Maintenance of Hydrofoil Systems

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In memory of hydrofoil designer Ivan Ivanovich Matveev

Abstract

Commercial hydrofoil vessels possess excellent hydrodynamic and economic characteristics in the range of craft with passenger capacity up to 300 and speed 30-40 knots. Since the performance of a hydrofoil is very sensitive to the proper state of the foil system, special maintenance service required to keep it in good working order is the major disadvantage of hydrofoils. Problems related to damage of foil systems as well as inspection and repair peculiarities of Russian-made craft are considered in this report. A new effective procedure allowing fast recovery of hydrofoil distortions is presented. The hydrofoil singing effect ascribed to self-excited oscillation of the trailing edge and a method for its elimination are discussed.

1. General consideration

Production of commercial hydrofoils in series began in Russia a half century ago. 1300 hydrofoil ships and thousands of small hydrofoil boats have been built. Hydrofoils made in Russia are recognized internationally, and about 200 hydrofoil vessels have been exported directly (Table 1). The main advantages of a hydrofoil over other types of water transportation in the range of passenger capacity up to 300 are low wash, high speed, seaworthiness and economic effectiveness. The major disadvantage of hydrofoil ships is the necessity for special technical service of foil systems; it is particularly serious for tandem schemes with increased lift-drag ratio, where the fore foil affects flow around the aft foil (Matveev et al., 2001).

Peculiarities of the maintenance of hydrofoil craft are caused by their specific structural elements: light-weighted alloy hulls, powerful engines, hydrofoils, complex geometry propellers, and inclined shaft lines. In this report we shall limit our considerations to effects related to the hydrofoil systems. In foilborne mode relatively small foil surfaces sustain high static load by supporting the whole weight of the ship. In operation, hydrofoil systems can be subjected to impacts with the sea's bed and floating objects; vibrations from shaft lines and propellers; and chemical and biological actions of the water environment. Additional lateral forces and modified lift forces act on foil systems during maneuvering. Foil-strut and strut-hull connections as well as foil surfaces sustain sharp wave loads in rough seas. All these factors may come down to the formation of dents, bends, cracks, breakage, or changes in the geometry of hydrofoil systems. The phenomenon of hydrofoil singing caused by flow-induced oscillations of the foil trailing edge may exceed the noise limits for commercial craft and accelerate fatigue processes.

	Raketa	Meteor	Voshod	Kometa	Kolhida	Olympia
Passengers	64	124	71	120	140	250
Service speed, knots	32	35	32	32	34	37
Range, nautical miles	270	320	270	240	200	300
Fuel consumption, kg/hour	165	316	144	286	396	698
Exported quantity	26	29	13	106	14	2

Table 1: Hydrofoil ships exported from Russia

2. Foil distortions, repair and inspection

Fatigue analysis and criteria with respect to hydrofoil devices are considered by Gurevich et al. (1971) and Moan et al. (1991). There are three types of unsteady loads leading to foil crack formation: low-frequency forces (~100 cycles per minute) appearing in rough seas; high-frequency forces (~1000 cycles per minute) due to unbalanced rotating masses in the engine-propulsor system and auxiliary mechanisms; and flow-induced oscillation of the foil structure. The highest level of vibration is observed in transitional regimes when engine power, rotation frequency, trim, incidence angles, foil immersion and ship speed are varied. Measured near the connection between the bow foil system and the hull, vibration frequencies corresponding to the highest loads are in the range 60–130 Hz, and maximal displacement amplitudes reach 0.1 mm (Ikonnikov et al., 1987).

Main defects of the forward surface-piercing foil devices appearing in use of the Kometa 342MC type ships are shown in Fig. 1. The main foil and brackets are made from steel 12X18H10T; the stabilizer is made from aluminum alloy AMg-61. Crack formation on the deeply submerged foils are also reported to appear on American (Olling et al., 1981) and Canadian (Eames, 1983) developments. Elimination of cracks is carried out by welding with preliminary surface preparation. In the case of crack appearance on the strut and foil spans, additional lists are installed.

