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APPROXIMATE NONLINEAR THEORY OF RECTANGULAR WING OF SMALL ASPECT RATIO MOVING NEAR A FLUID SCREEN AT LARGE FROUDE NUMBERS

by

K. K. Fedyayevskiy

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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α α		Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε ϵ		Rho	Ρ	ρ ϱ	
Zeta	Ζ	ζ		Sigma	Σ	σ ς	
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ ϑ		Upsilon	Τ	υ	
Iota	Ι	ι		Phi	Φ	φ ϕ	
Kappa	Κ	ϰ κ ϰ		Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	sin^{-1}
arc cos	cos^{-1}
arc tg	tan^{-1}
arc ctg	cot^{-1}
arc sec	sec^{-1}
arc cosec	csc^{-1}
arc sh	$sinh^{-1}$
arc ch	$cosh^{-1}$
arc th	$tanh^{-1}$
arc cth	$coth^{-1}$
arc sch	$sech^{-1}$
arc csch	$csch^{-1}$

Russian	English
rot	curl
lg	log

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APPROXIMATE NONLINEAR THEORY OF RECTANGULAR WING OF SMALL ASPECT RATIO MOVING NEAR A FLUID SCREEN AT LARGE FROUDE NUMBERS

K. K. Fedyayevskiy

(Moscow)

Developed in this article is an approximate nonlinear theory [2] for a rectangular wing of small aspect ratio moving in an unlimited medium near a fluid screen at large Froude numbers.

If from the experimentally determined moment value we subtract the moment of inertial nature, i.e., the moment corresponding to the circulation-free flow past the body and divide the difference by normal force, then the coordinate for the center of pressure thus obtained will correspond to a purely circulation (viscous) flow. Let us call a point with such a coordinate the center of the attached vortex. We will designate the coordinate of the attached vortex as

$$x_n = \frac{M_{z\,эксп} - M_{z\,ин}}{y_1}. \qquad (1)$$

The dimensionless coefficient of the center of the attached vortex

$$X_n = \frac{x_n}{b}.$$

In these formulas y_1 is normal force; b - root chord of the wing. As we know, in the selected coordinate system

$$M_{z\,ин} = -(r_2 - r_1)\frac{\rho V^2}{2}\sin 2\alpha,$$

where k_2 is the volume of the attached mass of fluid as the wing moves in a transverse direction; k_1 - analogous volume as wing moves in longitudinal direction. For thin wings $k_1 = 0$.

The experimental values of the center of the attached vortex are much more stable in comparison to the center of pressure, which for wings of a small aspect ratio moves rapidly toward the trailing edge as the angle of attack increases. The deduction of stability in the center of the attached vortex is also confirmed when we study the flow beyond the wing. This gives us reason as our first main hypotheses to assume that the position of the center of the attached vortex for the given shape of the wing in the plan does not depend on the angle of attack.

Comparison of the distribution of loads along wing chords of low aspect ratio calculated according to the linear theory and obtained experimentally shows that in determining the position of the center of an attached vortex we can use the values of the coefficient of the pressure center and the derivative of the coefficient of lifting force in the root section obtained from the linear theory.

Then, for a wing with a symmetrical profile, by finding the indeterminacy in the second term of expression (1), we get for a zero angle of attack

$$\overline{X}_{п}=C_{д.л.т}+\frac{\left(\frac{dm_{zнн}}{d\alpha}\right)_{\alpha=0}}{\left(\frac{dC_{yk}}{d\alpha}\right)_{\alpha=0}\frac{2rb}{s}},$$

where 2r is the span of an equivalent attached vortex of constant intensity.

As our second hypotheses for wings which are rectangular and elliptical in the layout we assume that the span of the attached vortex is equal to the mean geometric span of the wing, i.e.,

$$2r = \frac{s}{b}.$$

Experiments conducted to determine the zone of vorticity near the tips of the wings and spectra obtained in a hydrodynamic tunnel confirm this hypotheses.

