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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

ON THE EQUATION OF RELATIVE WEIGHTS OF AN AIRCRAFT

by

N. A. Fomin

FOREIGN TECHNOLOGY DIVISION

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EDITED MACHINE TRANSLATION

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ABSTRACT

Some applications of the relative weights of an aircraft and the relative weight coefficients are investigated. The entire weight (or mass) G_c of an aircraft is composed of the terms

$$G_c = G_k + G_{su} + G_t + G_{snaj}.$$

The four G terms on the right-hand side of this equation denote, respectively, the structural weight of the aircraft, the weight of all power equipment, the weight of fuel, and the weight of the crew, equipment, and payload. Dividing both sides of the total weight equation by G_c yields four relative weight coefficient terms whose sum is unity. These coefficients are useful in determining, among other factors, certain performance and economy characteristics of cruising speeds. The author concludes that the equation of relative weights is the basic equation which establishes the relationships between the flying characteristics of an aircraft and its parameters. Orig.art. has: 18 formulas and 2 figures.

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
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.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE 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}
rot	curl
lg	log

ON THE EQUATION OF RELATIVE WEIGHTS OF AN AIRCRAFT

N. A. Fomin

The total weight (mass) of an aircraft is composed of several parts with distinguishing features:

$$G_c = G_K + G_{cy} + G_T + G_{\text{cэг}}, \tag{1}$$

where G_K, G_{cy}, G_T, and $G_{\text{cэг}}$ are, respectively, the structural weight of the aircraft, the weight of all power equipment, the weight of fuel, and the weight of systems, equipment, crew, and payload.

The G_K depends on a number of parameters of the aircraft and its parts, mainly on wing loading p, wing aspect ratio λ, coefficient of rated overload n_Λ, the weight of the aircraft, etc.

The G_{cy} depends on the weight of the engine, the value of thrust of the aircraft, the weight of tanks, etc.

The G_T depends on specific fuel consumption, range of the aircraft, its cruising speed, weight of the aircraft, etc.

The $G_{\text{cэг}}$ in general is not directly connected with the parameters and characteristics of the aircraft or its weight and is determined in accordance with technical requirements, depending upon the type of aircraft and its function.

If we divide both sides of (1) by G_C we will obtain the equality

$$1 = \bar{k}_к + \bar{k}_{су} + \bar{k}_т + \bar{k}_{снг}, \qquad (2)$$

to which attention was turned for the first time by V. F. Bolkhovitdinov [1]; it is called the equation of relative weights of an aircraft, where $\bar{k}_к = \frac{G_к}{G_с}$, $\bar{k}_{су} = \frac{G_{су}}{G_с}$, $\bar{k}_т = \frac{G_т}{G_с}$, $\bar{k}_{снг} = \frac{G_{снг}}{G_с}$ are the relative weights of the structure, propulsion system, fuel, equipment, crew, and loads. The relative weight of the propulsion system can be presented as

$$\bar{k}_{су} = \bar{t}_0 \cdot r_0, \qquad (3)$$

where $\bar{t}_0$ is the starting trust-to-weight ratio of an aircraft with a turbojet engine and r_0 is the specific weight of propulsion system.

The relative weight of the fuel load $\bar{k}_T$ can be expressed as follows: for a given duration t' of flight of an aircraft with turbojet engine:

$$\bar{k}_т = s\psi\bar{t}_0 C_{e_0} \Delta t', \qquad (4)$$

and for a given range L_{max} of flight of aircraft with a turbojet engine at $M_{кр}$ = const and $H_{кр}$ = var,

$$\bar{k}_т = sR\psi C_{e_0} \frac{L_{max}\sqrt{c_{x_0} D_0}}{M_{кр}} + u, \qquad (5)$$

where s = 1.15-1.20 – a coefficient considering aeronautical margin,

$R = 0.00145$, if $\bar{k}_T \leq 0.3$,

$R = 0.001$, if $0.3 < \bar{k}_T < 0.5$,

$u = 0.0009\ H_{кр}$, if $\bar{k}_T \leq 0.3$ and $M < 2.0$,

$u = 0,0009\ H_{кр} + \psi\xi C_{T_0} \bar{t}_0 t''$, if $0.3 < \bar{k}_T < 0.5$ and $M > 2.0$,

$u = 0.0009\ H_{кр} + 0.09$, if $0.3 < \bar{k}_T < 0.5$ and $M < 2.0$,

ψ – coefficient, considering the influence of speed of flight on specific fuel consumption,

ξ – coefficient considering the influence of speed of flight on engine thrust,

Δ – relative air density,

t' – time of flight (for Formula 4),

t'' – time of acceleration [takeoff run] (for Formulas 4 and 5),

C_{T0} – specific fuel consumption,

c_{x_0} – drag coefficient at $c_y = 0$, $D_0 = c_{x_i}/c_y^2$

$M_{\text{кр}}$ – Mach number corresponding to cruising speed,

$H_{\text{кр}}$ – mean value of cruising altitude.

