Warp effects studied by a time-domain strip model and compared to model experiments

KARL GARME [a,1]

[a]*KTH, The Royal Institute of Technology, Sweden*

Abstract. A time-domain strip method, in the Zarnick tradition, is used to discuss the modeling implications when alongships geometrical variations are studied, eg. warp or motion with frequent bow submergence. Results from simulations and published model test results for three warped hulls and their parent prismatic hull, in calm water and regular waves are presented. It is concluded that warp can be modelled by the strip approach. Non-the less, method development is proposed and the importance of combining different numerical end experimental methods both in research and design is stressed.

Keywords. Strip-method, simulation, warp, HSC, seakeeping, bow submergence

1. Introduction

In the tradition dating back from the 1970ties, time-domain strip approaches have been used to investigate the seakeeping performance of planing High Speed Craft, HSC, e.g. [1], [2], [3], [4] the latter developed in [5] and used in the present study. The geometrical starting point is prismatic hulls and main issues addressed, have been design-loads and design-acceleration. This has been a rationale for focusing on the craft in head seas.

A strip method is based on the assumption that the governing hydromechanics can be described in 2-D cross-cuts. Some shortcomings from that assumption have been dealt with in different ways turning the method to something often referred to as 2 1/2 D. The time-domain has opened for the strip approach to reflect the non-linear motions and accelerations characterizing the HSC´s run in waves.

The non-linear strip method is often a good compromise between representation accuracy of the involved physics and efficient use of computational resources. In practical applications the option to simulate principally correct craft response have been valuable for investigating relations between response acceleration and structural weight [6], acceleration characteristics [7], ship response monitoring techniques [8] and as support in design and evaluation of model tank tests e.g. in prediction of structural loads [9] and [10].

The different published methods have shown to be useful design and investigation tools for relatively prismatic hull shapes. Warp, the longitudinal variation of deadrise, influence the seakeeping characteristics and could be a valuable component for the designer. Warp introduces three-dimensionalities challenging the strip approach. The mathematical formulation, already expressed by Zarnick [1] should catch warp.

[1] KTH, Centre for Naval Architecture, Teknikringen 8, 100 44 Stockholm Sweden; E-mail: garme@kth.se

Nonetheless, common for most implementations is the validation with respect to prismatic hulls only, generally in relation to the thorough experimental series by Fridsma [11] and [12]. The recent test series, performed at the University of Naples Federico II (see e.g. [13] and [14]), has added a reference data-set including warp. The present study examines the strip-method implementation, [5], in order to evaluate its validity with respect to warp. Results from simulations in calm water and regular waves of three warped hulls and their parent prismatic hull of the University of Naples experiments, are presented and discussed.

2. Simulation method and warp

The simulation model is a 2-dimensional time-domain strip method [4] and [5]. The coefficients in the equations of motions are up-dated at every time step and the solution describes the non-linear situation of the planing hull in waves. During the simulation, pre-calculated hydrostatic and hydrodynamic coefficients are collected with reference to the momentary sectional draught. The hydrostatic coefficients are defined relative to the wave surface level and the dynamic coefficients relative to the piled-up surface level. The hydrodynamic section loads are determined as the momentary time rate of change of fluid momentum for both chines-wet and chines-dry parts of the hull. The decrease of pressure close to the transom stern, not caught by the 2-dimensional theory, is treated by a semi-empirical correction of the load distribution, Figure 1.
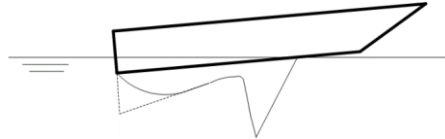

Figure 1. Principal correction, solid line, of the pressure (2-D force distribution) close to the transom.

The equations of motions are solved iteratively by a predictor-corrector technique in the time-domain. The method is validated for speeds, in terms of Froude number based on ship width $C_v > 2$, [5].

