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Development of the Tool for Predicting Hydrofoil System Performance and Simulating Motion of Hydrofoil-Assisted Boats

ABSTRACT

Hydrofoil technology is experiencing re-emergence due to demands for higher performance in both military and commercial sectors. Hydrofoil-assisted ships and boats use foils to partially or fully support a ship's weight. To reduce hydrodynamic resistance, a significant fraction of the ship hull is lifted out of the water. Hydrofoils can also be very effective in mitigating motions in rough seas. One of the factors limiting wider application of the hydrofoil technology is difficulty and high cost of developing high-performance hydrofoil systems. A set of computer programs that will improve design of hydrofoil-assisted boats is currently under development. This tool can be used for initial optimizing of complex hydrofoil configurations and for developing hydrofoil control systems. Steady and unsteady forces on hydrofoil system elements are represented in the general form suggested by fundamental hydrodynamic theories. Empirical corrections account for viscosity and other effects. Interactions between hydrofoil systems are included. The motion simulator can predict stability and maneuverability of hydrofoil-assisted boats and their motions in waves.

INTRODUCTION

Hydrofoils are characterized by the highest lift-drag ratio among all types of water-borne craft within the optimal regime for hydrofoils. Hydrofoil technology attracted significant attention in the second half of the twentieth century and thousands of hydrofoil boats were built. However, hydrofoil ships were displaced from a dominant position on the fast ferry market by simpler and lower-maintenance catamarans that are more efficient at larger relative dimensions (or lower relative speeds).

The hydrofoil technology is experiencing re-emergence. Retrofitting existing catamarans with hydrofoils and building new hydrofoil-assisted multi-hulls is a booming industry. Hydrofoils have significantly improved the efficiency of commercial fast ferries. Hydrofoil systems are successfully applied for motion mitigation on large fast ships and show similar promise for future Sealift ships. Although there are currently no serious attempts to introduce hydrofoil technology to the pleasure boat market, hydrofoils have reduced fuel consumption on small boats by nearly half and considerably improved seaworthiness. One of the problems preventing a wider use of hydrofoils is the complicated development process of efficient, robust, and inexpensive hydrofoil systems.

There are many publications on specifics of hydrofoil modeling. Some of the previous studies used a simplified approach (e.g., Sakic 1981, Latorre and Teerasin 1992) that did not account for many important factors, such as effects of motion history and interactions between foil systems. On the other hand, Computational Fluid Dynamics tools have recently been developed that can accurately simulate hydrofoil systems (e.g., Walree 1999, Migeotte 2002). However, these tools are computationally intensive and still partially rely on empirical knowledge.

This paper describes efforts to develop relatively simple engineering tools for practical hydrodynamic design of hydrofoil systems and boats. The basic idea is to represent the hydrodynamic forces in the form suggested by fundamental theories. Correlation factors are introduced that account for real-life effects neglected by theories. These factors are obtained either from other mathematical models addressing specific phenomena or from empirical knowledge (e.g., Ogilvie 1958, Egorov and Sokolov 1965).

An essential step in developing these engineering tools is validating them against experimental results. One of the requirements in this project is to keep the development cost low and the tool simple enough for use in practical parametric design. Therefore, some discrepancies between model results and test data can be tolerated. Design of hydrofoils and other advance marine vehicles is not as straightforward as that of conventional (usually slow) ships. Model testing is strongly recommended. Intermediate-scale prototypes are also useful for reducing the uncertainty of scale effects and in achieving optimal performance at the full scale. The engineering tool being developed is not considered as a substitute for testing, but as a means for preliminary optimizing of the ship design and reducing development time.

Physical phenomena most critical for realistic design of high-performance hydrofoil systems are outlined in the following sections. In particularly, a general formula for the lift of a hydrofoil section is given and its generalization to complex hydrofoil systems is outlined. We also discuss a tandem foil interaction, a convenient method for calculating unsteady hydrodynamic forces, and a development of 6D motion simulator for a hydrofoil boat. Correlations and functions are not presented here in details due to paper size limits and because of the proprietary nature of some correlations and methods.