Using the equation of relative weights (2) and the given equalities (3)-(5) it is possible to obtain expressions for "available" thrust-to-weight ratio $\bar{t}_{0p}$ (turbojet engine):

$$\bar{t}_{op} = \frac{1 - \bar{k}_{\text{к}} - \bar{k}_{\text{сът}}}{r_0 + s\psi\xi C_{T_0} \Delta t'}, \tag{6}$$

if duration of flight, is given, and

$$\bar{t}_{op} = \frac{1 - \bar{k}_{\text{к}} - \bar{k}_{\text{сът}}}{r_0} - \frac{sR\psi C_{T_0} L_{max} \sqrt{c_{x_0} D_0}}{r_0 M_{\text{кр}}} - \frac{a}{r_0}, \tag{7}$$

if range is given; they permit judging about the character of the influence of one or another parameter on the "available" thrust-to-weight ratio of the aircraft. It is necessary to keep in mind that use of the formula

$$\bar{t}_0 = \frac{P_{0\,\text{су}}}{G_c}.$$

is meaningful only for designed aircraft; to find $\bar{t}_0$ for projected aircraft in this way is impossible, since G_c is a quantity dependent of P_{0cy}. Analysis of (6) and (7) permits judging about the qualitative influence of different parameters on $\bar{t}_{0p}$.

Quantitatively this influence can be determined with help of the formulas

$$\bar{t}_0' = \bar{t}_0 \frac{1-\varepsilon_1 \bar{k}_\text{к}}{1-\bar{k}_\text{к}},$$

$$\bar{t}_0' = \bar{t}_0 \frac{1-\varepsilon_2 \bar{k}_\text{т}}{1-\bar{k}_\text{т}},$$

$$\bar{t}_0' = \bar{t}_0 \frac{1-\varepsilon_3 \bar{k}_\text{т}}{1-\bar{k}_\text{т}}, \qquad (8)$$

$$\bar{t}_0' = \bar{t}_0 \frac{1}{1+\bar{k}_\text{су}(\varepsilon_4 - 1)},$$

where $\varepsilon_1 = \frac{\bar{k}_\text{к}'}{\bar{k}_\text{к}}$, $\varepsilon_2 = \frac{C_{T_0}'}{C_{T_0}}$, $\varepsilon_3 = \frac{L_{max}'}{L_{max}}$, $\varepsilon_4 = \frac{r_0'}{r_0}$; $\bar{t}_0'$ is a new value of $\bar{t}_0$, obtained if $\bar{k}_\Pi$ is increased by $\Delta\bar{k}_\Pi$. If we increase thrust-to-weight ratio $\bar{t}_0$, installing on the aircraft two engines instead of one, at L_{max} = const, $G_\text{сэг}$ = const and $\bar{k}_\text{к}' = \varepsilon_1 \bar{k}_\text{к}$:

$$\bar{t}_0' = \frac{1-(\bar{k}_\text{к}\varepsilon_1 + \bar{k}_\text{т})}{\frac{0{,}5\,\bar{k}_\text{сэг}}{\bar{t}_0} + r_0\varepsilon_4}.$$

The formulas in (8) can easily be obtained from the equation of relative weights:

$$\bar{k}_1 + \bar{k}_2 + \bar{k}_3 + \bar{k}_4 = 1.$$

If $\bar{k}_1$ is increased by $\Delta\bar{k}_1$, then $\bar{k}_2$, $\bar{k}_3$, and $\bar{k}_4$ will be changed and the equation will take the form

$$\bar{k}_1 + \Delta\bar{k}_1 + \bar{k}_2' + \bar{k}_3' + \bar{k}_4' = 1.$$

Then $\bar{k}_n' = \bar{k}_n\left(1-\frac{\Delta\bar{k}_1}{1-\bar{k}_1}\right)$, $\Delta\bar{k}_n = -\bar{k}_n \frac{\Delta\bar{k}_1}{1-\bar{k}_1}$, $G_0' = G_0 \frac{1}{1-\frac{\Delta\bar{k}_1}{1-\bar{k}_1}}$.

