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Determination of the Oswald efficiency factor at the aeroplane design preliminary stage

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Abstract

A new engineering approach to the determination of Oswald's span-efficiency factor results in good convergence of calculated and experimental data. The proposed method allows to define its value more reasonably and to analyse possible ways of improving it.

Oswald's span-efficiency factor is a generalised parameter connected with an aircraft's aerodynamic efficiency. Specifically, for a parabolic drag polar, there exists a dependency:

$$\left(\frac{L}{D}\right)_{\max} = \frac{1}{2}\sqrt{\frac{\pi e A}{C_{D0}}}. \tag{1}$$

The Oswald efficiency factor ***e*** reflects the aeroplane lifting properties deterioration caused by the distortion of an elliptical lift distribution and accounts for the non-ellipticity of the lift distribution, the increase of profile drag of the wing, fuselage, tailplane, nacelles and various interference effects with angle of attack [1].

At the initial stage of the design the Oswald efficiency factor is rather difficult to compute. Nevertheless, several authors have tried to derive its analytical relation to the aeroplane geometrical parameters. However, the results are still not accurate enough.

The research covers only a steady flight regime area with linear dependency of lifting force on the angle of attack. It includes only aeroplanes of classical layout (not biplanes or other extraordinary schemes) and does not take into account the lifting force of tailplanes or canards.

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Nomenclature

λ	taper ratio (c_{tip}/c_{root})
Λ_{LE}	leading edge sweepback angle
ρ	radius of leading edge cross section
A	wing aspect ratio ($= b^2/S_{ref}$)
b	wing span
c	wing chord
C_D	drag coefficient
C_{D0}	zero lift drag coefficient
C_{Di}	induced drag coefficient
$C_{L\alpha}$	wing lift curve slope for incompressible flow
d	fuselage diameter at the wing attachment zone
D	drag
e	Oswald efficiency factor
k_F	fuselage cross section shape factor
L	lift
$(L/D)_{max}$	maximum lift-to-drag ratio
S_e	leading edge suction force, % of theoretical
S_{ref}	reference wing area
t	thickness of an airfoil
$\bar{W}_f$	relative fuel capacity

Real values of Oswald's efficiency factor for several aeroplanes are given in Table 1. As can be seen from the data Oswald efficiency factor values are within the limits from 0.6 to 0.85. It means that taking $e = 0.85$ instead of actual $e = 0.6$ gives an error in the lift-to-drag ratio equal to 1.5–2 that is not acceptable even at the preliminary design stage.

The Oswald efficiency factor is influenced by

- the wing planform (its aspect and taper ratio, leading edge sweepback angle);
- presence of a fuselage, nacelles and other components.

This influence is illustrated in Fig. 1 for three aeroplanes (F-104, F-18A and Falcon-900) with different aspect ratio but with approximately equal leading edge sweepback angle and taper ratio. It follows from this figure that with the aspect ratio decreasing at constant leading edge sweepback angle and taper ratio, the Oswald efficiency factor for a wing alone increases and tends to unity while for the aeroplane as a whole the converse is true. This paradox can be explained by the fact that the fuselage causes a loss in lift, leading to an irregular spanwise lift distribution. This example clearly shows that the fuselage is essential and its size should be taken into account even at the early stage of design.

Oswald's efficiency factor is influenced also by the wing leading edge cross-sectional shape which in the case of a correct profile can enforce the suction at the leading edge zone and decrease drag

Table 1
Oswald efficiency factor values for some airplanes

Aircraft	C_{D0}	A	e	$(L/D)_{max}$
Boeing 247D	0.0212	6.550	0.75	13.5
Douglas DC-3	0.0249	9.140	0.75	14.7
Piper J-3 "Cub"	0.0373	5.810	0.75	9.6
Beechcraft D17S	0.0348	6.840	0.76	10.8
Cessna "Cardinal" RG	0.0223	7.660	0.63	13
AntonovAn-12	0.0322	11.85	0.64	15.3
Ilyushin 11-18	0.0240	10.00	0.80	16.3
Yakovlev Yak-40	0.0240	9.000	0.82	15.5
Martin B-26F	0.0314	7.660	0.75	12
McDonnell F-4 "Phantom"	0.0217	2.820	0.70	8.8
Lockheed-Martin F-22 "Raptor"	0.0150	2.370	0.82	10.1
Sukhoi Su-27	0.0185	3.480	0.71	11.6
Mikoyan-Gurevich MIG-29	0.0225	3.430	0.85	10.1
Mikoyan-Gurevich MIG-AT	0.0238	5.350	0.61	12.6