Bending and swelling of the foil surface are removed by thermoplastic and mechanical methods. The first procedure is applied at small deformations (5 mm per 1 m) by heating and cooling the distorted foil surface. Heating is carried out in spot manner when metal thickness is less than 4 mm; otherwise - in strip way. The mechanical method is applied for bigger distortions and accomplished by hammer or special

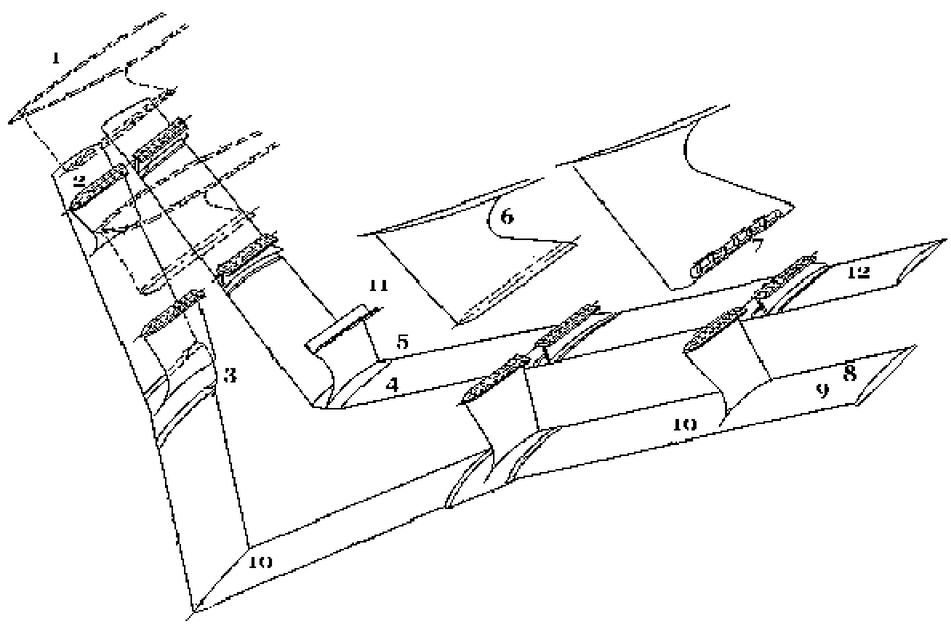

Fig. 1: Scheme of typical defects on the fore foil system on Kometa 342MC: (1) breach in isolation between foil system and hull; (2) weakening of bolt connections between strut and bracket; (3) cracks along the trailing knives near the struts; (4) cracks on both sides of the stabilizer near welds; (5) cracks on upper side of stabilizer between struts; (6) cracks along welds on the aft sides of brackets; (7) cracks along welds on the lateral side of brackets; (8) swelling on both sides of consoles; (9) cracks on the upper sides of consoles; (10) single cracks on both sides of foils along welds of the trailing knives, and bending of foil surface; (11) cracks along welds near hull-strut connections; (12) corrosion of the stabilizer surface

devices. Significantly damaged surfaces are substituted by whole lists or sections. In repair process stress concentrations in various connections should be smoothed out. Welds are located in areas with low tension, their number is minimal; and distances between them should not be too small.

Additional technological peculiarities of foil device repair are caused by high requirements with respect to the accuracy of detail geometry. Hydrodynamic properties of foil systems (lift, drag and moment) are very dependent on the accuracy of foil profiles and installation of the system. Erosion due to cavitation is strongly affected by the foil surface. The condition of struts and brackets attaching foils to the hull is also important. Violation of their smooth connections may lead to air penetration to the suction sides of foil surfaces. As an example of allowed deviations in foil systems, the acceptable errors for Meteor type ships (Kulik, 1971) are the following: for span size – 5 mm; for distance from center plane to bottom (board) strut – 3 (5) mm; for sweeping distance – 2 mm; for deadrise level – 4 mm; and for installed angle of incidence with respect to the baseline – 6'.

