COMPLEX CRITERIA ON EVALUATION OF SUBSONIC AIRCRAFT TRANSPORTATION CAPABILITIES

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As the areas of application of heat engines utilizing energy of liquid or gas hydrocarbon extended, the searching of criteria for assessment of engine efficiency as well as searching of possibility to increase the efficiency of fuel energy utilizing was also extended. From the point of view of theoretical aspect of the stated above issue, the outstanding scientists. Carno made a real breakthrough in this area and managed to describe the ideal cycle of heat engine operation in comparison with which there appeared an objective probability to evaluate the efficiency of fuel energy utilized by real heat engines. The second aspect (in spite of occasional sensational statements concerning alternative energy sources or about principal decrease of the fuel flow rate due to the generation of permanent mixtures added with water etc.) has not been realized in practice yet.

In the process of mutual work with outstanding Russian scientist and aircraft designer Bartini R. L. [1,2] and on basis of analysis of the activities accomplished in the area of transport vehicle issues [for example,3,4] by many other specialists, it became obvious that the great invention of Carno is applicable only for the engine. At the same time when it is used, a lot of factors depending upon engine parameters, aerodynamic and weight characteristics of the vehicle influence the resulting effect – transportation of cargo. For example, if an elegant auto was provided with large tractor wheels and was driven fast, the unreasonableness of fuel combustion will be obvious (even if the installed engine had high Efficiency Coefficient). Besides, the cost of the auto is the evidence of gross chargers made by design and manufacture companies. The stated above charges comprise also the cost of the fuel consumed during operation. More over, taking into consideration problems with environmental situation there is a necessity to include into complex assessment of transportation vehicle efficiency the advantages and disadvantages of the vehicle (from environmental point of view).

Substantiations for evaluation of the transportation vehicle performance level were published in numerous works written by

Beriev specialists: а) in comparison with ideal power values for cargo transportation (energy efficiency criterion *BaF*) and б) in comparison with obtained world-wide indexes for specific transportation criterion (criterion of structural efficiency – $\overline{U}$). More over, $\overline{U}$ criterion (for seaplanes) was added in order to take into consideration the probability of aircraft operation when afloat. It allowed to compare seaplanes between each other and it became inexpedient to make attempts and add the parameters of aerodrome planes (landplanes) [5…11 etc.] to the evaluation of the seaplane properties.

The purpose of this report is to make the specialists familiar with the specified complex criteria *BaF*, $\overline{U}$ and to compare them with the most wide-spread (for transport and passenger aircraft) criterion of fuel energy efficiency [10]:

$$T_e = \frac{m_g L_g}{m_t} \tag{1}$$

In (1): T_e – fuel energy efficiency;

m_t – mass of consumed fuel;

m_g – cargo weight;

L_g – range of cargo transportation.

With the help of analysis (1) it is possible to make the following conclusion for a lot of aircraft: it's value depends upon the takeoff mass and flight speed of the aircraft, that is why it's wrong to compare aircraft having different specified parameters by means of equation (1). That is why the maximum dependence T_e from takeoff mass was defined (for example for transport aircraft it is equal to $T_e = 0{,}5m_0^{0{,}44}$) in relation to the values (according to the stated above dependence) relative efficiency of utilization of fuel energy $\overline{T}_e$ was defined which can be used also for aircraft energy efficiency comparison and ranking.

Criterion of energy efficiency *BaF* is similar to the commonly-known Coefficient of Efficiency (КПД) in mechanics – η [12]. It represents the ratio of power $\overline{A}_S$ necessary for transportation of cargo of the defined mass with the required speed to the supplied power *W*:

$$BaF = \eta = \frac{\overline{A}_s}{\overline{W}} \tag{2}$$

Magnitude of the friction force *F* that is being overcome is equal to:

$$F = m_g f \tag{3}$$

This magnitude is applicable for the simplest model of cargo transportation (but not for transport vehicle!) with the mass m_g along the fixed surface with friction coefficient *f*.

Power $\overline{A}_S$ required for cargo transportation with the speed of V is the following:

$$\overline{A}_S = FV = m_g fV \tag{4}$$

Friction coefficient *f* (for aircraft) is the following:

$$f = \frac{1}{K}, \tag{5}$$

where *K* – cruising aerodynamic quality of the aircraft with mass equal to m_g is consequently simplified in the following way:

$$\overline{A}_S = m_g V / K \tag{6}$$

But this mechanical model (simple for defining of $\overline{A}_S$) is approximate because K magnitude has to be taken in accordance with statistical data for the aircraft of the type that is being analyzed in this report.