Now, let us assume for wings of a small aspect ratio an elliptical distribution of circulation with respect to span, i.e., we will assume that

$$\left(\frac{dC_{yk}}{d\alpha}\right)_{\alpha=0} = \frac{4}{\pi}\left(\frac{dC_y}{d\alpha}\right)_{\alpha=0}.$$

Then, we get the working formula for determining the distance between the center of the attached vortex and the leading edge:

$$\overline{X}_n = C_{\pi_{\text{л.т}}} + \frac{\left(\frac{dm_{z\text{нн}}}{d\alpha}\right)_{\alpha=0}}{\frac{4}{\pi}\left(\frac{dC_{y\text{л.т}}}{d\alpha}\right)} C_{\pi_{\text{л.т}}} + \frac{2\frac{k_2}{sb}}{\frac{4}{\pi}\left(\frac{dC_{y\text{л.т}}}{d\alpha}\right)}.$$

Calculation methods developed in the book by S. M. Belotserkovskiy [1] enable us to determine all values contained in this formula for the case of movement near a free interface at large Froude numbers, i.e., under the condition that on the free surface disturbed velocities which are parallel to the surface will be equal to zero. Figure 1 shows the dependences of coefficients X_n for a rectangular wing with λ = 0.25 as a function of the reverse value for immersion $\bar{h}=\frac{\eta}{l}$ (here η is the immersion of the leading edge of the wing, l - wing span).

In Fig. 1 we see that as immersion of the wing decreases the center of the attached vortex first shifts toward the leading edge of the wing, then begins to move toward the trailing edge. This is explained by the fact that the coefficient of the pressure center according to the linear theory is only slightly dependent on loading; the derivative of the coefficient of the moment of inertial nature (expressed as the coefficient of the attached mass k_{21}) decreases as loading decreases. Here this decrease is first very intense, then the moment coefficient stabilizes. The coefficient of the derivative of lifting force decreases as loading decreases, although this decrease is especially intense on the interface itself. However, it is primarily the descending branches of curves $x_{\pi}(\frac{1}{\bar{h}})$ which have practical value, since at extremely small values of $\bar{h}$ continuous flow is no longer realized.

In order to satisfy the boundary condition of the equality to zero of induced velocities which are parallel to the undisturbed surface, taking into account here the downwash β of free vortices, we must place over the interface a fictitious vortex, which is a mapping of the lower vortex relative to the undisturbed surface, as shown in Fig. 2.

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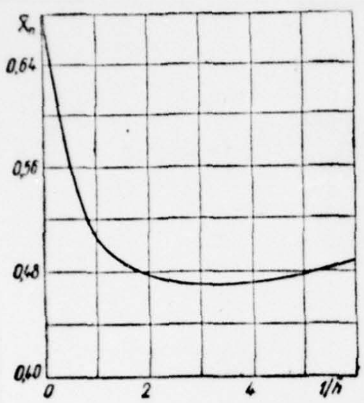

Fig. 1.

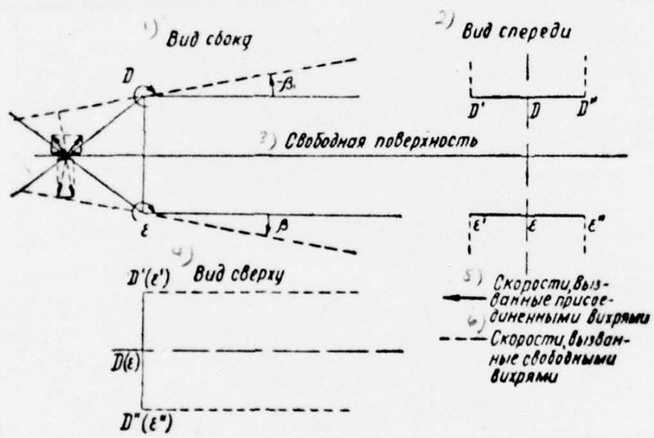

Fig. 2.

Key: (1) Side view, (2) Front view, (3) Free surface, (4) Top view, (5) Velocities induced by attached vortices, (6) Velocities induced by free vortices.

The intensity of the -shaped vortex is determined from the condition of satisfying the Chaplygin-Zhukovskiy postulate of the convergence of streams at a trailing point on the root section of a wing. The velocities induced at this point should be determined not only from the lower -shaped vortex, but also from the fictional upper vortex.

