input data is provided by a dedicated vision system.**

**In this study, the principles of an autonomous speed setting mechanism for APCs is presented. To enhance the operationability of planing crafts, the capability to predict the accelerations and motions these crafts are expected to exhibit based on the knowledge of the incoming waves is necessary. As a response to this demand, a MAPC model was developed, The MAPC model is based on the 2-dimensional strip theory, improves previously developed motion assessment models by implementing a near transom pressure correction and modified added mass coefficients and provides accurate results for the accelerations, angular velocities and expected motions in the longitudinal plane and in the time domain. To validate and calibrate the MAPC a Jet-Ski was retrofitted to an APC platform and instrumented with an Inertial Measurement System (IMS) to measure and record the linear accelerations and angular velocities experienced by the craft in seaway. The incoming waves were measured by a separately deployed wave buoy. The wave-induced pitch and vertical acceleration as computed by the model has been compared with these experimental data and the differences are addressed.**

***Keywords — Hydrodynamics, Autonomy, Planing crafts, Computation model, Navigation, Vision system***

## I. Introduction

The demand for high-speed planing crafts is progressively rising owing to their high-speeds and exceptional performance for civil, scientific and military applications. However, the seaworthiness of planing crafts presents a significant challenge, particularly in regard to large accelerations and motions in the longitudinal plane these crafts develop in seaway. These extreme motions pose a hazard to payload, crew and to the craft's structural integrity when operated at high-speed in seaway. Nevertheless the marine industry is becoming increasingly reliant on unmanned/autonomous systems for high-speed planing crafts. The study of autonomous operation of marine crafts is a research field that is rapidly growing, but most of the ongoing researches focus on autonomous navigation and path planing algorithms based on marine charts combined with some collision and obstacle avoidance systems [1], [2].

Currently, to the best of our knowledge, the existing autonomous navigation systems are not designed to address the seaworthiness challenges of Autonomous Planing Crafts' (APC) when operating in real seas. To enhance the operationability of APC's in seaway, these navigation systems require the ability for autonomous speed and course adjustment in response to the momentary sea state these crafts operate. Therefore, in this study, a computational model which can determine in real-time the expected accelerations and motions of a planing craft based on the knowledge of incoming waves is developed and integrated into the APC navigation system. The real-time motion computation model supported by vision and inertial sensors will assist the craft's autonomous navigation system by setting its momentary speed in seaway to limit movements and preserve craft's structure and payload safety and integrity.

This paper is structured as follows. The principles of the proposed autonomous speed setting algorithm are addressed in Section II. The modelling of the Motion Assessment of Planing Craft (MAPC) is presented in Section III. Validation of MAPC model with previous experimental and computation model is presented in Section IV. Full-scale sea trails, experimental vs computed results are presented in Section V. Experimental set up for validation of the vision system is presented in Section VI. The results from validations and comparisons performed in this study are discussed in Section VII. Finally the conclusions and scope for future works are presented in Section VIII.

## II. Principles of Speed Setting Mechanism

### *A. Existing Path Planning and Navigation Systems*

Several APC platforms have been developed for both research and military applications [3], [4]. The autonomous navigation systems for these platforms are typically equipped with:

1. A GUI that allows operators to prescribe complete mission plan by defining lines, orbits or waypoints and speed in the segments between waypoints for autonomous navigation.

2. An Obstacle Avoidance System (OAS), for deliberate navigational decision making to avoid collisions and offer safe operation of the craft in seaway.

3. An over the horizon communication system, for remote control operations (takeover) and telemetry beyond the line of sight distances.

These existing autonomous navigation systems cannot address the seaworthiness challenges of APCs when operated in real seas. While in manned operation, the skipper has some inherent capability to limit the accelerations by naturally adjusting the craft's speed and course in response to the crafts behavior as he feels and expects, in autonomous mode of operation the speed and course are predefined in the mission plan and in advance while adjustment as a response to the expected craft's behavior to incoming waves is not offered.