STEADY HYDRODYNAMIC FORCES

The lift force generated on a hydrofoil (**Figure 1**) is determined by formula

$$Z = C_z \frac{\rho U^2}{2} S \,, \qquad (1)$$

where C_z is the lift coefficient, ρ is the water density, U is the flow velocity with respect to the foil, and S is the one-side foil area. $S = \lambda b^2$, where λ is the foil aspect ratio and b is the effective chord. The lift coefficient of a hydrofoil with finite aspect ratio, moving under free water surface is

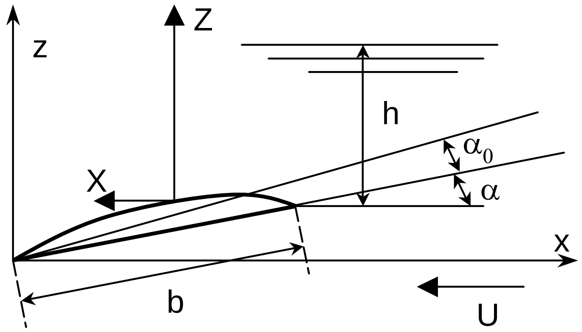

Figure 1: General scheme of a submerged hydrofoil.

$$C_z = \frac{k_\varphi \left(\dfrac{\partial C_z}{\partial \alpha}\right)_0 \left(\alpha + \alpha_0 - \Delta\alpha_0\right)}{1 + \left(\dfrac{\partial C_z}{\partial \alpha}\right)_0 \dfrac{k_\varphi}{\pi\lambda} \dfrac{1+\tau}{\varsigma + \theta}} \,. \qquad (2)$$

The derivative of the lift coefficient on the attack angle $\left(\dfrac{\partial C_z}{\partial \alpha}\right)_0$ is for a deeply submerged, infinite aspect ratio hydrofoil. For the ideal fluid and thin foil profiles this coefficient is equal to 2π. A correction to this coefficient that depends on the profile thickness-chord ratio, Reynolds number, and the trailing edge closure angle should be applied to account for these effects (e.g., Martin 1963). The apparent attack angle α is the angle between the line connecting trailing and leading edges and the horizontal plane. The effective zero-attack angle is α_0. This angle is a function of the foil camber, Reynolds number, and the trailing edge closure angle (Egorov and Sokolov 1965). The XFOIL program (Drela 1989) is another method for determining the effect of viscosity on the zero-attack angle. Discussions on the effect of Reynolds number can be found in (Walree 1999) and (Migeotte 2002). The proximity to the free water surface is accounted for by corrections $\Delta\alpha_0$ and k_φ to the effective attack angle and to the lift derivative, respectively. They are functions of the profile thickness-chord and submergence-chord ratios (Egorov and Sokolov 1965). Denominator in Eq. (2) is due to a finite aspect ratio λ; and τ is Glauert correction. The influence of the foil submergence that affects the vorticity wake is accounted by ς and the influence of struts is accounted by θ (Egorov and Sokolov 1965). This is a function of the strut positions and the foil submergence and aspect ratio.

Figure 2 compares the results of Eq. (2) and experimental data for the lift coefficient of a hydrofoil section at Reynolds number 2.5×10^6. This figure illustrates the uncertainties one should expect when using approximate mathematical models.

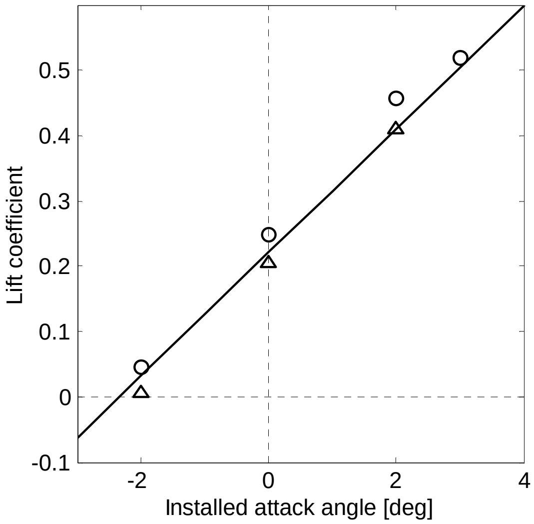

Figure 2: Lift coefficient for profile YS-920. ○, Δ experimental data for smooth and rough surface (Shen 1985); solid line, model prediction.