In keeping with the above, let us place a rectangular wing of small aspect ratio under the free surface such that in the presence of attack angle α the leading edge of the wing will have immersion (Fig. 3). The lower attached vortex is placed at distance x_n from the leading edge. Then, the coordinate of point A for the system of coordinates related to the upper attached vortex will be

(2)
$$x_D = \frac{\overline{CD}}{b} = \frac{(1-x_n)\cos\alpha}{\cos\beta} - [\sin\alpha + 2\eta + x_n \sin\alpha + (1-\bar{x}_n)\cos\alpha \operatorname{tg}\beta]\sin\beta;$$
$$y_D = \frac{\overline{AC}}{b} = -[\sin\alpha + 2\bar{\eta} + \bar{x}_n \sin\alpha + (1-x_n)\cos\alpha \operatorname{tg}\beta]\cos\beta.$$

In formulas (2) the lines above x and indicate that these linear dimensions refer to wing span b. The cosine of angle DAE

(3)
$$\cos\delta = \frac{\bar{x}_D^2 + \bar{y}_D^2 + (1-x_n)^2 - 4(\bar{\eta} + \bar{x}_n \sin\alpha)^2}{2\sqrt{\bar{x}_D^2 + \bar{y}_D^2}(1-\bar{x}_n)}.$$

The velocity induced at point A along the normal to the chord by

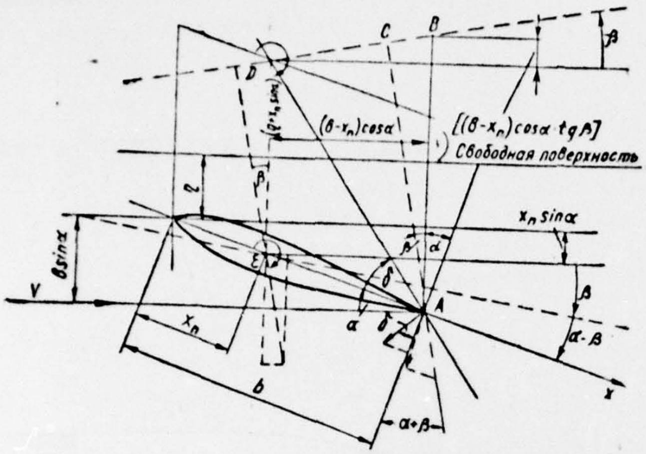

Fig. 3.

Key: (1) Free surface.

attached vortex D'D",

(4) $$(w_1)_D = \frac{w_{1D}}{v} = -\frac{C_{y0}}{4\pi}\frac{N_2\cos\delta}{\sqrt{\bar{x}_D^2+\bar{y}_D^2}\sqrt{\bar{x}_D^2+\bar{y}_D^2+\left(\frac{\lambda}{2}\right)^2}},$$

where $C_{y_0} = \frac{2\Gamma}{vb}$ is the dimensionless coefficient of the intensity of the -shaped vortex.

The velocity induced at point A along the normal to the chord by a pair of free vortices emerging from the attached vortex,

(5) $$(\bar{w}_2)_D = \frac{w_{2D}}{v} = -\frac{C_{y_0}}{4\pi}\frac{N_2}{\bar{y}_D^2+\left(\frac{\lambda}{2}\right)^2}\times \left[1+\frac{\bar{x}_D}{\sqrt{\bar{x}_D^2+\bar{y}_D^2+\left(\frac{\lambda}{2}\right)^2}}\right]\cos(\alpha+\beta).$$

The velocity induced at point A along the normal to the chord from attached vortex E'E" and from the pair of free vortices emerging from this attached vortex, will be

(6) $$(\bar{w}_1)_E + (w_2) = -\frac{C_{y_0}}{4\pi}\left\{\frac{\lambda/2}{(1-x_n)\sqrt{(1-x_n)^2+\left(\frac{\lambda}{2}\right)^2}} + \frac{\frac{\lambda}{2}\cos(\alpha-\beta)}{(1-x_n)^2\sin^2(\alpha-\beta)+\left(\frac{\lambda}{2}\right)^2}\left[1+\frac{(1-x_n)\cos(\alpha-\beta)}{\sqrt{(1-\bar{x}_n)^2+\left(\frac{\lambda}{2}\right)^2}}\right]\right\}.$$

The dimensionless coefficient of the intensity of the Π-shaped vortex is determined from the condition of satisfying the Chaplygin-Zhukovskiy postulate at point A of the root section of the wing:

(7) $$(\bar{w}_1)_D + (\bar{w}_2)_D + (\bar{w}_1)_E + (\bar{w}_2)_E + \sin\alpha = 0.$$