A pre-calculation technique is applied where the sectional added masses are pre-calculated and stored for a number of draughts. During the simulation, the momentary added masses and rate of change of added masses are calculated from the stored data picked with reference to sectional draughts at present time instant. This pre-calculation technique significantly reduces the computational effort.
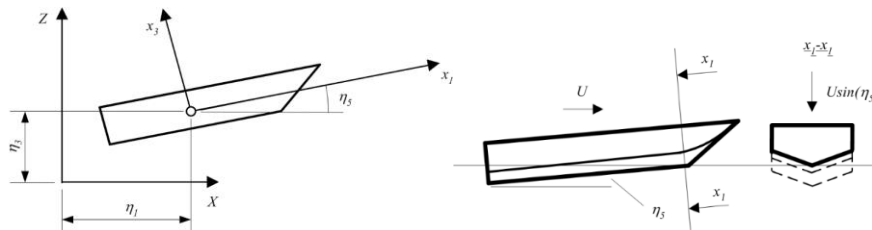

Figure 2.

Forces are defined in the hull-fix coordinate system (x_1, x_3), Figure 2, and expressed as the rate of change of momentum as the hull moves through the water. By looking through the x_1-x_1 plane, Figure 2, local forces are expressed as,

$$f_3 = \frac{d}{dt}(a_{33}u_3 + a_{31}u_1) + \rho g A \cos(\eta_5) \tag{1}$$

$$f_1 = \frac{d}{dt}(a_{11}u_1 + a_{13}u_3) - \rho g A \sin(\eta_5) \tag{2}$$

where $a_{i,j}$ are added mass coefficients, u_j incident flow direction and A submerged section area. Indices i and j represents the force and flow directions respectively in the hull-fix coordinate system. The global forces and moments thus computed as,

$$F_3 = \int_L f_3 dx \tag{3}$$

$$F_1 = \int_L f_1 dx \tag{4}$$

$$F_5 = -\int_L (f_3 x_1 dx_1 - f_1 x_3 dx_3) \tag{5}$$

The sectional added mass coefficients; a_{33}, a_{31}, a_{13} and a_{11}, are computed based on 2D potential flow theory and assuming that the incident flow velocity can be divided as projections on the sections' normal vector and the resulting pressure, result in both forces both in and out of the section plane. Consequently and reasonably, a_{31}, a_{13} and a_{11} all are zero for a section in a prismatic part of the ship.

Developing Eqs. (1) and (2), it is noted that both added mass coefficients, and velocity components are time dependent. This leads to terms $\frac{d\bar{u}}{dt}a$ and $\frac{da}{dt}\bar{u}$. The first relate to the ship motion and constitutes partly of terms proportional to pitch velocity, i.e. damping and partly proportional to acceleration that can be placed in the right hand side of the equation of motion,

$$(M + A)\ddot{x} = \bar{F} \tag{6}$$

The second term develops to,

$$\frac{da}{dt}\bar{u} = \left(u_1 \frac{da_{11}}{dt} + u_3 \frac{da_{31}}{dt} \quad u_1 \frac{da_{13}}{dt} + u_3 \frac{da_{33}}{dt} \right) =$$
$$= \begin{pmatrix} u_1 \left(\frac{da_{11}}{dx_3}\frac{dx_3}{dt} + \frac{da_{11}}{dx_1}\frac{dx_1}{dt} \right) + u_3 \left(\frac{da_{31}}{dx_3}\frac{dx_3}{dt} + \frac{da_{31}}{dx_1}\frac{dx_1}{dt} \right) \\ u_1 \left(\frac{da_{13}}{dx_3}\frac{dx_3}{dt} + \frac{da_{13}}{dx_1}\frac{dx_1}{dt} \right) + u_3 \left(\frac{da_{33}}{dx_3}\frac{dx_3}{dt} + \frac{da_{33}}{dx_1}\frac{dx_1}{dt} \right) \end{pmatrix} \tag{7}$$

where the added mass derivatives are expressed as spatial derivatives in a hull fixed coordinate system and the time derivatives as section velocity in and through the x_1-x_1 plane of Figure 2. The expressions principally follow the original model by Zarnick [1]. Anyway, note that for a prismatic hull only the first term of the second term in the in-plane force component is non-zero, thus a vertical force in the body-fix coordinate system, expressed by,

$$\frac{da}{dt}\bar{u} = \left(0 \quad u_3\left(\frac{da_{33}}{dx_3}\frac{dx_3}{dt}\right)\right) \tag{8}$$

The other terms and also the alongships force component will for a prismatic hull only be non-zero in the bow. When, on the other hand, a warped hull invokes the complete expression in Eq. (7).

