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HYDRODYNAMICS OF OSCILLATING WING ON THE PITCH ANGLE

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Abstract

Purpose: *research of the hydrodynamic characteristics of a wing in a nonstationary stream.* ***Methods:*** *The experimental studies of the hydrodynamic load acting on the wing of 1.5 elongation, wich harmonically oscillated respect to the transversal axis in the frequency range of 0.2–2.5 Hz. The flow speed in the hydrodynamic tunnel ranged of 0.2–1.5 m/s.* ***Results:*** *The instantaneous values of the coefficients of lift and drag / thrust on the pitch angle at unsteady flow depends on the Strouhal number.* ***Discussion:*** *with increasing oscillation frequency coefficients of hydrodynamic force components significantly higher than the data for the stationary blowing out of the wing.*

Keywords: angular acceleration; angular velocity; drag-thrust; dynamic load; lift; oscillating wing.

1. Introduction

In most devices which utilize a wing profile as a working element, the flow is unsteady. It is typical, for example, for a propeller in skewed stream or for a hydraulic turbine with vertical axis (Darrieus rotor).

The validity of corrections or additional terms for determining dynamic characteristics of hydraulic multiblade turbine using the modified Zhukovsky's theorem for a grid of profiles can be confirmed or denied by either a direct numerical solution of non-stationary turbine rotor flow problem, or by direct experiment. However, in an experiment with a turbine it is almost impossible to track instantaneous characteristics of the profile, which determine the turbine parameters. It is possible to use the data of an oscillating wing hydrodynamics.

Many works study the hydrodynamic characteristics of a wing, which oscillates in a flow. Most of them are theoretical and numerical studies [1–6]. Some experimental work is mainly focused on the assessment of the propulsive characteristics of an oscillated wing [7–9]. The papers [10, 11] attempts to investigate the mechanism of transitional processes in the boundary layer and flow structure of an oscillating hydrofoil and origin of the vortex at a subsonic flow.

Systematic analysis of oscillating profiles is given in the experimental work [12], but there are presented only averaged over a period characteristics of the wing, that makes the results virtually inapplicable to a turbine.

Given these circumstances, it is worthwhile to return to analysis of an unsteady flow about a single profile and determine the instantaneous parameters (thrust-drag, lift) at its oscillatory motion in an impinging stream.

The aim of this work is to determine the instantaneous values of hydrodynamic characteristics of a rigid wing, which oscillate in the flow over a pitch angle. The basis of the research is an experiment in hydrodynamic tunnel.

2. Objective

The object of research is a small aspect ratio wing of rectangular shape in plan with small end plates. The wing profile is symmetrical, chord b = 120 mm, elongation $\lambda = 1.5$ ($\lambda = l / b$, where l – wingspan), the relative profile thickness c = 20%.

The experiments were conducted in the hydrodynamic tunnel (HDT) over the velocity range of $U = 0.2 - 2.0$ m/s.

Wing (Fig. 1) was attached to the two-component strain gauge in the working section of HDT. The wing was made rotating about the transversal axis Z using the electric mechanism. The wing rotation axis is offset from the leading edge on the distance $x_e = 0.3\ b$.

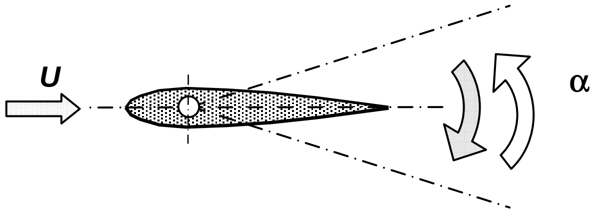

Fig. 1. Scheme of the oscillating wing

The electrical actuator provided such motion that the wing rudder angle $\boldsymbol{\alpha}$ varied harmonically in time t:

$$\alpha(t) = \beta \sin \omega t$$

where ω is angular frequency of oscillation, β is amplitude of angular oscillation.

We considered unsteady flow regimes at two values of the rudder angle amplitude: $\beta = 15°$ and $\beta = 30°$. The first value of the angle amplitude is less than the critical angle of attack (18°– 20° at steady flow, Fig. 2), the second value is higher.