## B. Speed Setting Mechanism Description

For autonomous speed modulation, a vision system is installed and integrated on the APC platform. The vision system (stereo camera) is stabilized in two axes (roll, and pitch). The vision system algorithm anticipates the elevation of the waves ahead of the craft at a constant distance from the craft and in the inertial reference frame using stereo imaging 3D reconstruction. The incoming seaway wave elevation data provided by the vision system algorithm and the required speed of the APC are fed as input to the MAPC. Based on this input the MAPC predicts the expected vertical accelerations and pitch accelerations of the APC in response to the incoming waves. The predicted acceleration values of the crafts are compared with the threshold/permissible motions and acceleration values. The difference between the predicted and the threshold motion and acceleration values are provided as an input to the Speed Setting Algorithm. A scheme for the speed setting mechanism is shown in Fig. 1. The Speed Setting Algorithm will momentarily and in real-time adjust the APC speed to a speed equal to or slower than the required speed as a function of the expected APC's predicted motions.

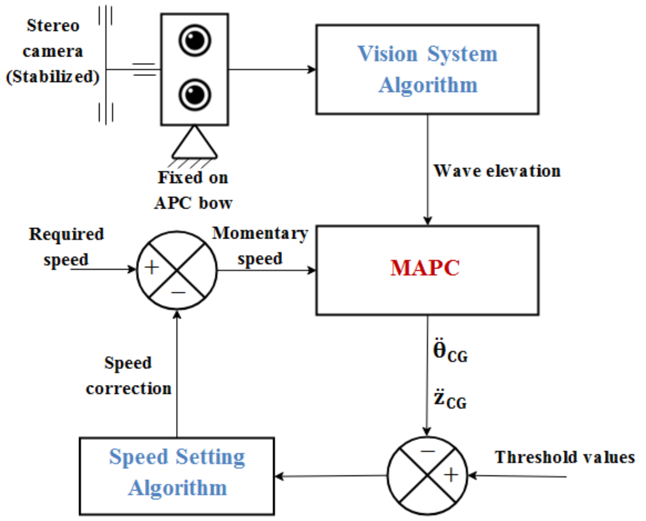


Fig. 1. Autonomous speed setting mechanism of the APC

# III. Dynamic Modelling of APC

## A. Motion Computation Model

One specific and vital need for credible prediction of the motions in seaway of APCs is that these motions and accelerations have a significant impact on the craft's operability, and its structure and payload integrity. In addition, the operational activity (scientific/military) is particularly affected by the intensity of the motions developed by the craft in seaway. Therefore, prediction of crafts dynamics in seaway and accordingly autonomous selection of the speed is one key to successful operation in autonomous mode. Predicting the motion of a planing craft presents a significant challenge because of waves-hull interactions, the forces on the hull are dependent on the motion of the waves, which in turn is a function of the motion of the hull. The dynamic pressure dominance, changes in the wetted length, spray effect, considerable changes in the sinkage of the craft and its trim angle are all among the factors that should be considered for accurate modelling of motions of planing crafts in seaway.

Modelling of planing craft behavior in seaway originated with the studies of Martin [5] and Zarnick [6]. Their works were based on a 2D strip theory approach (2D+t), in which the hull is divided into thin strips (sections) and each section is separately treated. The hydrodynamic lift force acting on each section was calculated based on the theory of a wedge penetrating the water surface. Later, few researchers have focused on improving Zarnick's model by increasing the accuracy in prediction of the 2D forces, the most notable works include:

1. Garme's [7] work on near transom pressure correction affecting both the hydrostatic and the hydrodynamic terms of the load distribution.

2. Payne's [8] work on improved added mass theory to account for the excess lift for wet chine wedges.

This study focuses on development of the MAPC. Consequently, a mathematical model for analysis and simulation of APC dynamics was developed following the work of Zarnick [6] and by incorporating the pressure correction [7] and modified added-mass theories [8]. The APC is modelled as a series of strips or impacting wedges. Nonlinear time domain simulations were performed using 2D+t theory. MAPC is capable to predict the craft motions operating in head or following seas in the longitudinal plane. This model is the basis to the autonomous speed setting mechanism incorporated in the craft's autonomous navigation system presented in Section II.