3. Methodology

Simulation, with the model [5], is made in calm water and in regular waves for the four hull models experimentally investigated at the University of Naples Federico II. One model, *Monohedral*, is prismatic except for the bow. The other three, *Warp1*, *Warp2* and *Warp3* are warped with increasing extent. All models have sections with constant deadrise and the geometries are in that sense simple and well-designed for method validation and development. Conditions and response data are taken from [13] and [14]. All simulation are made at full-scale, in this case 10 times the model size. Time is scaled according to the Froude model law.

The four models are run through the pre-calculation procedure for determining added mass and displacement data. The floating condition at zero speed is checked by the simulation modelled run at low speed for numerical stabilisation (0.1 m/s model scale) and with the transom stern correction turned off, thus finding static equilibrium of displacement forces only. Floating conditions and key input-data and pre-calculation section and draught spacing follow from Table 1.

Table 1. All values in full-scale. Weight in metric tonnes, longitudinal centre of gravity *LCG* in m, pitch gyradius k_{yy} in m, trim at zero speed τ_0 in degrees and draught at transom in m. Pre-calculation are specified by number of sections and distance between draughts. Both longitudinal and vertical spacing are equidistant.

	Hull conditions			Pre-calc.		Floating condition	
	Weight	*LCG*	k_{yy}	nof sec.	ΔT	$\tau_{0\text{-}exp}/\tau_{0\text{-}calc}$	$T_{A\text{-}exp}/T_{A\text{-}calc}$
Mono	32.59	6.97	5.83	99	0.0148	1.66/1.70	0.96/1.01
Warp1	32.66	6.60	5.57	100	0.0145	1.66/1.48	1.06/1.05
Warp2	32.59	6.09	5.49	100	0.0145	1.66/1.62	1.10/1.11
Warp3	32.47	5.86	5.19	100	0.0145	1.66/1.38	1.08/1.08

All models are simulated in calm water at the six speeds ($0.84 \leq C_v \leq 3.66$) reported by [14] investigating the model´s ability to simulate the running attitude. Simulations are also made for runs in the set of 10 regular waves and for the two higher speeds (C_v: 2.26 and 2.82) of the Naples series [14]. In regular waves the heave and pitch response are studied together with acceleration at the centre of gravity and at the bow. All simulations are made with a 0.005 s time step.

4. Results

4.1. Calm water

The simulated running attitude follows the trend seen from the experiments. Trim decrease and the craft run higher as the speed increase. A pattern that becomes more pronounced with increasing warp as shown in Figure 3. Except for the lowest speed, the hulls are planning with the bow sections out of the water.
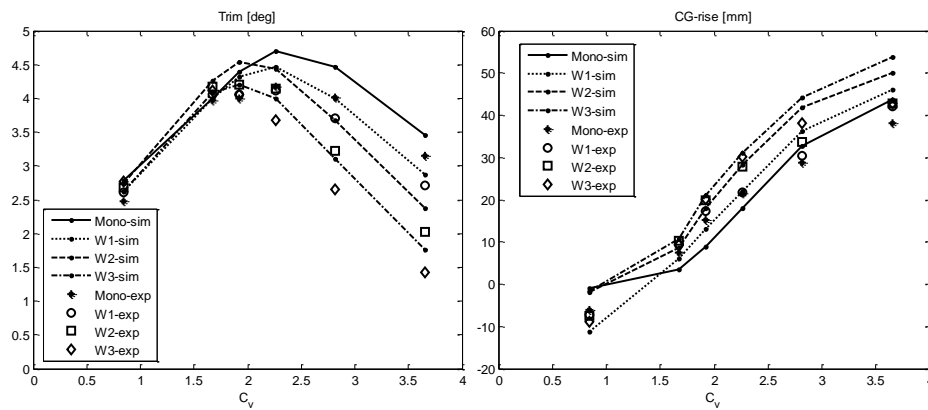

Figure 3. Running attitude in calm water, present simulation and experiment data from [13]. Exp. sinkage data has been re-computed to CG-rise data.