More exact is the model of «Equivalent body» (EB) where cargo is put into the drop-shaped body И-721 [13] having minimum aerodynamic resistance during flight in the analyzed subsonic mode (fig. 1).

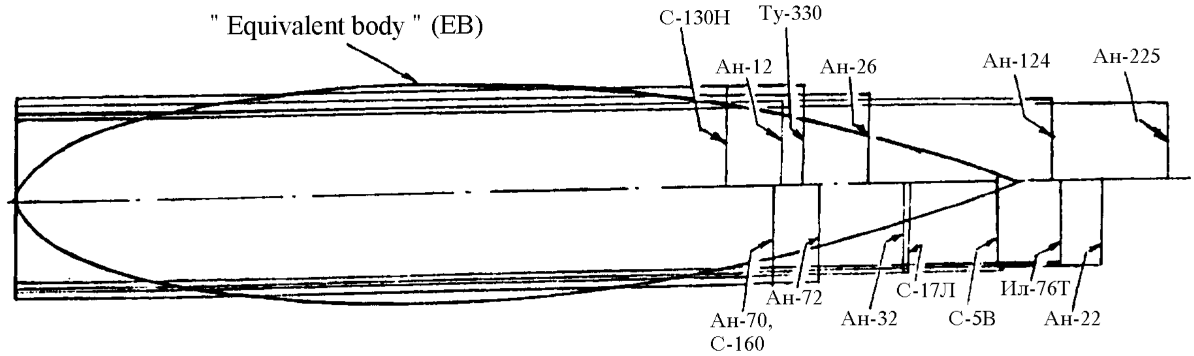

Fig. 1. Integrated dimensions of cargo compartments of transportation jet aircraft and of the unified EB

As soon as indivisible cargo volume defines the volume of EB with the length and length section diameters values depending upon the volume, we define the drag resistance of EB under the speed V and air density ρ at the altitude of cruising flight. We multiply the EB drag resistance by the speed and get the ideal power value for transportation of cargo $\overline{A}_S$:

$$\overline{A}_S = (Q_{x\,et})_g V = 1{,}813 \cdot 10^{-5} \cdot C_x \cdot \rho \cdot V^3 \cdot E_g^{0{,}66} \qquad (7)$$

In (7) : $(Q_{x\,et})_g$ – EB drag resistance;

C_x – coefficient of EB drag resistance (for EB И-721 magnitude is $C_x = 0{,}032$);

E_g – indivisible cargo volume.

To make it clear that it is not possible to get the power for cargo transportation less than $\overline{A}_S$ let's take a group of passengers as cargo. The common minimum cargo volume which defines the volume, dimensions and required power for EB transportation will be acquired if the passengers are arranged inside of the EB in horizontal position. Undoubtedly, it's not convenient for passengers to be conveyed like this in real life. In this case EB and consequently $\overline{A}_S$ will increase. And, similarly, if structural elements of the aircraft – fuselage, wing, power plants, etc. are taken into consideration, the value of the required power will increase. But for the purposes of Efficiency Coefficient calculation we need only the minimum value of $\overline{A}_S$. This value is the ideal value defined in accordance with (6).

If the quantity of fuel consumed by the Power Plant of the aircraft increases, the value of the supplied power $\overline{W}$ will also increase. The quantity of fuel consumed by the Power Plant depends upon the specified "make-weight" for transportation of the aircraft itself together with crew, fuel and cargo inside (but not for transportation of cargo separately), of real aerodynamic quality of the aircraft and weight efficiency of the structure and also of the effectiveness of power plant engines. But we mentioned only fuel energy consumption (characterized by hourly consumption of fuel) for operation of power plant during cruising flight. Definition of $\overline{W}$ should also comprise the expenses on creation of aircraft, tests, preparation and serial production, development of the required infrastructure for operation, as well as expenses on investigation of the issue concerning the advantages and disadvantages of aircraft-environment mutual interaction, etc. If we assume that aircraft cost Z includes all the specified above expenses and fuel energy consumption per one aircraft then we can define the quantity of fuel Q_{ET} equivalent to the consumed fuel by means of dividing the cost by the specific fuel cost during $\overline{C}_Z$ calculation:

$$Q_{ET} = Z / \overline{C}_Z \qquad (8)$$

If we divide this value by aircraft total flying time T, we will get the equivalent additional hourly fuel consumption $\overline{Q}_{ET}$ that is taken into account in the value $\overline{W}$:

$$\overline{W} = Aq\left[\frac{Q_{ET}}{T} + \overline{m}_T\right] = Aq\left[\overline{Q}_{ET} + \overline{m}_T\right] \qquad (9)$$

Here: A – mechanical heat equivalent,

q – fuel thermal power.