Hence

(8) $$C_{y_0} = \frac{4\pi\sin\alpha}{\begin{aligned}&\frac{\lambda/2}{(1-\bar{x}_n)\sqrt{(1-\bar{x}_n)^2+\left(\frac{\lambda}{2}\right)^2}} + \frac{\lambda/2\cos(\alpha-\beta)}{(1-\bar{x}_n)^2\sin^2(\alpha-\beta)+\left(\frac{\lambda}{2}\right)^2}\times\\ &\times\left[1+\frac{(1-\bar{x}_n)\cos(\alpha-\beta)}{\sqrt{(1-\bar{x}_n)^2+\left(\frac{\lambda}{2}\right)^2}}\right]+\\ &+\frac{\lambda/2}{\sqrt{\bar{x}_D^2+\bar{y}_D^2}\sqrt{\bar{x}_D^2+\bar{y}_D^2+\left(\frac{\lambda}{2}\right)^2}}\cos\delta+\\ &+\frac{\lambda/2}{\bar{y}_D^2+\left(\frac{\lambda}{2}\right)^2}\left[1+\frac{\bar{x}_D}{\sqrt{\bar{x}_D^2+\bar{y}_D^2+\left(\frac{\lambda}{2}\right)^2}}\right]\cos(\alpha+\beta)\end{aligned}}$$

The downwash at points E' and E" are determined from the relationship of the vertical velocity component v_y to the horizontal velocity component v_x at points E' and E".

The velocity induced by the attached vortex D'D" will be horizontal

$$(9) \qquad (w_{1x})_D = -\frac{C_{y_0}}{8\pi}\frac{\lambda}{2(\bar\eta+\bar x_n\sin\alpha)\sqrt{4(\bar\eta+\bar x_n\sin\alpha)^2+\lambda^2}}.$$

The two free vortices which emerge from the detached vortex D'D" give us the horizontal

$$(10) \qquad (\bar w_{2x})_D = \frac{C_{y_0}}{8\pi}\frac{\lambda\sin\beta}{4(\bar\eta+\bar x_n+\sin\alpha)^2\cos^2\beta+\lambda^2}\times \times\left[1-\frac{2(\bar\eta+\bar x_n\sin\alpha)\sin\beta}{\sqrt{4(\bar\eta+\bar x_n\sin\alpha)^2+\lambda^2}}\right]$$

and vertical components of velocity

$$(11) \qquad (\bar w_{2y})_D = \frac{C_y}{8\pi}\frac{\lambda\cos\beta}{4(\bar\eta+\bar x_n\sin\alpha)^2\cos^2+\lambda^2}\times \times\left[1-\frac{2(\bar\eta+\bar x_n\sin\alpha)\sin\beta}{\sqrt{4(\bar\eta+\bar x_n\sin\alpha)^2+\lambda^2}}\right].$$

The free vortex which emerges from the attached vortex at point B' gives us the horizontal velocity component

$$(12) \qquad (\bar w_{2x})_B = -\frac{C_{y_0}}{8\pi}\frac{\sin\beta}{\lambda}$$

and the vertical velocity component

(13) $$(\overline{w}_{2y})_E = \frac{C_{y_0}}{8\pi}\frac{\cos\beta}{\lambda}.$$

By adding the vertical (11) and (13) and horizontal velocities of the impinging flow v with the horizontal velocities (9), (10), and (12), we get, bearing in mind the smallness of angle β (tg β = sin β = β and cos β = 1),

(14) $$\beta = \frac{V_y}{V_x} = \frac{\frac{C_{y_0}}{8\pi}\left\{\frac{\lambda}{4(\overline{\eta}+\overline{x}_n\sin\alpha)^2+\lambda^2}\times\left[1-\frac{2(\overline{\eta}+\overline{x}_n\sin\alpha)\beta}{\sqrt{4(\overline{\eta}+x_n\sin\alpha)^2+\lambda^2}}\right]+\frac{1}{\lambda}\right\}}{1-\frac{C_{y_0}}{8\pi}\left\{\frac{\lambda}{2(\overline{\eta}+\overline{x}_n\sin\alpha)\sqrt{4(\overline{\eta}+\overline{x}_n\sin\alpha)^2+\lambda^2}}-\frac{\lambda\beta}{4(\overline{\eta}+\overline{x}\sin\alpha)^2+\lambda^2}\times\left[1-\frac{2(\overline{\eta}+\overline{x}_n\sin\alpha)\beta}{\sqrt{4(\overline{\eta}+\overline{x}_n\sin\alpha)^2+\lambda^2}}\right]+\frac{\beta}{\lambda}\right\}}.$$

The coefficient of intensity of the -shaped vortex is determined according to formulas (8) and (14) by subsequent statements. In order to calculate coefficient C_{y_0} in the first approximation we use the angle of downwash of the free vortices β in the zero approximation.