## B. Motion Equations

Following previous works, only the equations of motion in the longitudinal plane are considered, see Fig. 2. The expressions for the surge $x_{CG}$, heave $z_{CG}$, and pitch $\theta_{CG}$ (where CG refers to the craft's center of gravity) directions are presented in expression (1):

$$
\begin{aligned}
M\ddot{x}_{CG} &= T\cos\theta_{CG} - N\sin\theta_{CG} - D\cos\theta_{CG} \\
M\ddot{z}_{CG} &= -T\sin\theta_{CG} - N\cos\theta_{CG} + D\sin\theta_{CG} + W \\
I\ddot{\theta}_{CG} &= Tx_t + Nx_n - Dx_d
\end{aligned}
\tag{1}
$$

## C. Forces Acting on an APC

The total hydromechanic normal force N acting on the planing craft is the summation of the hydrodynamic lift force $F_{dyn}$ and the hydrostatic lift force $F_{sta}$. When a wave impinges the hull, the immersion of hull volume changes along the length of the craft and there are external forces due to hydrodynamic forces $F_{dyn}$ and hydrostatic forces $F_{sta}$. The planing craft impinged by waves is shown in Fig. 2

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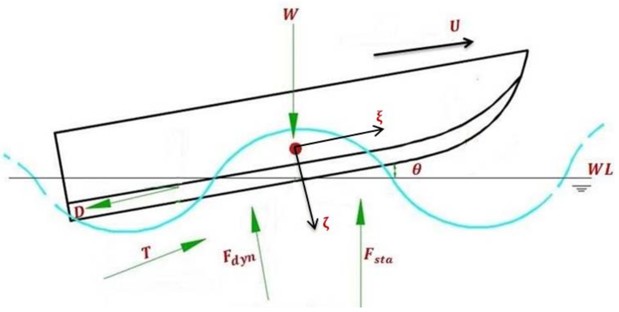


Fig. 2. Forces acting on a planing craft in waves

### D. Hydrodynamic Lift Force Associated with the Change in Fluid Momentum- $F_{dyn}$

The elemental hydrodynamic normal force associated with the change in fluid momentum which develops on a transverse strip of a planing surface is given by (2).

$$f_{hyd} = \frac{D}{Dt}\left(m_a . V\right) \tag{2}$$

In the presented model, the Payne's [8] approach to consider the effect of chine immersion on added mass is applied. Accordingly, once the chines are fully immersed, the added mass continues to increase ($\Delta m_a$) as shown in Fig. 3 (b) with the incremental added mass coefficient ($\Delta C_m$) as given in (3) then included in (4).

$$\Delta C_m = \frac{\Delta m_a}{\frac{\pi}{2}\rho b^2} \tag{3}$$

$$C_m = C_{mo}\left(1 + k\frac{z_c}{2b_{\max}}\right) = C_{mo} + \Delta C_m \tag{4}$$

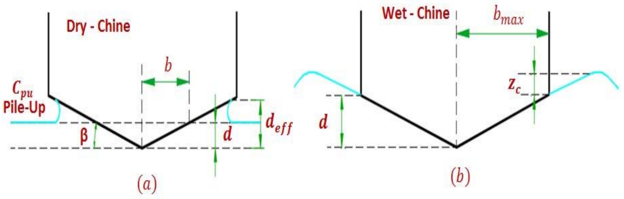


Fig. 3. Effective penetration, (a) Dry-chine (b) Wet-chine

Where:

$C_{mo} = \left(1 - \frac{\beta}{2\pi}\right)^2$, is the added mass coefficient

$k$ : Experimental coefficient, $k = 2.05\left[1 - \left(\frac{2\beta}{\pi}\right)^{9/2}\right]$

Thus, the following expressions are used for added mass calculations (5) and (6).