Thus, the dependency for defining *BaF* criterion in accordance with the diagram using EB will be the following [8]:

$$BaF = \frac{\overline{A}_S}{\overline{W}} = 1{,}813 \cdot 10^{-5} \cdot C_x \cdot \rho \cdot V^3 \cdot E_g^{0{,}66} \Big/ Aq\left[\overline{Q}_{ET} + \overline{m}_T\right] \qquad (10)$$

BaF is complex technical and economic criterion able to define the following: to what extent ideal values of power required for transportation in the specified conditions are less than real consumptions of fuel energy taking into consideration creation, operation and utilization of the aircraft and infrastructure for it's usage as well as mutual interaction with the environment at all stages of transportation system existence. Due to this criterion we can make conclusions concerning energy efficiency of the aircraft: the more is *BaF*, the higher is it's radiant efficiency not only for one separate flight but for the whole society. The stated above criterion helps to reveal «weak points» of the transportation vehicle during service life.

Simplified value *BaF* at $\overline{A}_S$ determined using equation (6) will be as follows:

$$BaF = \frac{m_g V}{KAq[\overline{Q}_{ET} + \overline{m}_T]} \qquad (11)$$

Having multiplied both parts of the equation (11) by the time of the cruising flight τ and having reduced the constant values to the N coefficient, we will get the following:

а) Numerator: product $m_g V\tau = m_g L_g m_g$ expressing the virtual operation on cargo transportation within the criterion of fuel energy efficiency (1);

б) Denominator: hourly fuel consumptions-flight time product. Flight time is equal to the quantity of the consumed fuel $m_T = [\overline{Q}_{ET} + \overline{m}_T]\tau$;

в) value $N = [KAq]^{-1}$.

Magnitude (11) taking into consideration (1) is as follows:

$$BaF = N\frac{m_g L_g}{m_t} = NT_e \qquad (12)$$

As it can be seen the developed *BaF* criterion coincides with the traditional T_e criterion but it is evident that it is much more profound for estimation of aircraft energy efficiency because in the equation $m_T = [\overline{Q}_{ET} + \overline{m}_T]\tau$ includes wider scope of fuel energy consumption that is unavoidable during implementation of the transportation vehicle into transport system. Fuel energy consumption will comprise also everything that is connected with service life of the vehicle taking into consideration mutual interaction with the environment. What concerns more exact version (in accordance with EB diagram), *BaF* criterion (due to comparison of the actual fuel energy consumption with ideal consumption required for cargo transportation) is substantial for evaluation of energy efficiency not only for aircraft but also for automotive vehicles of different types. More over, the approximated calculations on different types of vehicles indicate the extremely low Efficiency Coefficient of fuel energy utilization as compared with the ideal values (fig. 2).

Generally speaking, fig. 2 shows that increase of the gross production rate is directly connected with the launching mass of the transport vehicles and it leads to the increase of Efficiency Coefficient of their usage, i.e.the efficiency of fuel energy utilization. In other words, large transport vehicles are more economic, than vehicles of less size. And it is not correct to compare, for example, fuel consumption per one passenger at the distance of 100 km for liner A380 and for auto (as it was stated recently by Russian Mass Media as the confirmation of the effectiveness of new aircraft). The problem is that auto can take few passengers and it's fuel consumption should be compared with the consumption of the aircraft having the same weight. So, fuel consumed by the auto (about 2-3 liters per passenger/per every 100 км of the way) is many times less than fuel consumed by the equivalent aircraft.

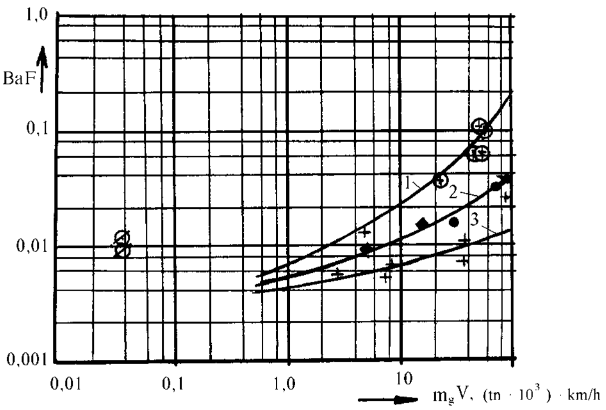

Fig. 2. *BaF* Values (m_gV) for different types of Transport Vehicles (TM):
1,⊕ – water displacement vessel; 2,• – passenger aircraft; 3,+ – military aircraft ;4,♦ – amphibian aircraft; ∅ – autos

Another complex criterion for assessment of transport efficiency of aircraft was obtained out of transportation criterion that had been offered by Bartini R.L. – $\overline{P}$ [14]:

$$\overline{P} = \frac{m_g}{m_0} \cdot V \cdot L_g \qquad (13)$$

(In this equation in addition to the given above markings m_0 – take-off weight of the aircraft).