Setting $P'_{cy} = P_{cy}$, we will obtain

$$\bar{t}_0' = \bar{t}_0\left(1 - \frac{\Delta\bar{k}_1}{1 - \bar{k}_1}\right)$$

or

$$\bar{t}_0' = \bar{t}_0\left(1 - \frac{\Delta\bar{k}_{\text{н}}}{1 - \bar{k}_{\text{н}}}\right) \qquad (9)$$

For actual realization of an aircraft with a prescribed M number of horizontal flight to be possible requires first of all equality of "available" and "required" thrust-to-weight ratio. The latter can be expressed on the basis of the equalities

$$M_{max} = 0{,}0148\sqrt{\frac{p\bar{t}_0\xi}{c_x}}$$

and

$$M_{\text{кр}} = 0{,}012\sqrt{\frac{p\bar{t}_0\xi}{c_{x_0}}}.$$

Thus,

$$\bar{t}_{0\text{п}} = \frac{4650\, M_{max}^2 c_x}{\xi p}, \text{ if } M_{max} \text{ is given,}$$

or $\qquad (10)$

$$\bar{t}_{0\text{п}} = \frac{6060\, M_{\text{кр}}^2 c_{x_0}}{\xi p}, \text{ if } M_{\text{кр}} \text{ is given.}$$

Equating $\bar{t}_{0p}$ and $\bar{t}_{0\text{п}}$, we have

$$\frac{1 - \bar{k}_{\text{н}} - \bar{k}_{\text{car}}}{r_0 + s\psi\xi\Delta C_{T_0} t'} = \frac{4650\, M_{max}^2 c_x}{\xi p} \qquad (11)$$

and

$$\frac{1-\bar{k}_{н}-\bar{k}_{сот}}{r_0}-\frac{sR\psi C_{T_0} L_{max}\sqrt{c_{x_0} D_0}}{r_0 M_{кр}}-\frac{u}{r_0}=\frac{6950 M_{кр}^2 c_{x_0}}{\xi p}. \qquad (11')$$

From this we will obtain equations with respect to M which enabling us to determine that value of M_{max} or $M_{кр}$ which is possibly and practically realizable for an aircraft with the selected parameters:

$$\bar{k}_{н},\ \bar{k}_{сот},\ p,\ c_{x_0},\ C_{T_0},\ r_0,\ L_{max} \text{ or } t'.$$

$$4650 M_{max}^2 c_x (r_0 + s\psi\xi\Delta C_{T_0} t') - \xi p (1 - \bar{k}_{н} - \bar{k}_{сот}) = 0, \qquad (12)$$

$$6950 M_{кр}^2 c_{x_0} - M_{кр}\xi p (1 - \bar{k}_{н} - \bar{k}_{сот} - u) + sR\psi\xi C_{T_0} L_{max} p\sqrt{c_{x_0} D_0} = 0. \qquad (12')$$

Any greater value of M can be found with decrease

$$L_{max},\ \bar{k}_{н},\ r_0,\ C_{T_0},\ c_{x_0},\ t'.$$

Any smaller value of M will provide the possibility of increasing

$$L_{max},\ \bar{k}_{сот},\ t'.$$

Solving the first equation (12), we will obtain for M at a given duration t'

$$M_{max}=\sqrt{\frac{\xi p (1-\bar{k}_{н}-\bar{k}_{сот})}{46500 c_x (r_0 + s\psi\xi C_{T_0}\Delta t')}} \qquad (13)$$

Note. For determination of the value of M_{max} it is possible to use graphic procedure. Pursuing several values M, determine ξ, c_x, and ψ and by (13) calculate M_{max}. Construct a curve in coordinates $M_{зад}$ and $M_{ист}$ (Fig. 1); M_{max} can be found from its intersection with a straight line drawn from the origin of the coordinates at an angle of 45°; $M_{зад}$ and $M_{ист}$ must be taken in the same scale.

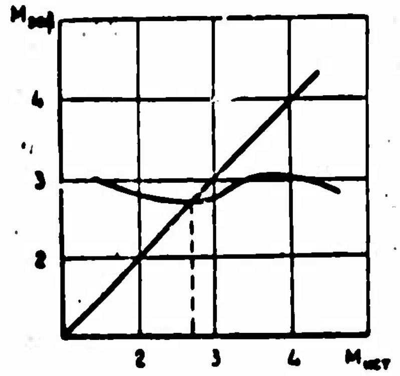

Fig. 1. Example of graphic solution of equation (13).