After determining C_{y_0} in the first approximation, dependence (14) is used to find the angle of downwash β in the first approximation. From this angle, according to formula (8), coefficient of the second approximation is calculated etc.

Figures 4 and 5 show the results of the indicated calculations from the I to V approximations, respectively, for a wing with an aspect ratio of λ = 0.25 and relative immersion of $\bar{h}=\frac{\eta}{l}=1{,}7$ ($\bar{\eta}=\frac{\eta}{b}=\bar{h}\lambda=0{,}425$). From the figures it is apparent that in calculating C_{y_a} at attack angles of up to 15° the third approximation is sufficient. At attack angles of 25° five approximations are required.

As the zero approximation for the downwash angle of free vortices for the first calculation it is convenient to take β = (1/4) α, while for subsequent calculations - β values obtained for another (closer) immersion.

For determining the normal force which acts on a thin wing we must determine the longitudinal components of the velocities induced by free vortices E' and E" and also by the -shaped vortex D'D" in the central section of the attached vortex.

The velocity induced by free vortices E' and E" in the central section of the attached vortex

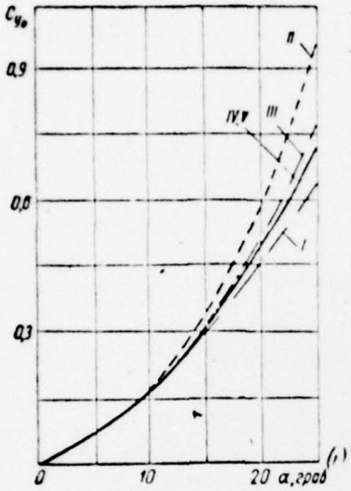

Fig. 4.

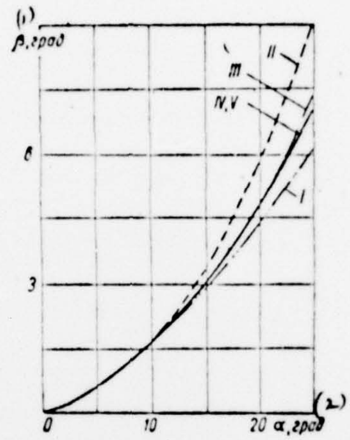

Fig. 5.

Key: (1) α, deg.

Key: (1) β, deg, (2) α, deg.

(15) $$(\bar{w}_{2x_1})_E = \frac{C_{y_0}}{2\pi\lambda}\sin(\alpha-\beta).$$

Then we calculate the longitudinal component of the velocity induced by attached vortex D:

(16) $$(\bar{w}_{1x_1})_D = -\frac{C_{y_0}\cos\alpha\lambda}{16\pi(\bar{\eta}+\bar{x}_n\sin\alpha)\sqrt{4(\bar{\eta}+\bar{x}_n\sin\alpha)^2+\left(\frac{\lambda}{2}\right)^2}}.$$

Finally, the longitudinal component of the velocity induced by free vortices D' and D"

(17) $$(\bar{w}_{2x_1})_D = \frac{C_{y_0}\lambda}{8\pi}\frac{\sin(\alpha+\beta)}{4(\bar{\eta}+\bar{x}_n\sin\alpha)^2\cos^2\beta+\left(\frac{\lambda}{2}\right)^2}\times \times\left[1-\frac{2(\bar{\eta}+\bar{x}_n\sin\alpha)\sin\beta}{\sqrt{4(\bar{\eta}+\bar{x}_n\sin\alpha)^2+\left(\frac{\lambda}{2}\right)^2}}\right].$$