Hydrodynamic resistance of a hydrofoil system includes profile, inductive, and wave drag components. Struts have profile, spray, and sometimes cavitation drag components (Egorov and Sokolov 1965, Voitkunsky 1985). Hydrofoil sections crossing the water surface may also generate spray drag. Special fences are usually installed on hydrofoil and strut sections near the operational waterline to minimize this drag component and to avoid foil ventilation. High-performance hydrofoils should operate in the subcavitating regime. The boundary of the subcavitating domain for a particular profile is a function of the lift coefficient, profile thickness-chord ratio, and cavitation number.

For calculating hydrodynamic forces on the complex surface-piercing foil systems, such as employed on modern hydrofoil fast ferries (**Figure 3**), we propose to apply the transverse strip approach. The foil span is divided into a number of sections and the local lift coefficient is computed for each of the sections considering the local foil profile, local flow characteristics, and the global span of the hydrofoil system.

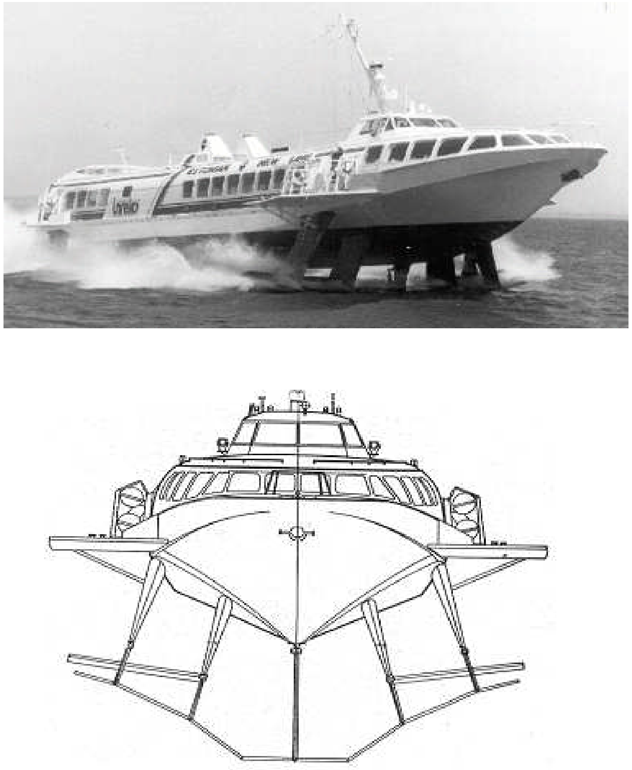

Figure 3: Photo and front view of a hydrofoil fast ferry of Olympia class.

One of the initial variants of the bow hydrofoil system of Olympia-class ship (**Figure 3**) was tested on a model scale at chord-length Reynolds number $5.5\text{-}8.0 \times 10^5$. Measured lift and drag are presented in **Figure 4** by open circles. Predictions for this system by the theory outlined in this paper are shown by crosses. (Some details of the foil system geometry are known to us only approximately.) Adequate agreement between model and test results is observed in **Figure 4** in the range of operational attack angles and submergences. Underprediction of the lift can be partly attributed to a reduced viscous influence on the lift derivative and a zero-attack angle in the vicinity of free water surface (Migeotte 2002). Another important factor is the non-uniform distribution of the lift force along the span of a hydrofoil. On a single zero-dihedral hydrofoil, the central sections are more heavily loaded than the sections near the tips. Therefore, a hydrofoil with deeper submergence of the central part will generally produce higher lift than predicted by the approach outlined here, although the influence of struts will partly compensate for this effect. Simple semi-empirical corrections can be applied to account for such phenomena in engineering design of hydrofoil system.