Measurement procedures check the installed incidence angles, the geometry of profiles and positioning of the foil system with respect to the hull. This inspection is carried out upon worsening of ship performance due to damage of the foil systems (collisions with floating objects and sea's beds); before operational season; and after repair of foil devices. Checking of foil profiles is carried out by templates or rulers; installed incidence angles – with the help of strings, optical quadrant, and a hose level (Fig. 2). Note that the angle of baseline inclination to the horizontal line should be also determined. Elimination of the error in installed incidence angles is accomplished by detachment of the foil system and installing the appropriate wedge gaskets in hull-bracket or strut-bracket bolt connections.

Space inside some sections of the foil systems is connected with environment, so that it is filled by water when ship is in service. Before winter non-operational period such caverns are blown by a dry air. Foil systems on the vessels working in warm seas should be cleaned from biological formations at least once in twenty days to keep the proper hydrodynamic performance of the craft.

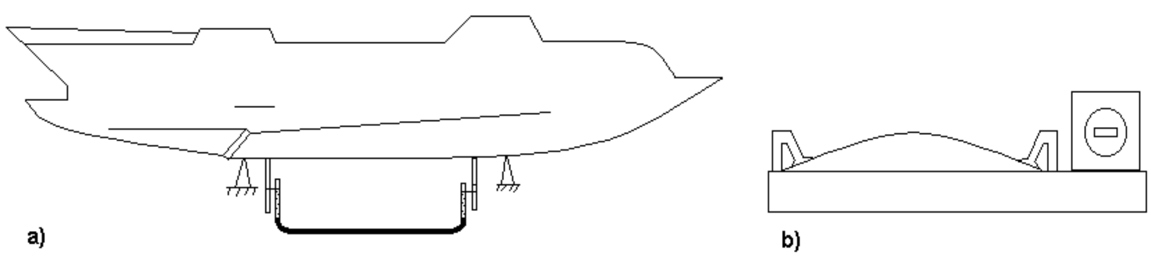

Fig. 2: Measurement of installed attack angle: a) determination of hull inclination by a hose level; b) finding the installed angle of the foil plane by a quadrant

3. Estimation and compensation of hydrofoil deformations during operational season

In this section we consider only distortions of foil profiles and installed incidence angles of hydrofoils. Such deformations can be treated by the original method developed by I.I. Matveev (1999); this method allows operators significantly decrease repair time, that is very important during operational season. The advantages of the proposed procedure are simplicity and quickness of the repair in comparison with the standard procedures requiring complex repair of the foil sections and changes of hydrofoil installation as mentioned above. This method has been successfully applied to Russian-made hydrofoil vessels operating in the Mediterranean basin.

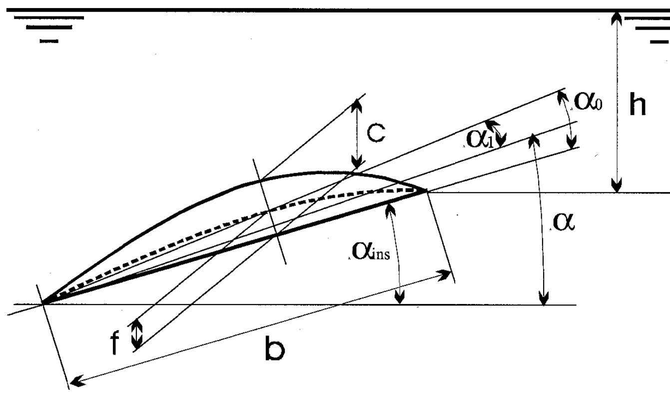

Fig. 3: General configuration

The foil profile characteristics, namely the curvature of the mean line and the profile thickness, determine the attack angle α_0 corresponding to zero lift and the correction to this angle α_1 due to the free water surface (Fig. 3). The approximate expression for the lift coefficient (Voitkunsky, 1985) is

$$C_y = dC_y/d\alpha\,(\alpha_{ins} + \alpha_0 - \alpha_1), \tag{1}$$

where $dC_y/d\alpha$ is the derivative of the lift coefficient with respect to the angle of attack, and α_{ins} is the installed geometrical angle of incidence. Since the derivative remains nearly constant with profile deviation, the change of the initial lift coefficient for the deformed cross-section is due to the difference between the current and initial attack angles $\Delta\alpha$ given by the expression

$$\Delta\alpha = \Delta\alpha_{ins} + \Delta(\alpha_0 - \alpha_1)\,. \tag{2}$$

The increment of the angle of incidence is found by measurements as the difference between the actual and design values. We express the second term in (2) in terms of distortion of the profile. The characteristic deformations of the cross-sections, which cause the change of the mean line and profile thickness, are combinations of the distortions of the upper and lower surfaces of the profile (Fig. 4).