4.2. Regular waves

The overall simulation results are illustrated in Figure 4 and Figure 5 together with experiment results picked from [14]. Generally, the simulations fairly well repeats the experiments. It is noted that acceleration, most clearly seen in the bow, are overestimated in the simulation when motions are large (and overestimated too). This seems to be more pronounced when warp is large.
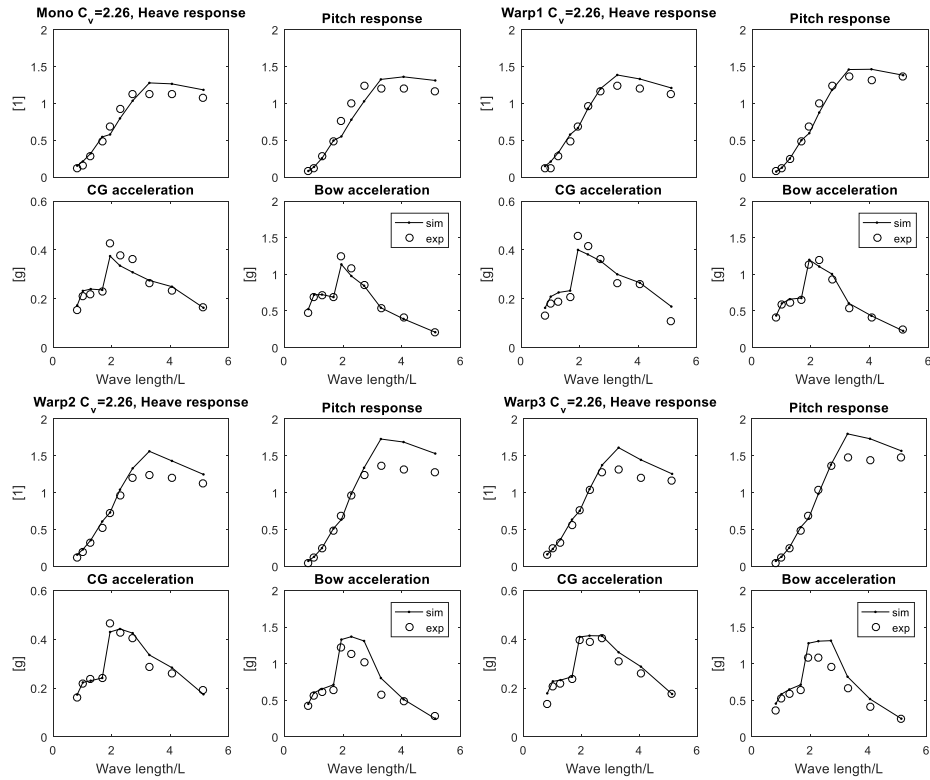
Figure 4. Heave, pitch, acceleration at the centre of gravity and at the bow (85% of *LOA* from transom) for the four hulls at C_v=2.26. Heave and pitch is non-dimensional crest-to-trough data and acceleration is half the crest-to-trough values, similar to how the experiment data is presented in [14] and also indicated in the graphs. Note. Exp. acc. data in the CG acceleration graph is the reported acceleration at 38% of *LOA*.
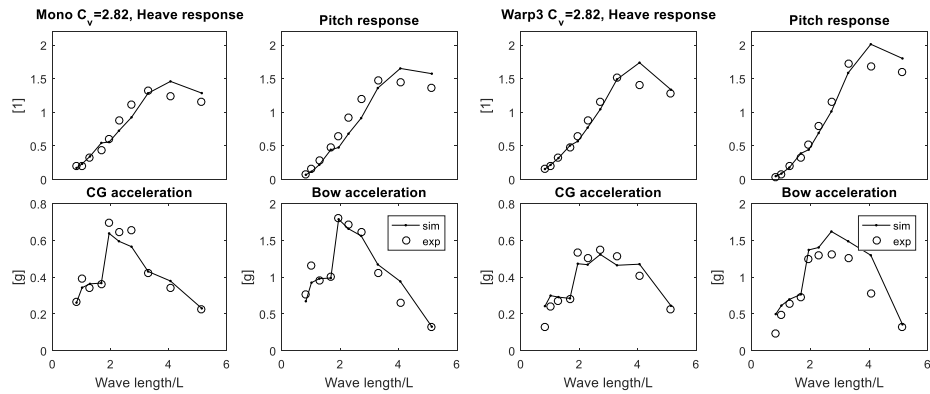

Figure 5. Heave, pitch, acceleration at the centre of gravity and at the bow (85% of *LOA* from transom) for the *Monohedral* and the *Warp3* hulls at C_v=2.82.