$$m_a = \frac{\pi}{2}\rho b^2 C_m \quad b < b_{\max} \text{ (Dry-chine, Fig 3(a))} \tag{5}$$

$$m_a = \frac{\pi}{2}\rho b_{\max}^2 C_m\left[1 + k\frac{z_c}{2b_{\max}}\right] \quad b = b_{\max} \text{ (Wet-chine, Fig 3(b))} \tag{6}$$

### E. Hydrostatic Lift Force - $F_{sta}$

The elemental buoyancy force on a strip having a wedge shape is assumed to act vertically and is equal to the equivalent static buoyancy multiplied by a correction factor $C_{bf}$ given by (7)

$$f_{sta} = C_{bf}\rho g A_w \tag{7}$$

### F. Near Transom Pressure Correction

For crafts in planing mode, flow separation is observed at the chines and stern, reducing the pressure in these regions to atmospheric. Consequently, a strict 2-dimensional analysis may overestimate the lift at these regions. To overcome this and following the work of Garme [7] a correction term affecting both the hydrostatic and the hydrodynamic terms is implemented. The correction approach is to multiply the 2-dimensional load distribution by a 'weight function' (8) which equals to 0 at the transom and approaches 1 at a distance afore.

$$\begin{aligned} C_{tr}(\xi) &= \tanh\left(\frac{2.5}{a}\xi\right) \\ a &= a_c \times 2b_{\max} \times Fr_b \\ C_{tr} &= \tanh\left(\frac{2.5}{0.34 \times 2b_{\max} \times Fr_b}(\xi - \xi_{tr})\right) \end{aligned} \tag{8}$$

Following systematic experiments on several models Garme [7] selected a value of 0.34 for $a_c$ .

## IV. Computation Model Validation and Comparison with Previous Works

The computation model MAPC was validated with the experimental results of Fridsma [9] and with previous computation model [6] to examine influence of the implemented improvements on the results accuracy in comparison with other existing computation model [6].

### A. Comparison of Computed Motions and Accelerations with Previous Works

In Fig. 4 and 5 a comparison of computed peak vertical accelerations and double amplitude pitch angle of the APC with that of previous computation model [6] and experimental works [9] is presented. It is observed that the present model, following the implemented improvements as described in Section III.D and III.F predicts the behavior of the planing craft in seaway with a better accuracy, on the order of 10% in comparison with a previous, well recognized, computation model [6].

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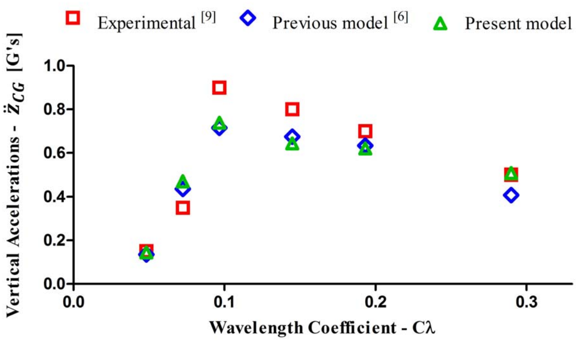


Fig. 4. Vertical acceleration at CG comparison with previous works

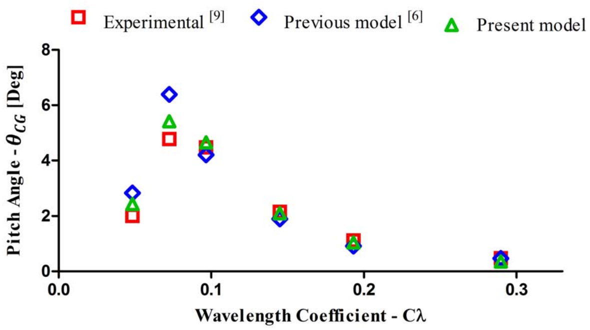


Fig. 5. Pitch angle at CG comparison with previous works

## V. Experimental Set-up for Computation Model Validation

For validation of the MAPC a Yamaha SJ700BK Jet-Ski was retrofitted to an APC platform (Fig. 6) to perform experiments in autonomous mode. The seaway wave elevation data used as an input for the computation model was recorded using a self-developed wave buoy. The MAPC predicted motions and accelerations for the recorded waves were compared with the actual motion data recorded by an Inertial Measurement System (IMS) installed on the APC.