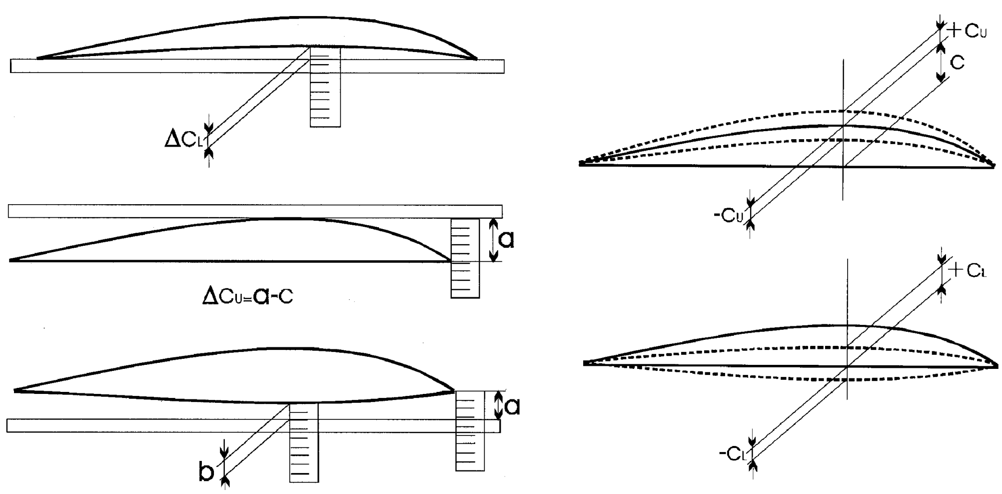

Fig. 4: Measurement technique

We make use of the empirical dependence for α_0 and α_1 on the relative thickness and immersion, applied at the Central Hydrofoil Design Bureau:

$$\alpha_0 = 2\, n\, f\, /\, b\,, \qquad (3)$$

$$\alpha_1 = g\, n\, c\, /\, 2\, b\,, \qquad (4)$$

where *c* is the foil thickness; *b* is the foil chord; *n* is the viscous correction, which can be taken equal to *0.85*; *f* is the curvature of the mean profile line; and *g* is the free surface correction

$$g = exp(-2.5\, h / b\,) / (\, 2 - exp(-2.5\, h / b\,)\,)\,, \qquad (5)$$

where *h* is the foil immersion. The second term in (2) becomes

$$\Delta\, (\, \alpha_0 - \alpha_1\,) = n\, (\, (\Delta C_U + \Delta C_L\,) - g\, (\Delta C_U - \Delta C_L\,) / 2\,) / b\,. \qquad (6)$$

The distortions ΔC_U and ΔC_L are taken with their signs: positive values (upward from nominal) correspond to increase of the mean profile line. For deeply submerged foil sections, we can disregard $d\alpha_1$, and the simplified formula (angle is in degrees) becomes

$$d\alpha_0 = 48.7\, (\Delta C_U + \Delta C_L\,) / b\,. \qquad (7)$$

In repair processes, it is more convenient to use the dimensions given by the instruments, namely minutes for angular distortions; millimeters for deviations of profile ordinate; and meters for the chord of a foil. Then the increment of zero lift angle of the deformed cross-section is

$$d\alpha_0 = 2.9\, (\Delta C_U + \Delta C_L\,) / b\,. \qquad (8)$$

Method for finding deformations of a plate-convex profile is shown in Fig. 4. Such measurements are carried out at several stations to find the local deformations.