The accomplished calculation of maximum of the product (m_g L_g) defining the maximum of $\overline{P}$ criterion made possible to reveal the only for each aircraft maximum possible $\overline{P}$ magnitude at values m_g и L_g being optimal for maximum load-carrying capacity mm and the maximum design range of the flight Lm (fig. 3, 4):

$$(m_g)_{opt} = (m_t)_{opt} = 0{,}5m_m \qquad (14)$$

$$(L_g)_{opt} = 0{,}5L_m \qquad (15)$$

(Stated above conclusion coincided with the conclusion of Mr. M.Terry made in accordance with other facts [3]). Taking into consideration items (14, 15) maximum value $\overline{P}$ is converted into:

$$U = 0{,}25\overline{m_0}L_mV \qquad (16)$$

where $\overline{m_0}$ is load ratio, that is ratio of maximum load-carrying capacity m_m (equal to the sum of cargo weight m_g and fuel weight m_T) – takeoff mass m_0.

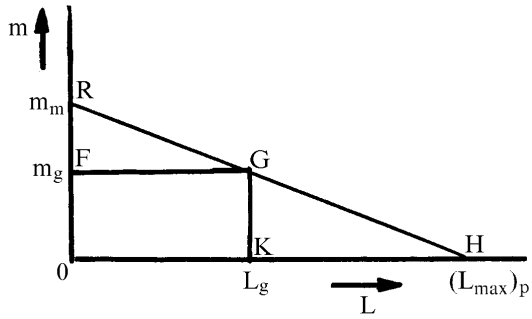

Fig. 3. Linear model of dependence $m_g(L_g,)$ for aircraft

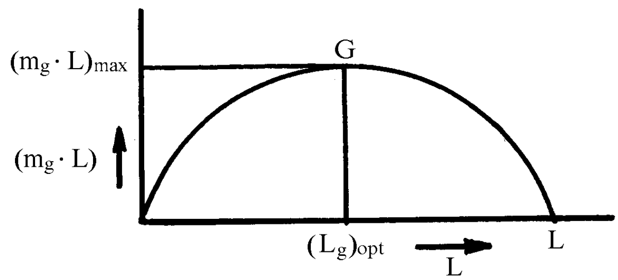

Fig. 4. (m_g L_g) product – L dependence

When applying static values U of real aircraft to the ensemble field «U – m_0», there is a possibility to describe the enveloping design dependence $U_{max} = U(m_0)$ (for each type) in the form of parabola:

$$U_{max} = A(m_0)^{\alpha}, \qquad (17)$$

"Average weighed" dependence U_{nom} (fig. 5 for seaplanes) can be described in the same way.

The obtained envelope curve is criterion U maximum level, obtained by the aircraft construction industry for the period of static parameters processing. In order to define the takeoff mass m_0, we can establish the level of efficiency (in relation to the level specified above) of one or another aircraft using relative values and compare aircraft efficiency level magnitudes between each other regardless of weight:

$$\overline{U}_{LA} = \frac{U}{U_{max}} \qquad (18)$$

Dependency (16) can be also represented finally in the following way:

$$U = 0{,}25\overline{m}_0 L_m V = 0{,}5\overline{m}_0 V T_e \qquad (19)$$

It can be done taking into consideration cargo weight $(m_g)_{opt}$ – optimum fuel weight $(m_T)_{opt}$ equality resulting from the magnitude mm (regardless of specific features of seaplanes).

Thus, as it results from (19), criterion $\overline{U}_{LA}$ evaluates capability of the aircraft to accomplish transportation of cargo more precisely than criterion $\overline{T}_e$ which doesn't include load ratio $\overline{m}_0$ and flight speed V.