Fig. 6. The experimental APC platform

### *A. Computed vs Experimental Motions and Accelerations of APC in Seaway*

The experimental trials were performed in real seas, 500(m) away from the shore to avoid breaking waves. As the developed computation model is valid only for crafts operating in planing mode the APC was operated at different planing speeds with Froude number, $Fr = \frac{U}{\sqrt{g \times L_{WL}}}$, between 1 to 4. The data from both the IMSs of the wave buoy and the APC were recorded at a frequency of 400Hz throughout the sea trials. The recorded data from both IMSs were filtered using Madgwick AHRS filter [10].

The seaway wave elevation data as recorded by the wave buoy and following filtration was fed as an input to the MAPC and the predicted vertical accelerations and pitch angle values were obtained.

Fig. 7 shows a visual sample of computed and experimental vertical accelerations time history of the APC at a speed of 10 [m/sec]. Fig. 8 shows a visual sample of computed and experimental pitch angle time histories of the APC at a speed of 15.8 [m/sec].

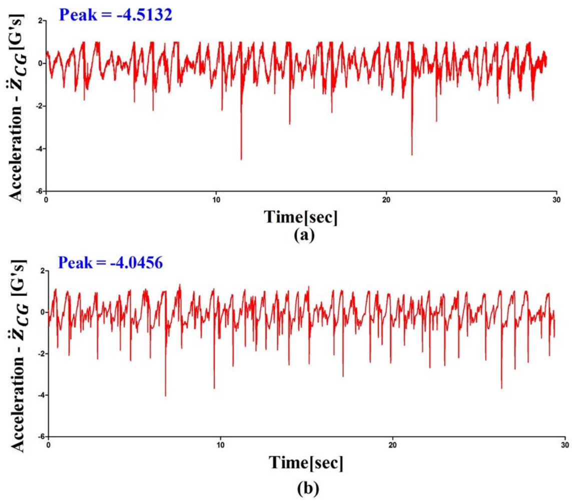


Fig. 7. Vertical acceleration at an average speed of 10 m/s, (a) experimental and (b) computed

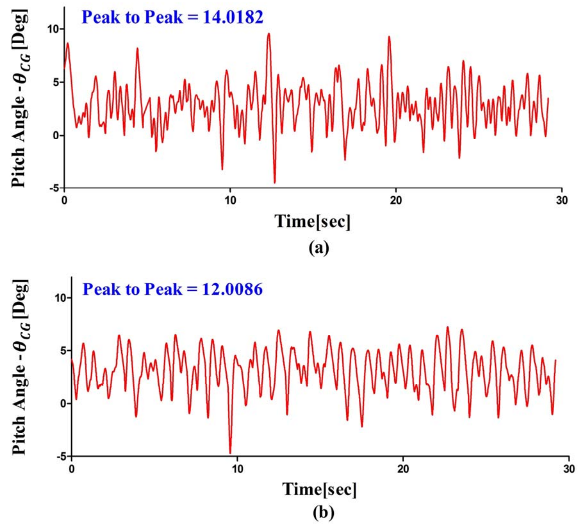


Fig. 8. Pitch angle at an average speed of 15.8 m/s, (a) experimental and (b) computed

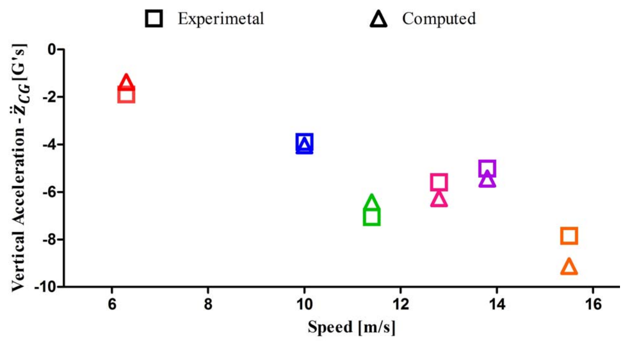


Fig. 9. Peak vertical accelerations at CG at different speeds and momentary seaway

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In Fig. 9 and 10 a comparison of computed vs experimental peak vertical accelerations and peak to peak pitch angle of the APC at different speeds and momentary seaway is presented.