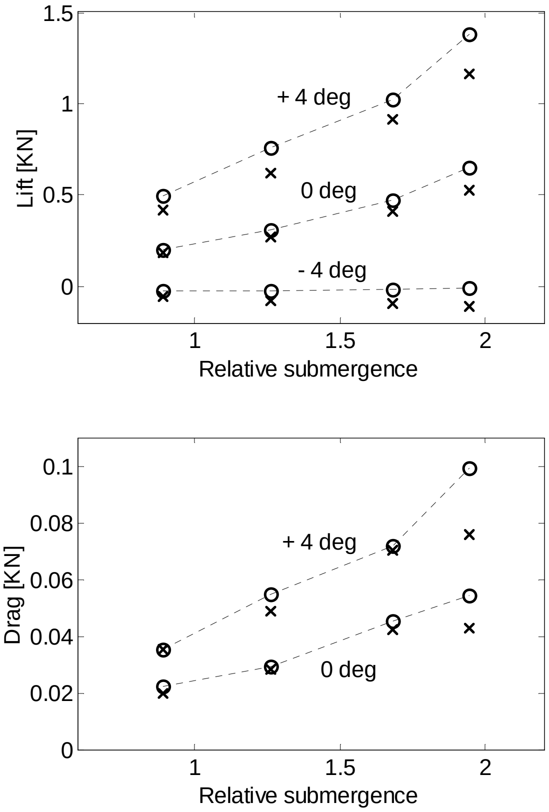

Figure 4: Lift and drag generated on the model-scale fore foil system of one experimental variant of Olympia class hydrofoil. ○ experimental data (Matveev I.I. 1999); × theoretical results.

FOIL INTERACTIONS

A hydrofoil moving in the proximity of the free water surface creates a wave system behind it (**Figure 5**). If another hydrofoil is placed in the upwash region in the wave system, then the lift force generated on this foil will incline forward effectively creating thrust. The length of the wave hollow is approximately proportional to the speed and a square root of the span of the front foil. The deviation of the water surface from the undisturbed level depends on the front foil geometry, its submergence, lift coefficient, and the ship speed. Expressions for engineering calculations of these values are available (Kolyzaev, Kosorukov, and Litvinenko 1980, Bai-Qi 1981, Voitkunsky 1985). Besides the effect of deforming the water surface, there is also the influence on the stern foil by the trailing vortices of the front foil. For shallow submerged hydrofoils, the influence of the free water surface should be accounted for when estimating this effect (e.g., Voitkunsky 1985).

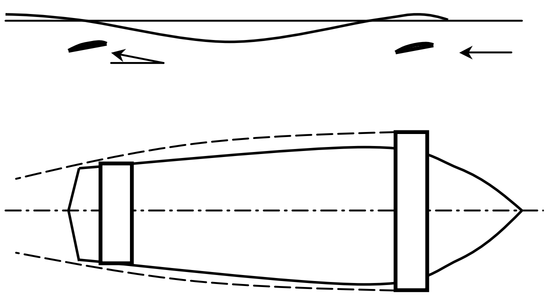

Figure 5: Wave hollow behind a hydrofoil and tandem hydrofoil arrangement.

Tandem hydrofoil systems have found widespread applications in the second half of the last century (Matveev K.I. and Matveev I.I. 2001). However, the complexity of their development and production is a significant barrier to introducing new ships. Special maintenance is also required (Matveev 2001). Hydrofoil-assisted ships, where the weight is only partially supported by hydrofoils, are becoming more popular. Such ships use simpler hydrofoil systems, and a portion of the hull always remains in contact with water, simplifying the propulsion system arrangement. Interactions between hulls and foils on such boats are complicated, and optimization of the performance of new configurations requires complex analysis or elaborate testing programs (Migeotte 2002).