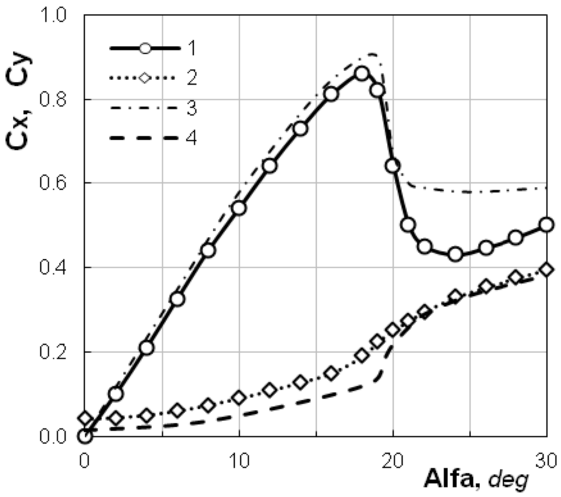

Fig. 2. Lift C_y (*1*,*3*) and drag C_x (*2*,*4*) coefficients of the wing with the elongation $\lambda = 1.5$, depending on the angle of attack in the steady flow: *1*,*2* – present work, *3*,*4* – [12, 13]

Wing oscillation frequency f was adjusted in the range of 0.2°– 2.0 Hz.

The working section (WS) of HDT is a square with dimensions of 400 mm × 400 mm. Its cross sectional area is $S_{HDT} = 0.16$ m^2. The blockage of WS by the wing varied over a half-period of oscillations within the range $S_{yozWING} / S_{HDT} = 3 \div 7\%$, depending on the amplitude of angular defelection of the wing profile.

During a test, given the wing rudder angle frequency f and flow velocity U, the instantaneous values of longitudinal (F_x) and transverse (F_y) components of hydrodynamic force acting on the wing were measured, as well as the wing deflection angle α. The information from the sensors was displayed and recorded on the digital oscilloscope.

In the course of experiments, the wing rudder angle frequency varied and correspondingly varied a value of the recorded force. To ensure the accuracy of the force component measurement, the entire data range was divided into several subranges. The signal amplification coefficient was specified such that the measurement error did not exceed 3÷5% over a subrange. The accuracy of rudder angle measurements was ± 0.25 degrees.

Design features of the strain-gauge suspension, in which sharp-directed minimum stiffness in mutually perpendicular direction is implemented, ensured that there is no mutual influence of the components F_x and F_y.

The assembly of the oscillating mechanism drive and the wing is balanced as much as possible.

To eliminate the influence of the signal from the residual mechanical inertial component of the force, two series of experiments were conducted. Initially the wing was made oscillating in still air. The phase matching recorded signal was subtracted from the data of the wing test at the corresponded frequency in the hydrodynamic tunnel. Final information contained only the hydrodynamic load data.

3. Results and Discussion

Test results are presented in the form of the hydrodynamic coefficients C_y and C_x:

$$C_y = F_y / S\,q\,, \quad C_x = F_x / S\,q\,,$$

where $q = (1/2)\,\rho\,U^2$ is the velocity pressure, U is the flow speed in HDT, S is the wing area.

At the beginning we determined the hydrodynamic coefficients of the wing (C_y, C_x) depending on the angle of attack α in a steady flow, i.e. in the absence of the wing oscillations ($\omega = 0$) (Fig. 2). These data are consistent with those of other authors [12, 13].

In case of wing oscillations in a flow, it is important to know both the integral hydrodynamic characteristics and instant values of dynamic load.

Typical flow characteristics for oscillating wing over the pitch angle presented as the dependences of the lift coefficient amplitude $C_{y\,A}$ on the oscillation frequency of the wing ($f = 0.31 \div 2.0$ Hz) with amplitude $\beta = 30°$ for different values of the flow velocity ($U = 0.22 \div 1.5$ m / s), shown in Fig. 3.

These data are presented as functions of the dimensionless parameter V_t / U (Strouhal number Sh), where U is flow velocity in WS HDT, $V_t = \omega r$

is maximum value of (transverse) velocity of the wing trailing edge the oscillation period (Fig. 1), $r = b - x_e$ is distance from the trailing edge to the rotation axis.

Kinematic parameter V_t / U is the reciprocal of the relative speed λ_p, which by its nature is similar to the advance ratio of a propeller.