In order to keep the lift coefficient constant, the sum of the geometrical incidence angle and the angle of attack for zero lift must be zero. For the local character of the distribution of the deformations considered, it is inconvenient to compensate them by changing the installation of the foil system (or foil sections). In this case, it is effective to apply a correction to the deformed sections by bending the trailing edge (Fig. 5). For such corrections, not only the curvature of the mean profile line changes, but so also does the geometrical incidence angle. The values of $\Delta'\alpha_{ins}$ and $\Delta'\alpha_0$ obtained in this way have the same sign; that characteristic improves the effectiveness of the bending. Using dimensions considered above (angle in

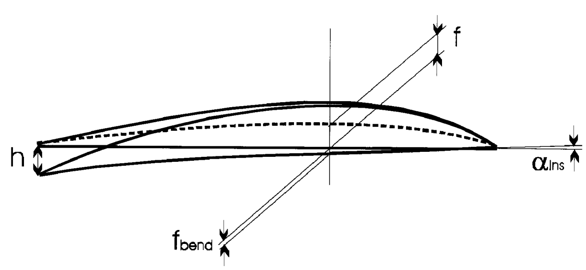

Fig. 5: Influence of bending on the attack angle

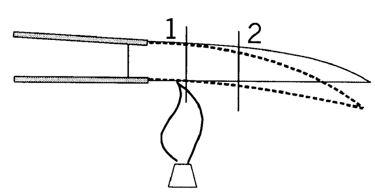

Fig. 6: Thermal bending of a trailing edge

minutes and chord in meters), the desired value of the segment profile bending Δh (in millimeters) for compensation in the change of the attack angle computed by (2), when bending length is chosen to be *0.1b*, is

$$\Delta h = 0.16\, b\, \Delta\alpha\,. \qquad (9)$$

To bend the trailing knife (a massive element with welded upper and lower plating lists) the following technique can be applied (Fig. 6). A line is drawn in chalk at a distance ~100 mm from the trailing edge. The flame of a burner heats a foil along the line until the metal acquires a cherry color. Length of the heated area is 0.4-0.5 m. Then fast cooling is carried out from the heated side by a water jet. Shrinkage of the metal takes place, accompanied by smooth curving of the profile (for the case shown in the picture the trailing edge comes down). The same effect is reached by imposing a welded joint on the line. In cooling, the joint pulls the metal to itself. The results of bending are checked by a template. When pouring water, light knocking of the edge through a wood gasket is carried out. The whole area requiring correction is worked up this way. If the bending is not enough, the same procedure is accomplished along a parallel line 2 shown in Fig. 6.

4. Hydrofoil singing

When a new hydrofoil ship is commissioned, so-called hydrofoil singing is sometimes observed. Hydrofoil singing is a tonal sound caused by interaction of the foil trailing edge with incoming flow. The intensity of the excited tone often exceeds the intensity of the noise from engine-propulsor and other systems. The problem of hydrofoil singing emerged on Russian-made river boats of types Raketa, Polesie and Dolphin with steel foil systems. But especially critically it was manifested on the sea-going Kometa and Olympia (Fig. 7), which has the bow foil system made from titan alloy.

Hydrofoil singing can be classified as a special type of single-degree-of-freedom flutter. Consider a physical model. The boundary layers generated on the moving foil leave from the trailing edge as a vortex sheet (Fig. 8). Vortices of opposite circulation are formed in turn with a certain frequency depending on the flow speed and a characteristic vertical size by analogy with the Karman vortex street behind a cylinder. Periodic vortex separation is accompanied by a periodic vertical force acting on the foil. Structural peculiarities of the foil system leads to the assumption that only that part of the foil located near the trailing edge can react to this unsteady force. When the eigen frequency of the trailing edge is close to the vortex shedding frequency, the amplitude of edge oscillation becomes maximal. Motion of the trailing edge feeds back to the vortex separation, so that self-excited oscillations appear, characterized by frequency locking.