One high-performance tandem-type configuration is shown in **Figure 6**. It is especially attractive for shallow-water or heavy ships. The front foil creates a wave hollow behind itself, and a planing stern with a propulsion system is located in the favorable upwash flow region. The middle foil system consists of two separate foils at the sides of the boat. These mid foils operate outside the wave hollow generated by the front foil. The location of the mid foils can be chosen to provide favorable front-to-middle foil interaction. Mid foils can also augment the upwash flow at the planing surface. Therefore, all interactions between hydrodynamic elements in this configuration are favorable. Other significant advantages of this system include improved roll stability, more uniform distribution of hydrodynamic support along the ship structure (which reduces bending moments in the hull), and better seakeeping.

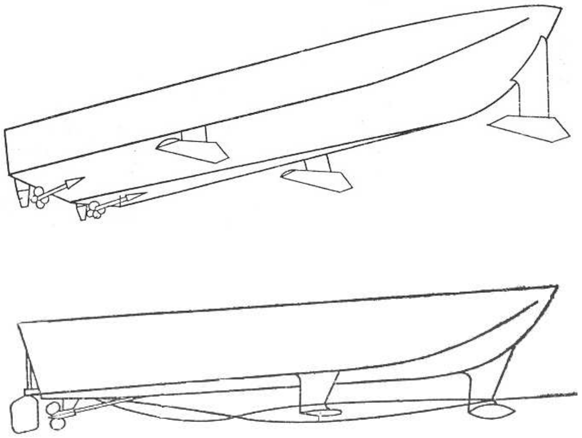

Figure 6: Scheme of a boat with positive interactions between hydrodynamic elements (Maksimov et al. 1975).

UNSTEADY FORCES

When predicting unsteady motions of a boat, one must know unsteady hydrodynamic forces on hydrofoils. If unsteady processes are sufficiently slow (e.g., in long waves), then a quasi-steady approach can be applied to calculate forces using Eqs. (1-2). If disturbances are small and periodic, then the forces (both amplitude and phase) will depend on Strouhal numbers (or frequency). In essentially unsteady problems, the fully unsteady methods for calculating forces should be applied.

Vortex-lattice methods have been used for hydrofoils (e.g., Walree 1999), but the complexity of this technique makes it inconvenient for parametric design studies of multi-component hydrofoil systems. In our approximate approach, we use analytical results obtained for simple problems with added empirical corrections accounting for real-life effects. For example, a general form of the unsteady hydrodynamic lift on a hydrofoil can be expressed as follows (Egorov and Sokolov 1965)

$$Y = Y_{qs} + Y_{am} + Y_{vw} . \qquad (3)$$

The quasi-steady force Y_{qs} is calculated by Eq. (1) but with the effective attack angle $\alpha_{ef} = \left(-V_1 + b\omega/4\right)/U$, where ω is the angular velocity along the transverse axis, $V_1 = V_y - U\alpha$, V_y is the vertical velocity of a hydrofoil, and α is the apparent attack angle.

$$Y_{am} = -\frac{d\left(\Delta m V_1\right)}{dt} . \qquad (4)$$

This is the force of an inertial nature that depends on the added mass. For rectangular hydrofoils, the added mass can be approximated as for a plate with corrections for the finite aspect ratio and relative submergence $\Delta m = \rho\pi\left(b/2\right)^2 b\lambda k(\lambda) f_1(h/b)$.

The last force depends on the shed vorticity

$$Y_{sv} = -\frac{1}{2}\rho b^2 \lambda U \, f_1(h/b) \times$$
$$\times \int_0^{s_1} \frac{\gamma(s)ds}{\sqrt{\left(s - s_1 - b/2\right)^2 - \left(b/2\right)^2}} , \qquad (5)$$

where $\gamma(s)$ is the circulation density in the wake at a horizontal coordinate s, and s_1 is the current coordinate of the hydrofoil trailing edge. For several classical cases (e.g., harmonic variations, steady acceleration, etc.) and idealized hydrofoil profile, the intensity of shed vorticity can be determined analytically; in other cases it can be found numerically in a time stepping process. This method for calculation of unsteady hydrodynamic lift gives results in acceptable agreement with experimental data (Egorov and Sokolov 1965).