The data of all tests at different speeds and different frequencies presented in such form lie on one universal experimental curve.

Maximum values of longitudinal force coefficient $C_{X\,max}$ (thrust) and minimum value of the longitudinal force coefficient $C_{X\,min}$ (drag) as a function of the Strouhal number have similar form.

Variations of the transversal (*a*) and the longitudinal (*b*) hydrodynamic force components within the one period of oscillation as a function of instantaneous value of the wing pitch angle are shown in Fig. 4. We present typical data of dynamic load on the wing for several oscillation regimes, characterized by the Strouhal number. Fig.4 shows several data sets at same Strouhal number but different amplitude of angular oscillations of the wing (β = 15° and β = 30°).

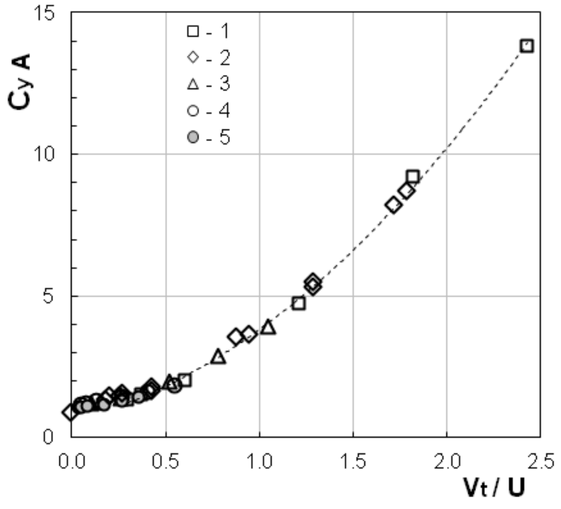

Fig. 3. Amplitude of oscillations of the wing lift coefficient $C_{y\,A}$ for different values of the frequency *f* and the flow velocity *U* with amplitude β = 30°, depending on the parameter V_t / U . *1* – *U* = 0.22 m/s; *2* – 0.31m/s; *3* – 0.5m/s; *4* – 1.0m/s; *5* – 1.5m/s, respectively oscillation frequencies *f* = 0.31, 0.5, 1.0, 1.5 и 2.0 Hz.

With increasing frequency of the wing harmonic oscillations (as well as with an increase in the dimensionless parameter V_t / U) maximum value of the transversal forces (lift) coefficient C_y, within one half-cycle of oscillation, shifts from limit angles of rudder wing to lower values of pitch angle (from α = 28° to α = 14° in Fig. 4, *a*.

For the drag coefficient values (thrust) C_x, an opposite effect is observed. As the value of dimensionless parameter V_t / U of wing oscillations grows, maximum values of the coefficient C_x is moves closer to limit values of the dynamic wing rudder angle (Fig. 4, *b*).