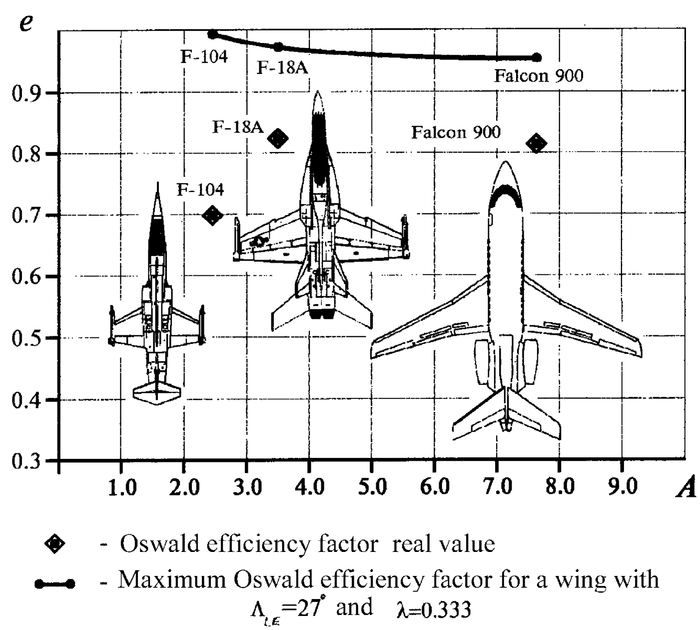

Fig. 1. Influence of the fuselage on the airplane Oswald efficiency factor.

due to lift. This leading edge suction force effect on a relative fuel capacity is illustrated in Fig. 2. It can be seen that for the hypothetical tailless layout with a small wing aspect ratio ($A = 2$) the increase of the leading edge suction force from 0 to 0.9 is followed by the increase in Oswald efficiency factor up to 0.83 and the corresponding max lift-to-drag ratio rise, that produces a benefit

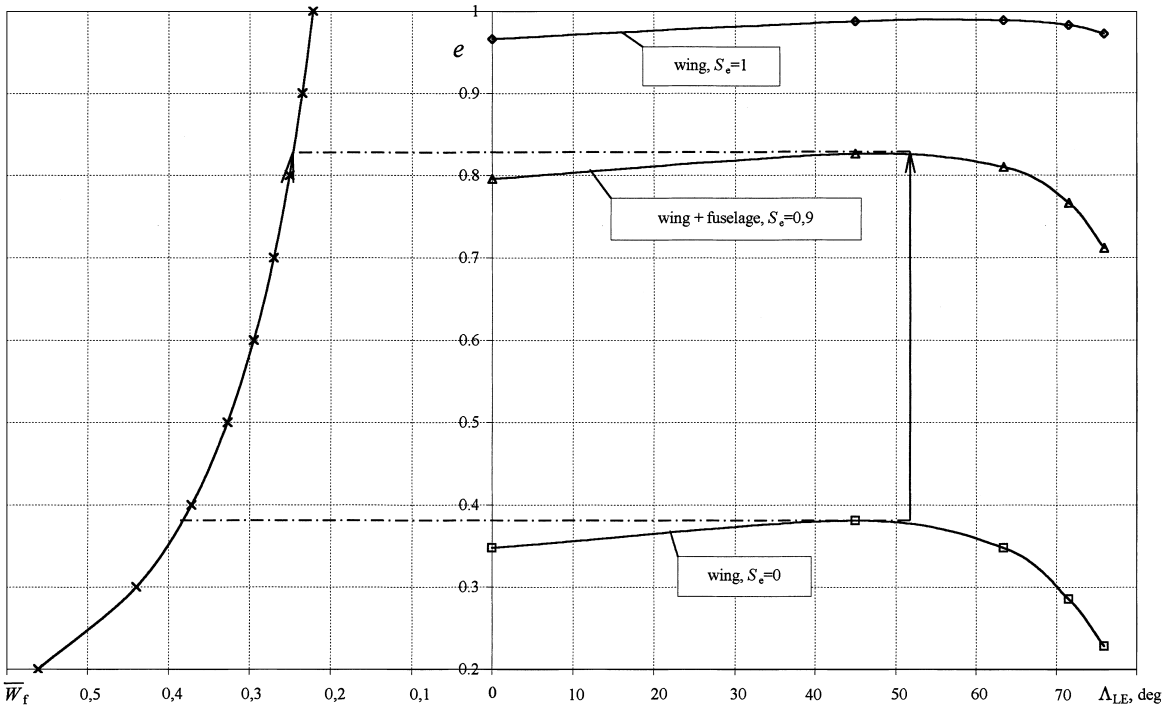

Fig. 2. Effect of the leading edge suction force on a relative fuel capacity.

in fuel capacity at a given range of flight up to $\sim 13\%$. So, the correct shape of the leading edge allows to increase distinctly the fuel efficiency.