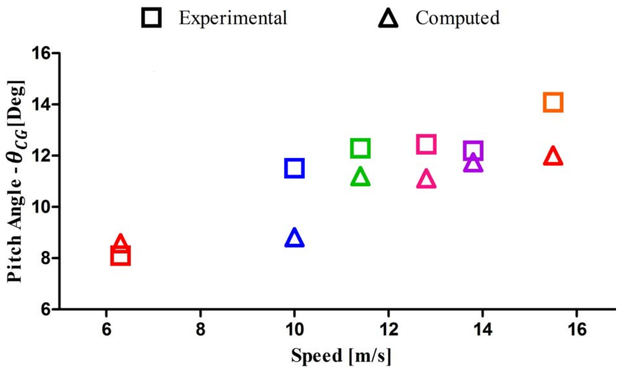


Fig. 10. Peak to peak pitch angles at different speeds and momentary seaway

## VI. Experimental Set-up for Vision System Validation

To verify the accuracy of the vision system measured wave elevation data, an experiment was performed in a wave pool in the science park of the Weizmann Institute of Science.

### A. *Vision Sensors Measured Wave Elevation*

The wave pool generates waves of constant amplitude. Wave height was first measured manually. Then, a wave buoy equipped with an IMS was deployed in the wave pool to measure the wave height. The wave elevation from the wave buoy is presented in Fig. 11 (a). Further, videos were taken using a ZED stereo camera. Based on the stereo imaging, 3D reconstruction of the scene (except for occlusions) was recovered. Both the intrinsic and extrinsic parameters of the stereo cameras supplied by the manufacturer were used. The next step was to find matching points in both images in order to triangulate the real-world data points. This task is quite difficult due to a similarity of features in the images. In order to find dense matching, Epic flow [11] algorithm was used, and applied it in a bi-directional manner: from the left image to the right and vice-versa. A match was considered to be valid only for pixels that had an end-point-error of 3 pixels or less for images with a resolution of 1920x1080 pixels (HD). The point cloud was validated by measuring the size of the wave amplitude from the data, which is known to be 12cm. The last step was to decide at which distance from the camera the water surface has to be observed. A distance of 4m from the camera was taken at that particular scene. The amplitude values of all the pixels in that range were averaged to get the wave elevation as shown in Fig. 11 (b). The wave elevations from wave buoy Fig. 11 (a) and from vision system Fig. 11 (b) are observed to be equal with a wave height of 12-12.5 cm corresponding to the manual measurement of 12cm and frequency of 0.5Hz.