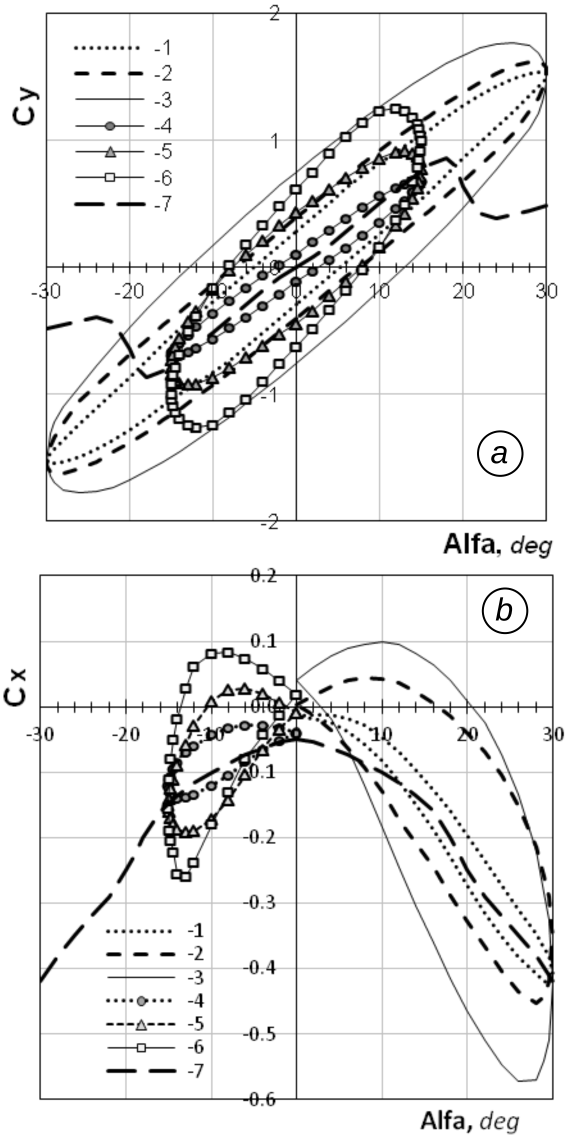

Fig. 4. Variation of transverse C_y (*a*) and longitudinal C_x (*b*) coefficients of hydrodynamic force component within a one period of oscillation as a function of the instantaneous value of the pitch angle α, at different frequencies and amplitudes of the wing oscillations.
1,2,3 – *U* = 0.31 m/s, β = 30°;
4,5,6 – *U* = 0.5 m/s, β = 15°.
1 – V_t / U = 0.2, 2 – 0.2
7, 3 – 0.43, 4 – 0.14, 5 – 0.28, 6 – 0.41, 7 – 0.

For comparison, Fig. 4 (curve *7*) also shows the results for steady wing flow (ω = 0) (Fig. 2). Instantaneous values of the hydrodynamic parameters of oscillating wing are significantly higher than the corresponding characteristics in a steady flow.

At dynamic change of the pitch angle, the instantaneous value of the angle of attack of the wing increases (decreases) by the angle determined by the reciprocal of the advance.

When in the process of reducing the pitch angle the angle of attack becomes negative, the oscillating creates trust. However, accounting only for the 'real' angle of attack we could hardly obtain dynamic loads on the profile on the basis of steady flow analysis, because at maximum deflection of the wing its angular velocity is zero and the 'real' angle of attack is equal to a steady pitch angle. At maximum pitch angles, dynamic characteristics of the profile are determined by inertial force components that depend on angular acceleration of the oscillating profile.

For a given harmonic law of rudder wing on the pitch angle, angular velocity reaches a maximum when the profile passes a neutral position ($\alpha = 0$), while maximum acceleration is when the wing is deflected on maximum angle ($\alpha = \beta$).

When we utilize a dimensionless parameter $K = 1 / (1+Sh^2)$, the dynamic test data of the oscillating wing in a flow can be represented in more concise form (Fig. 5).

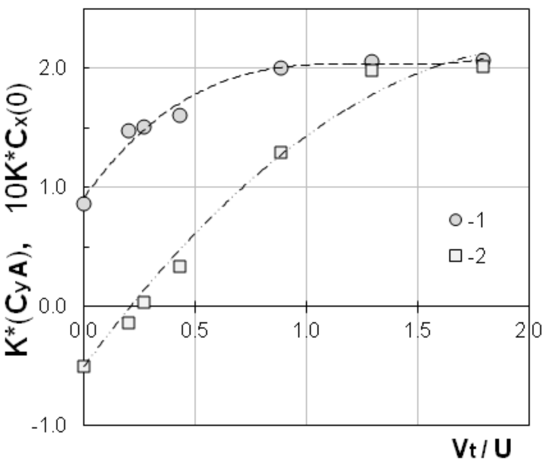

Fig. 5. Maximum values of the lift coefficient C_{yA} (*1*) and longitudinal force (drag-trust) during passing a zero pitch angle ($\alpha = 0$) $C_x(0)$ (*2*) for different values of the wing oscillation frequency ($f = 0.0$, 0.23, 0.31, 0.5, 1.0, 1.5, 2.1 Hz), at flow velocity $U = 0.31$ m / s, depending on the parameter V_t / U.

Transient variation of the angle of attack leads not only to an increase of dynamic loads on the profile, but also to a qualitative change in their structure, depending on the rate of angular velocity variation and direction of the angle of attack variation, especially at a supercritical angle of attack.