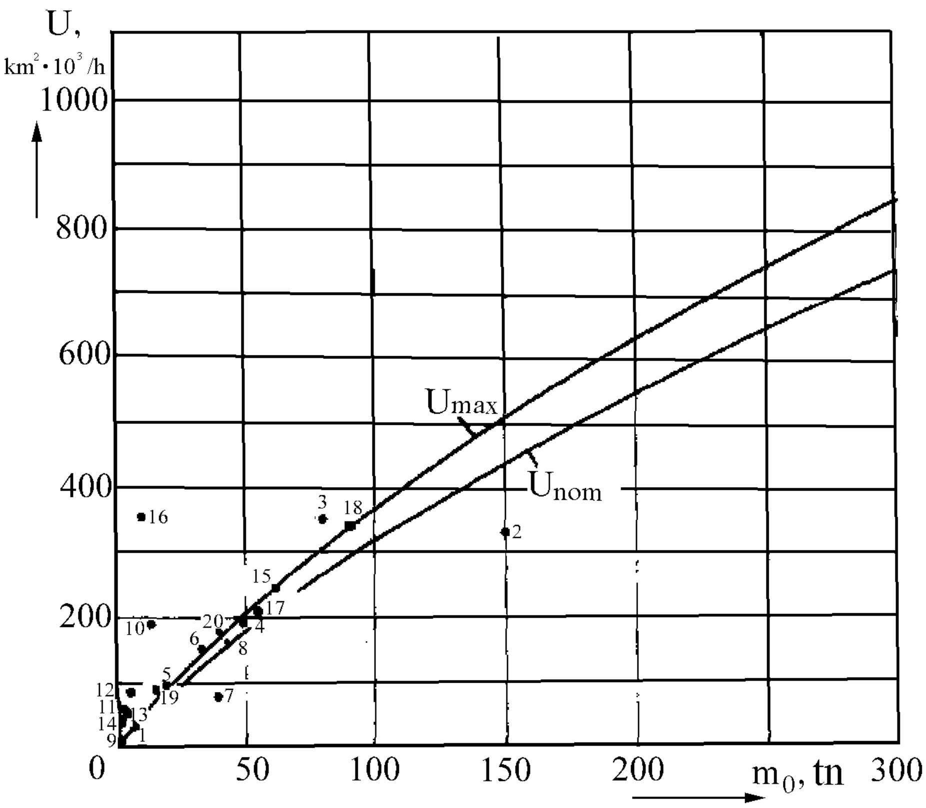

Fig. 5. Results of U criterion calculation for jet and turboprop seaplanes and dependence calculation $U_{max}(m_0)$, $U_{nom}(m_0)$

1 – SR/A1; 2 – SR/45; 3 – XP6M; 4 – Бе-10; 5 – P-1; 6 – Бе-12; 7 – PS-1; 8 – US-1A; 9 – TR1; 10 – Do24A; 11 – «Avalon-680»; 12 – G21C; 13 – Sea-Star; 14 – «Super-Vision»; 15 – XP5Y-1; 16 – «Dolphiner»; 17 – SH-5; 18 – A-40; 19 – CL-415; 20 – Be-200

The identity of equations (16) and (17) allows to resolve one of the most important tasks regarding aircraft pattern synthesis – definition of it's takeoff mass in accordance with the specified parameters of freight flow. Availability of $U_{max} = U\ (m_0)$ relation and calculated takeoff mass allows also to define prototypes of the aircraft intended to be developed.

All the said above proves the fact that Bartini R.L. was extremely penetrating and offered transport criterion.

Here is the conclusion of the materials represented in this report:

1) Criterion of fuel efficiency *Te* is evaluation criterion of the first approximation for the aircraft having similar mass, speed, altitude of the flight and load ratio.

2) Fuel efficiency criterion – T_e (due to it's dependability from aircraft takeoff mass) can be used for approximate establishment and comparison of aircraft technical level by defining it's relation to the maximum design statistic criterion $(T_e)_p$, i. e. by calculation of $\overline{T}_e$.

3) Criterion for evaluation of energy efficiency *BaF* is the most full technical-economic criterion used for assessment of technical level of the aircraft. But economic basis (due to unstable currency rates and aircraft prices as well as other insufficiently systemized charges and lack of methodology for environment interaction assessment, etc.) for calculation of this criterion is not enough yet. That is why it is advisable to use *BaF* criterion at the stages of creation of transport systems (when it is necessary to compare complexes of transport vehicles and infrastructures for their usage).

4) Cargo shipment structural efficiency criterion U and relative criterion $\overline{U}$ for establishing the technical level of the aircraft are more full and scientifically proved than fuel efficiency criterion. Their application allows to evaluate whether aircraft meet modern standard or not as well as to compare aircraft between each other. As statistical information is being collected this criterion is able to become the basis for generation of standard values during airplanes certification.

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