Bearing in mind that on the line of attached vortex E we find the longitudinal component of the dimensionless velocity of the impinging flow, equal to cos α, and using the N. Ye. Zhukovskiy theorem, we find an expression for the coefficient of normal force of a thin wing:

(18) $$C_{y_1} = C_{y_0}[\cos\alpha + (\bar{w}_{2x_1})_E + (\bar{w}_{1x_1})_D + (\bar{w}_{2x_1})_D].$$

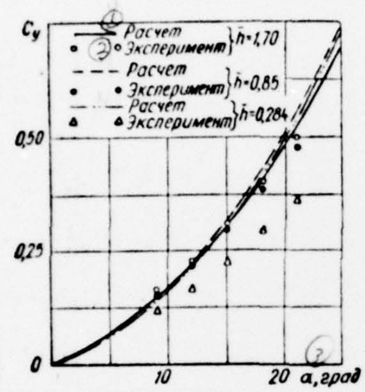

Fig. 6.
Key: (1) Calculation, (2) Experiment, (3) α, deg.

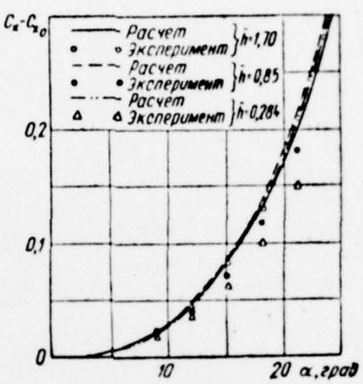

Fig. 7.
Key: (1) Calculation, (2) Experiment, (3) α, deg.

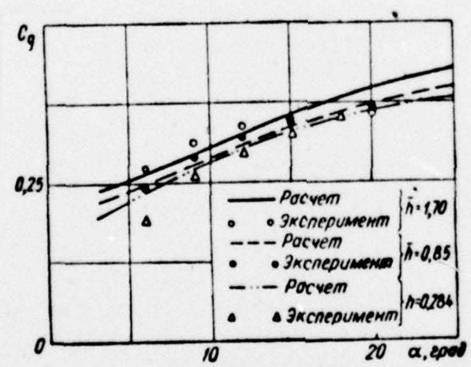

Fig. 8.

Key: (1) Calculation, (2) Experiment, (3) α, deg.

For thin wings, as a result of separation of the flow on the leading edge, there is no suction force, and, by projecting the coefficient of the normal force onto the velocity axes, we get for lifting force

(19) $$C_y = C_{y_1}\cos\alpha$$

and for the coefficient of increased resistance, caused by the presence of the angles of attack,

(20) $$C_x - C_{x_0} = C_{y_1}\sin\alpha.$$

The coefficient of the longitudinal moment relative to the leading edge equals the sum of coefficients of the moment of vortex nature and the moment of inertial nature, and in the coordinate system used in Fig. 3 is written in the form of

(21) $$m_z = m_{z\text{в}} + m_{z\text{ин}} = C_{y_1}\bar{x}_n - \frac{k_2}{sb}\sin 2\alpha.$$

Finally, the dimensionless coordinate of the center of pressure

(22) $$C_n = \frac{x_y}{b} = \frac{m_z}{C_{y_1}} = \bar{x}_n - \frac{k_2}{sb}\,\frac{\sin 2\alpha}{C_{y_1}}.$$

Figures 6-8 show the results of calculating the coefficients of lifting force, coefficients of increased resistance, and coefficients of the center of pressure of a thin wing with an aspect ratio of λ = C.25 for several relative immersions.

Theoretical curves for the smallest relative immersion h = 0.284 lie above the experimental points, which can be explained by the presence in this immersion of the air-filled vortex filaments flow past.

The substantial nonlinearity of the moment coefficient results in a situation where the center of pressure moves rather rapidly toward the trailing edge of the wing as the angle of attack increases.

It is interesting to note that the two-fold decrease in relative immersion, in a case where the coefficients of lifting forces remain virtually unchanged, has a noticeable effect on the position of the center of pressure. As relative immersion decreases the center of pressure moves toward the leading edge, also confirmed by the experiment.

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H300 USAICE (USAREUR)	1		
P005 ERDA	2		
P055 CIA/CRS/ADD/SD	1		
NAVORDSTA (50L)	1		
NAVWPNSCEN (Code 121)	1		
NASA/KSI	1		
544 IES/RDPO	1		
AFIT/LD	1		