It should be noted that the wing deformation is also important for Oswald's efficiency factor but it can be considered at the later design stages.

Let us express the Oswald efficiency factor for an aeroplane as

$$e = e_w k_F, \tag{2}$$

where

$$e_w = \frac{e_{w/S_e=1}\, e_{w/S_e=0}}{S_e e_{w/S_e=0} - (1 - S_e) e_{w/S_e=1}}, \tag{3}$$

denotes the Oswald efficiency factor reflecting the difference between the actual wing circulation distribution and an elliptical one, and the influence of the leading edge suction force, and k_F is a correction factor to incorporate the influence of a fuselage cross section shape on the induced drag.

Thus the following tasks should be solved for calculating the aeroplane is Oswald efficiency factor:

- wing Oswald efficiency factor calculation with full implementation of the leading edge suction force $e_{w/S_e} = 1$;

Table 2
Coefficients for Eq. (5)

λ	a_1	a_2	a_3	a_4	a_5
1.0	0.5269	0.1230	0.0441	– 0.0057	0.0032
0.5	0.4919	0.1413	0.0157	0.0054	0.0061
0.2	0.5160	0.1176	0.0156	– 0.0023	0.0071
0.0	0.5694	0.1202	0.0083	– 0.0028	0.0081

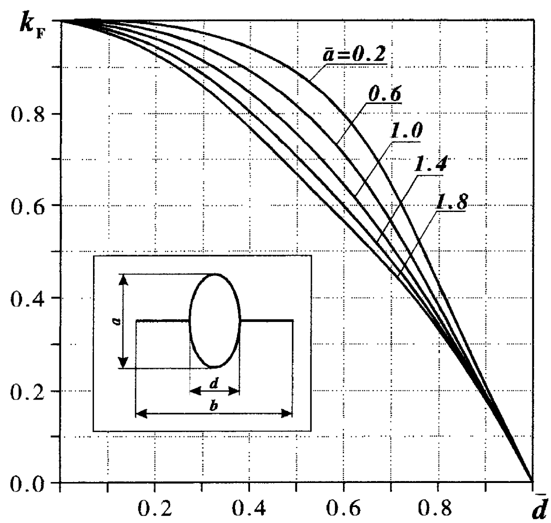

Fig. 3. Cross section shape factor for the elliptical fuselages.

- wing Oswald efficiency factor calculation at zero leading edge suction force $e_{w/S_e=0}$;
- calculation of the relative leading edge suction force S_e;
- calculation of the fuselage cross section shape factor k_F.

Solutions of all mentioned tasks are considered below in brief.

Wing Oswald efficiency factor calculation with full implementation of the leading edge suction force is based on a vortex model of a simple shape wing flow.

$$e_{w/S_e=1} = \frac{C_{L\alpha}}{\beta A}\tilde{y}^{e}_{cg}, \tag{4}$$

where $\tilde{y}^{e}_{cg} = 2\bar{y}^{e}_{cg}/b$ is the relative distance between the trailing vortex centres of gravity in the Treffetz plane; and $\beta = \sqrt{1-M^2}$ the compressibility correction.

Empirical dependencies with variable coefficients were obtained for calculation of the distance between the vortices:

$$\tilde{y}^{e}_{cg} = a_1 + a_2\beta A + A\tan\Lambda_{LE}(a_3 + a_4\beta A + a_5 A\tan\Lambda_{LE}) \tag{5}$$

Values of the coefficients for different taper ratios are given in the Table 2.

Table 3
Airplane geometrical parameters

Aeroplane	Geometrical parameters						
	A	λ	Λ_{LE} (deg.)	t/c	ρ (m)	S (m^2)	$\bar{d}$
MIG-AT	5.66	0.357	5	0.13	0.076	17.67	0.221
MIG-29	3.43	0.323	42	0.05	0.019	38	0.298
Su-27	3.48	0.294	42	0.05	0.014	62	0.3
F-22	2.37	0.263	42	0.05	0.034	78	0.32
An-12	11.85	0.357	9	0.16	0.097	121.7	0.108

Table 4
Considered flight regimes

Aeroplane	Flight conditions	
	M	H (m)
MIG-AT	0.6	5000
MIG-29	0.85	5000
Su-27	0.85	5000
F-22	0.85	5000
An-12	0.4	4000