BOAT DYNAMICS

The ultimate goal of the model under development is motion prediction of a hydrofoil craft in both calm water and in unsteady operations, including rough seas. The motion simulator integrates the boat dynamics equations applying the expressions for the forces outlined above. When conducting such modeling, two or more coordinate systems are usually used. For example, equations of motions are written in the ship-fixed coordinate system where inertial moments do not change. Motion trajectory is presented in the space-fixed system. When disturbances are small, the equations can be simplified. Sometimes the problem can be reduced to motions in the coordinate sub-spaces, such as the vertical plane motion (pitch, heave, surge) for seakeeping in head and following waves, or lateral motion (sway, yaw, roll) for maneuvering. Our tool incorporates all degrees of freedoms, with the ability to study reduced-order problems.

The general form of the dynamics equations are written as

$$\begin{aligned}&\left(M+\Delta M\right)\underline{\ddot{x}} = \\ &= \underline{F}(\underline{x},\underline{\dot{x}};history;waves;control)\,, \quad (6)\end{aligned}$$

where M is the inertial matrix, ΔM is the added mass matrix, and $\underline{x}$ is the vector of six coordinates. The generalized force vector on the right-hand side of Eq. (6) depends on the position and velocities of the craft, history of its motion, sea waves, and control system actions (e.g., flaps on hydrofoils). Besides forces acting on the hydrofoils, the forces generated on the appendages and propulsors, as well as the forces due to above-water hull motion in still or windy air, are included.

An interesting phenomenon in the dynamics of a hydrofoil craft is the unsteady fore-aft foil interaction. In complete CFD methods, these interactions are accounted for by the vorticity shedding from and the waves produced by the forward foil. In our simplified approach, only the unsteady interaction due to the water surface deformation is implemented, similar to (Kaplan 1955). This mechanism is dominant for surface-piercing and shallow submerged foils. A variation in the water surface deformation produced by the forward foil is felt by the aft foil after time delay $\tau = L/U$, where L is the distance between hydrofoils. This approximation is sufficient for useable engineering results.

The dynamic system outlined here is applied for simulating vertical plane motion in waves of the model of one variant of Olympia-class hydrofoil. Experimentally obtained steady lift and drag coefficients (which are functions of attack angle and submergence) were used with the addition of unsteady forces, wave-induced forces, and the fore-aft foil interaction. Calculated amplitudes of heave and pitch in following waves are compared in **Table 1** with experimental data and with results obtained by simpler (but still nonlinear) theory which neglects vorticity wake and the fore-aft foil interaction. Following waves are usually the most adverse wave direction for a hydrofoil craft. It should be noted that the final, optimized configuration of the Olympia hydrofoil, which additionally employs controlled flaps, has motions in high seas 2-10 times lower than those for the hydrofoil system variant studied here. Higher accuracy between test data and experimental results that may be needed for design optimization will require using sophisticated CFD methods for modeling hydrofoil craft dynamics.

Motion parameter	Heave	Pitch
Experimental data (Matveev I.I. 1999)	35 mm	2.1 deg
Prediction by the presented theory	30 mm	2.4 deg
Prediction by the theory neglecting foil interaction and vorticity wake	38 mm	2.8 deg

Table 1: Amplitudes of heave and pitch in following waves of the model of one experimental variant of Olympia class hydrofoil. Speed 5.4 m/s (Fr $_D$ = 2.7); wave height 130 mm; wave length 3.25 m.

CONCLUDING REMARKS

An engineering tool for calculating hydrodynamic forces on hydrofoil systems and for modeling boat dynamics is being developed. It will be used for designing hydrofoil-assisted craft. This relatively simple approach is suitable for parametric studies of the influence of foil elements on hydrodynamic performance, seakeeping, and maneuverability. Controlled foil sections that improve boat performance will also be incorporated into the tool. Planing and semi-planing hull elements will be added to model transitional regimes of pure hydrofoil boats and service regimes of hydrofoil-assisted ships. Further development of the tool towards CFD will also be considered.

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