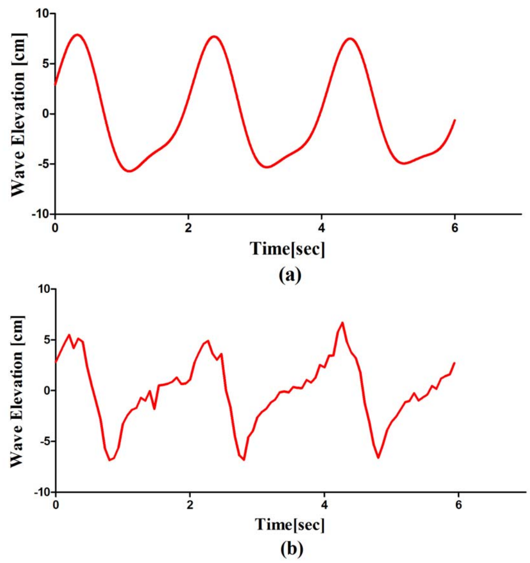


Fig. 11. Wave elevation (a) wave buoy (b) vision system

## VII. Results and Discussion

From the comparisons presented in Section IV.A it is clear that the enhanced and improved computation model MAPC is predicting the vertical acceleration and pitch angle values more accurate in comparison to the previously existing computation model. In case of vertical accelerations at CG a decrease in error up to 10% is observed. While in case of pitch angle a decrease in error up to 20% is observed. In Section V.A, the MAPC computed vertical accelerations and pitch angle values shows an excellent agreement with the experimental values recorded by the IMS in the experiments with our APC. The percentage of error in vertical acceleration at CG varies from 8 to 23%. It can be observed from Fig. 9 that at Fr = 1.3 the computation model has under-predicted the acceleration value, but at higher speeds as Fr progresses between 2.1 to 3.3 the computation model has slightly over-predicted the measured vertical acceleration values. The percentage of error in pitch angle varies from 4 to 21%. From Fig. 10 at Fr = 1.3 it is observed that the pitch angle is slightly over-predicted, but at higher speeds the computation model slightly under-predicted the pitch angle at all speeds.

## VIII. Conclusions and Future Work

The earlier developed model for 2D+t motion assessment of a planing craft in seaway is improved here by updating the method of calculating the hydromechanical forces. As presented in Section IV and V, the computed results show an excellent agreement with the experimental values recorded by the IMS installed on the APC. In comparison with previously existing computation models where the difference between predicted vs measured accelerations often exceeded 30%, the present model largest error was limited to 23%. Consequently, the MAPC is a valid motion computation model for APCs'. In our autonomous planing craft application, a linearized computational scheme based on this model is employed to predict in real-time the craft behavior in seaway and its results will be provided as input to a speed setting algorithm to control the crafts speed and keep the

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craft's accelerations and motion under a preset threshold value (Fig. 1).

Future scope of this work includes the development of the speed setting algorithm, integration of all components and conducting of experiments to test the performance of the entire system in real-time.

## NOMENCLATURE

$\beta$ : Deadrise angle of cross section [deg]
$\rho$ : Density of water [kg/m$^3$]
$\xi,\zeta$ : Body coordinates
$\xi_{tr}$ : Body fixed coordinate at transom
$\theta_{cg},\ddot{\theta}_{cg}$ : Pitch angle and acceleration at CG
$A_w$ : Wetted cross sectional area [m$^2$]
$a$ : Near transom correction length[m]
$a_c$ : Dimensionless correction length
$b$ : Instantaneous wetted cross sectional beam[m]
$b_{\max}$ : Max cross sectional beam[m]
$C_\lambda$ : Wave length coefficient
$C_{bf}$ : Buoyancy force correction factor
$C_m$ : Added mass coefficient
$C_{pu}$ : Pile up coefficient
$C_{tr}$ : Near transom correction coefficient
$D$ : Frictional Drag force [N]
$d_{eff}$ : Effective depth of penetration[m]
$d$ : Penetration depth[m]
$Fr_b$ : Beam Froude number
$Fr$ : Froude number
$f_{hyd}$ : Sectional hydrodynamic lift [N/m]
$F_{hyd}$ : Total hydrodynamic lift [N]
$f_{sta}$ : Sectional hydrostatic lift [N/m]
$F_{sta}$ : Total hydrostatic lift [N]
$g$ : Gravitational acceleration [m/ sec$^2$]
$I$ : Mass moment of inertia in pitch [kg.m$^2$]
$L_{WL}$ : Length of water line [m]
$M$ : Mass of the ship [kg]
$m_a$ : Sectional added mass
$N$ : Hydromechanic Normal force [N]
$T$ : Thrust force [N]
$U,V$ : Velocity of the craft in $\xi,\zeta$ direction [m/sec]
$W$ : Weight of the ship [N]
$WL$ : Water Line
$x_t$ : Moment arm of thrust force[m]
$x_d$ : Moment arm of frictional drag force[m]
$x_n$ : Moment arm of normal force[m]
$x_{cg},\ddot{x}_{cg}$ : Surge displacement and acceleration at CG
$z_{cg},\ddot{z}_{cg}$ : Heave displacement and acceleration at CG
$z_c$ : Local chine submergence [m]

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