The quantity $M_{кр}$ can be found also, using a graphic solution (Fig. 2), taking the following functions for plotting of curves:

$$6950\, M_{кр}^{3} c_{x_0} r_0 = \theta_1$$

and

$$M_{кр}\,\xi p\,(1 - \bar{k}_s - \bar{k}_{сот} - u) - \\ - sR\psi C_{v_0} L_{max}\,\xi p \sqrt{c_{x_0}}\, D_ц = \theta_2. \qquad (14)$$

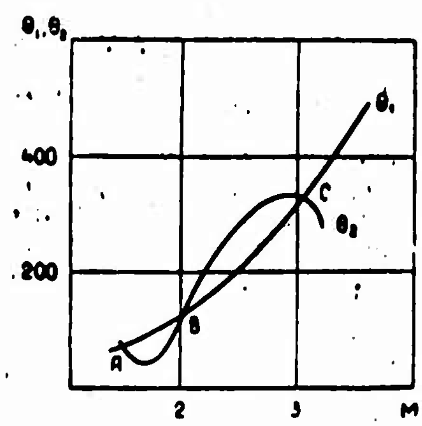

Fig. 2. Example of graphical solution of equation (14). In points A, B, and C a given value of L_{max} can be obtained, other things being equal and with corresponding values of $M_{кр}$ and t_0. Between points A and B the given value of L_{max} and other things being equal cannot be obtained.

The point of intersection of these curves on the graph in coordinates M, θ_1, and θ_2 will determine the unknown value $M_{\text{кр}}$.

From (13) and (14) it is easy to see that to each M, at constant values of all parameters, there will correspond its own $\bar{k}_{\text{к}}$, which can be called the "necessary" specific weight of the structure of the aircraft. Using (11) and (11'), it can be expressed:

$$\bar{k}_{\text{к}_\text{н}} = 1 - \bar{k}_{\text{сот}} - \frac{4650\, M^2_{\max}\, c_x}{\xi p}\left(r_0 + s\dot{\psi}\Delta C_{T_0}\, t'\right) \qquad (15)$$

or

$$\bar{k}_{\text{к}_\text{н}} = 1 - \bar{k}_{\text{сот}} - \frac{6950\, M^2_{\text{кр}}\, c_{x_0}\, r_0}{\xi p} - \frac{sR\psi C_{T_0}\, L_{\max}\sqrt{c_{x_0} D_0}}{M_{\text{кр}}}. \qquad (16)$$

The "available specific weight of the structure $\bar{k}_{\text{кр}}$ is the weight which can be obtained at given strength of the structure and selected parameters of wing, fuselage, etc. It can be expressed by these formulas:

for aircraft with sweptback wing,

$$\bar{k}_{\text{кр}} = \left(0{,}027\, \varphi\mu\, n_A \frac{G_c^{\frac{1}{3}}}{\cos\chi}\sqrt{\frac{\lambda}{p}} + \frac{5{,}5}{p}\right)(1 + \beta_1\lambda_\Phi\, m + \beta_2) + 0{,}065, \qquad (17)$$

for aircraft with delta wing of small aspect ratio,

$$\bar{k}_{\text{кр}} = \left(0{,}049\, \varphi\mu\, n_A\, G_c^{1/3}\sqrt{\frac{\lambda}{p}} + \frac{5{,}5}{p}\right)(1 + \beta_1\lambda_\Phi\, m + \beta_2) + 0{,}065. \qquad (18)$$

Here G_C – in m total weight (mass) of aircraft,

β_1 = 0.07-0.09 – for supersonic aircraft,

β_1 = 0.065-0.08 – for heavy subsonic and transonic aircraft,

β_1 = 0.08-0.115 – for transonic transport aircraft,

$m = 1$ – for supersonic aircraft,

$n = 1.2\text{–}1.3$ – for subsonic and transonic aircraft,

$\beta_2 = 0.27$ – for supersonic aircraft,

$\beta_2 = 0.15$ – for subsonic and transonic aircraft,

$\varphi = 1 - \frac{3(\eta+1)}{\eta+2}(\bar{z}_1\varepsilon_1\bar{k}_\tau + \bar{z}_2\varepsilon_2\bar{k}_{c\tau})$ – coefficient of relief of wing,

η – wing taper,

ε_1 – portion of fuel in wing,

$\bar{z}_1$ – relative coordinate in fractions of semispan of CG of fuel in wing,

$\bar{\varepsilon}_2$ – portion of weight of propulsion system in wing,

$\bar{z}_2$ – relative coordinate in fractions of semispan of CG of power plant.

The major problem of designing reduced to ensuring the equality of "available" $\bar{k}_{\text{кр}}$ to "necessary" $\bar{k}_{\text{кп}}$.

On the basis of the material outlined above it can be concluded that the equation of relative weights of an aircraft is the fundamental equation with which the relationships between the flight characteristics of an aircraft and its parameters are established.

Literature

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