Obviously, that at $Sh \to 0$ results must match the steady flow profile at a corresponding angle of attack for both the lift coefficient, C_y, and drag coefficient, C_x. However, at a supercritical angle and the amplitude of profile oscillation of $\beta = 30°$ there is no a decrease in C_y at growing angle of attack, even at small values of $Sh = 0.21$. Moreover its value is significantly higher than the airfoil lift coefficient at steady regime, indicating that the inertial component makes an effect even at low frequencies of the profile oscillations. When the parameter *Sh* increases, the coefficient C_y depends on the angle of deflection in the same manner.

The drag coefficient C_x of the oscillating profile essentially differs from that at a steady regime, especially at greatest angles of deflection, that also indicates an effect of the inertial force component. At a greater *Sh*, drag coefficient C_x of the oscillating profile is reduced and changes its sign, which means that the oscillating profile generates thrust.

It should be noted that at a higher oscillation frequency, trust prevails the drag force within a period. At such regimes of flow about the pitching wing, a hydrodynamic propulsion appears. However hydrodynamic efficiency in this case is lower than [12, 14] two-degrees-of-freedom oscillated wing.

4. Conclusions

The experimentally determined dynamic load on the oscillating wing in a flow over a wide ranges of flow speed, frequency and amplitude of the oscillations allowed to formulate the following conclusions:

– instantaneous values of the drag-thrust and lift coefficients depend on frequency of the wing oscillation, and many times exceed the value of hydrodynamic load at the corresponding angle of attacks in a steady regime. Unsteady flow about a wing leads to significant dynamic overloads on the construction;

– at dynamic variation of pitch angle, the instantaneous value of the wing angle of attack varies on a value determined by the reciprocal of the advance.

– when the parameter *Sh* reaches a value of the order of *1*, instantaneous longitudinal component of force averaged over the period of oscillation changes its sign, indicating creation of thrust by the oscillating profile;

– normalization factor 1 / (1+Sh^2) allows to unify the coefficients of lift and drag forces at unsteady motion of the profile;

– the measurements of hydrodynamic characteristics of the oscillating wing supports the conclusion obtained for propellers working in an downwash flow. Analysis of full-scale measurements and laboratory test data show that determining a variable force generated on the blades in this manner, based on the curves of action, results in a smaller value of the variable load compared to its real value. This, in turn, leads to an underestimation of the fatigue strength of a propeller behind the hull (for example) of a hydrofoil ship.

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Гідродинаміка крила, що коливається за кутом тангажа

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Мета: Дослідження гідродинамічних характеристик крила в нестаціонарному потоці. **Методи дослідження:** Експериментальне вивчення гідродинамічного навантаження, котре діє на крило подовженням 1.5, яке коливається в потоці по гармонійному закону щодо поперечної осі в діапазоні частот 0.2-2.5 Гц. Швидкість потоку в гідродинамічної трубі становила 0.2-1.5 м / с. **Результати:** Миттєві значення коефіцієнтів підйомної сили і опору / тяги в залежності від кута тангажа при нестаціонарному обтіканні залежать від числа Струхаля. **Обговорення:** Зі збільшенням частоти коливань коефіцієнти компонент гідродинамічної сили, що діє на крило, зростають і можуть істотно перевищувати параметри для стаціонарної продувки.

Ключові слова: крило, що коливається, кутова швидкість; кутове прискорення; навантаження динамічне; опір-тяга; підйомна сила.

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Гидродинамика колеблющегося крыла по углу тангажа

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Цель: Исследование гидродинамических характеристик крыла в нестационарном потоке. **Методы исследования:** Экспериментальное изучение гидродинамической нагрузки, действующей на крыло с удлинением 1.5, которое колеблется в потоке по гармоническому закону относительно поперечной оси в диапазоне частот 0.2- 2.5 Гц. Скорость потока в гидродинамической трубе составляла 0.2-1.5 м / с. **Результаты:** Мгновенные значения коэффициентов подъемной силы и сопротивления / тяги в зависимости от угла тангажа при нестационарном обтекании зависят от числа Струхаля. **Обсуждение:** С увеличением частоты колебаний коэффициенты компонент гидродинамической силы на крыло возрастают и могут существенно превышать параметры для стационарной продувки.

Ключевые слова: динамическая нагрузка; колеблющееся крыло; подъемная сила; сопротивление-тяга; угловая скорость; угловое ускорение.

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