Figure 6 shows the simulation time-series of the *Monohedral* in the same conditions as in the example of measured response shown in [14], Fig 34. Response characteristics as well as magnitudes show close similarity.
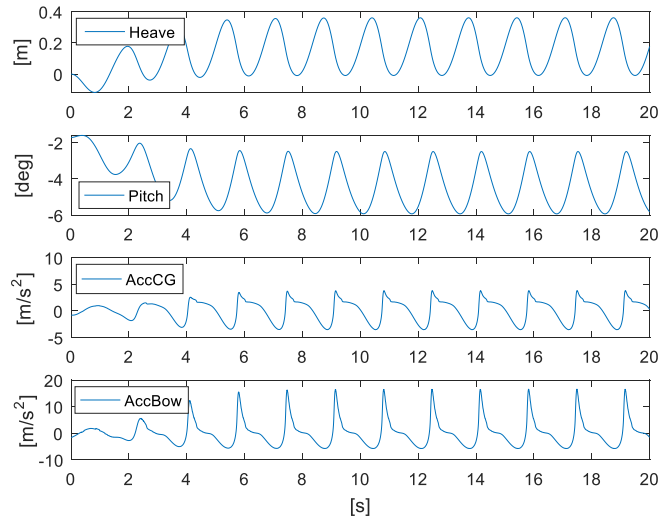

Figure 6. Heave, pitch, acceleration at the centre of gravity and at the bow (85% of *LOA* from transom) for the *Monohedral* at C_v=2.26 in regular waves of λ/LOA=1.94. The same case are shown in [14], fig 37, and matches reasonably well the time series shown here. Note that pitch is defined with opposite signs and that the simulation is in "full-scale" thus with a scale factor of 10 relative to the model test.

An expected effect by warp is decreased bow acceleration. In the experiment series [14] this seems to be most clearly seen at higher speeds and shorter wave lengths. Plotting the simulation results for bow acceleration at C_v=2.82 together with the published experiment data, the trend, shown by [14] with lower acceleration for warped hulls than for the parent prismatic hull at short wave lengths but the opposite for long waves, although not that pronounced, is captured, Figure 7. Note again that the largest discrepancy between simulation and experiments is at the wave lengths resulting in large motion (λ/LOA=3.28 and 4.06).
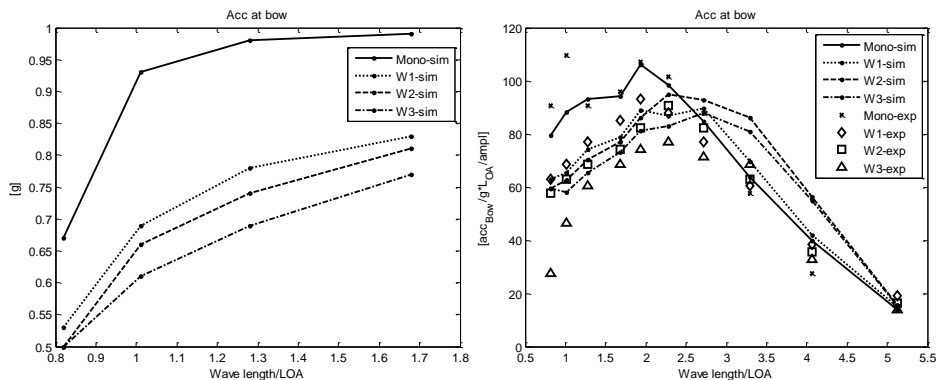

Figure 7. Acceleration at bow simulated at C_v=2.82. Right, plotted with the experiment results of [14] Fig 35.

5. Conclusions

The study indicate that warp and other 3D geometrical attributes such as transom stern effects can be modelled by the time-domain strip approach. The running attitude in calm water is well estimated for all investigated hulls and the response in regular waves show fair agreement with the published experiment data it is compared with.

Identified discrepancies at large motions can be an effect from bow section submergence, indicating a weakness in modelling the forces on sections with more pronounced along-ships curvature than the warp on the main part of the investigated hulls.

As ship motion becomes large, bow emergence is a regular event. Particular caution, and improved knowledge on how the pressure develops, is needed in order to more accurately model the effects from bow submergence in the present simulation structure. The study points at development areas of the simulation model, hence in the treatment of the along-ships derivatives and possibly also in the potential flow model calculating the along-ships and coupling added mass coefficients. Such development would benefit from seakeeping experiment data including detailed pressure measurements on HSC bows.

6. References

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