Wing Oswald efficiency factor calculation at zero leading edge suction force is defined with a formula

$$e_{w/S_e=0} = \frac{C_{L\alpha}}{\beta \pi A}. \tag{6}$$

Precise calculation of the leading edge suction force is difficult at the stage of preliminary design. That is why a special algorithm was developed based on the simplified empirical dependencies corresponding to the data obtained by Schemensky [2]. Comparison of the calculation results with empirical data for flat wings with symmetrical profiles have shown good convergence in the researched range of characteristics. It allows to recommend the following approximate expression (applicable at relative leading-edge curvatures $\bar{\rho} = \rho/t = 0.9 - 2.5\%$) for the S_e initial evaluation

$$S_e = 0.974 - 0.0976 \ \exp\left[-0.456\left(\frac{A\lambda}{\cos \Lambda_{LE}}\right)\right] \tag{7}$$

Calculation of the fuselage cross section shape factor is carried out with the help of a graphical dependency in the form $k_F = k_F(\bar{d}, \bar{a})$, where $\bar{d} = d/b$ is the relative fuselage diameter at the zone of wing attachment, and $\bar{a} = a/d$ the relative fuselage cross section size.

An example of such a dependency for fuselages with elliptic cross section is presented in Fig. 3.

Table 5
Calculation results and experimental data

Aeroplane	Parameter	***e*** calculated by Eq. (2)	Experimental data
MIG-AT	e	0.82	0.61
	C_{D0}	0.022	0.0238
	$(L/D)_{max}$	12.8	12.6
MIG-29	e	0.87	0.85
	C_{D0}	0.0225	0.0225
	$(L/D)_{max}$	10.13	10.1
Su-27	e	0.86	0.71
	C_{D0}	0.0185	0.0185
	$(L/D)_{max}$	11.3	11.6
F-22	e	0.87	0.82
	C_{D0}	0.015	0.015
	$(L/D)_{max}$	10.34	10.1
An-12	e	0.73	0.64
	C_{D0}	0.028	0.0322
	$(L/D)_{max}$	15.5	15.3

The proposed method for the Oswald efficiency factor calculation was tested on several known aircraft samples. The results presented in the supplement allow to conclude that this engineering method is completely applicable to the preliminary design problems.

Supplement: The Oswald efficiency factor calculation method proposed by the authors has been tested on several aeroplanes: MIG-AT, MIG-29, Su-27, F-22 and An-12 with geometrical parameters given in Table 3.

Calculations have been carried out only for one steady flight regime for each aeroplane with parameters listed in Table 4.

Calculation results and experimental data are presented in Table 5.

References

[1] Torenbeek E. Synthesis of subsonic airplane design. Delft: Delft University Press, 1982. p. 148.
[2] Schemensky RT. Empirical methods, vol. 1, AFFDL-TR-73-144.

Obituary

O.S. Samoylovich

The first author of this article sadly died before the completion of the final version. The following summary of his career characterizes him as a distinguished aircraft designer and academic.

Oleg Sergeevich Samoylovich (1926–1999) was a Deserving Person of Science and Engineering of the Russian Federation, Doctor of Technical Sciences and Professor. He graduated in 1957 with the highest marks from the Moscow Aviation Institute (MAI) on the specialization "Airplane Design". During his main industrial career (1957–1985) O.S. Samoylovich was associated with the design bureau installed by P.O. Sukhoy, where he started as an engineer and subsequently became Deputy Chief Designer and Chief Designer. As Deputy General Designer he executed direct management over the conceptual design of the T-4, Su-24, Su-25 and Su-27 aircraft. He was in possession of 26 USSR invention certificates and five foreign patents (USA, United Kingdom, France and Korea).

O.S. Samoylovich was a recognized leader in the development and introduction into industrial practice of computer-aided design methods. He worked as the USSR Aviation Ministry Chief Designer on airplane CAD systems, he was a member of an interdepartmental commission on design automation and of the USSR Academy of Science Council on the methodology of artificial intelligence. Since O.S. Samoylovich combined his industrial work with academic activities as a professor in the Central Institute for the USSR Aviation Ministry (aimed at improving the qualification of workers at the ministry) and in the Moscow Aviation Institute, he published 16 academic and scientific articles. He was also member of two Expert Councils of the Russian Federation Higher Attestation Committee supervising the preparation and defence of dissertations for the doctoral degree.

O.S. Samoylovich delivered invited lectures on aircraft design at the Massachusetts Institute of Technology (1991), the University of Michigan (1992), the University of Tokyo (1994) and the Technical University of Berlin (1994). He was the recipient of five USSR decorations, and the following distinctions were awarded to him: the USSR Lenin Prize Laureate (1976) and USSR Council of Ministers Premium Laureate (1981).

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