Fig. 7: Hydrofoil Olympia (chief designer – I.I. Matveev)

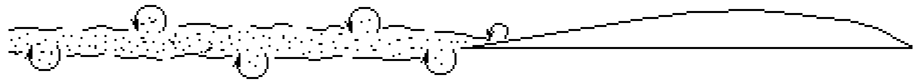

Fig. 8: Vortex sheet leaving from hydrofoil trailing edge

Experiments carried out in trials of the first Olympia type ship (Matveev, K.I. et al., 1997) demonstrated the validity of this model. Hydrofoil singing was recorded over the wide range of speed, and different harmonics were observed. In Fig. 9 the dependence of the dominant frequency and the intensity of the 400 Hz tone are given for the speed interval 15.5–19 m/sec. The locking region is clearly pronounced, and within it, sound power is high.

Hydrofoil singing has very negative effects: first, the noise level is unacceptable for passenger transportation; second, vibration of the foil structure participating in singing effect leads to fatigue of the system and crack formation in the regions of aft knives on foils and struts (Fig. 1). Elimination of hydrofoil singing on foil devices made from stainless steel was usually achieved by cutting the trailing edge, so that natural frequency of the system was increased and vortex shedding frequency was decreased. However, this approach is unacceptable for foils made from titanium alloy; the necessary length to be cut is so large that it would lead to the degradation of the hydrodynamic properties. A new method (Matveev, I.I. et al., 1997) was proposed: the trailing edge is lifted by a certain value by special profiling, and the curvature of the surface on the lower side of modified part is selected to be smaller than the one on the upper side. This procedure allowed elimination of the tonal sound without degrading the lift-drag ratio of the vessel. Nowadays that method is successfully applied on other hydrofoils.

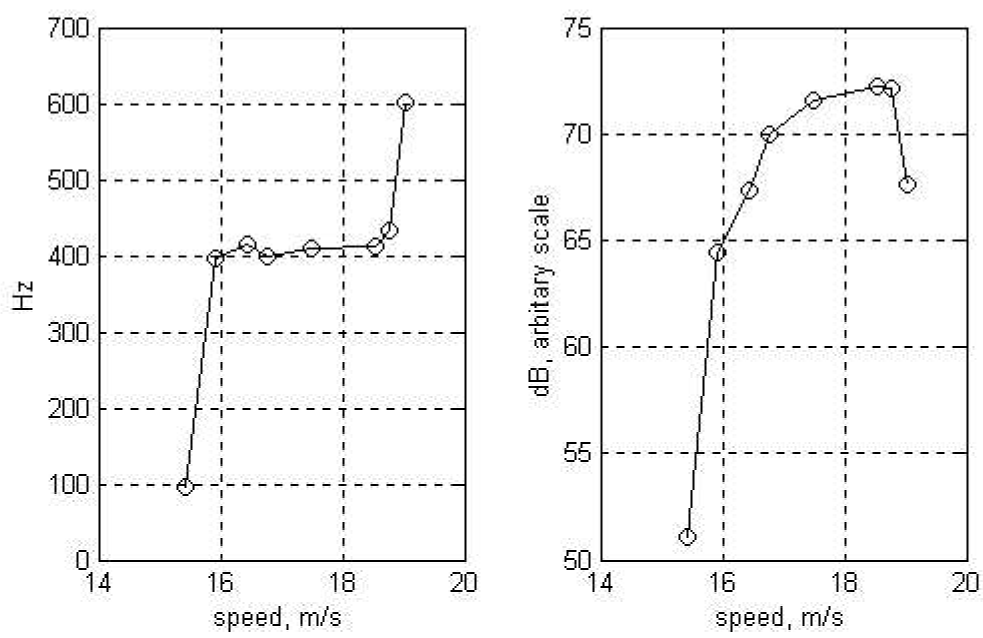

Fig. 9: a) Dominant frequency at speed range 15.5-19 m/s, b) intensity of 400 Hz tone versus speed

5. Conclusion

Hydrofoil ships with tandem scheme possess the best hydrodynamic characteristics and economic effectiveness in the range of small fast passenger ferries. Continuation of their mass presence in the fast sea transportation market is therefore highly probable. Exploitation shortages of this kind of high-speed craft can be avoided by taking advantage of the experience and current knowledge. Correspondingly, the time for repairs during operational seasons will be less, and the service quality will be higher. New materials providing better strength properties for the foil systems, and advanced welding technology, should be applied on the next generation of hydrofoils.

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