UDK 621.735

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MATHEMATICAL SIMULATION OF FUEL BURN SCHEDULE EFFECT ON AIRPLANE CENTER-OF-GRAVITY POSITION

Formulas to describe shape of fuel tanks arranged in wings, wing center section and fuselage are proposed on the base of wing shape analysis of real transport category airplanes. Methods of fuel burn sequence designation and fuel transfer methods are analyzed. Method accounting ribs with baffle check valves influence on airplane center-of-gravity position is considered. Algorithm for transport category airplane center-of-gravity position calculation depending on current fuel level in tanks and pitch angle, accounting specified number and arrangement of fuel tanks in wings, wing center section and fuselage, fuel burn schedule, and number and arrangement of ribs with baffle check valves is proposed. Basing on this algorithm and its program implementation, calculation of center-of-gravity position in the process of fuel utilization was carried out for some passenger airplanes (Ан-148, B-737-400, A-310, DC-10, B-747). The algorithm proposed can be used for determination of reasonable number and arrangement of ribs with baffle check valves, more complicated mathematical models creation, and also for making course and diploma projects.

Key words: *airplane fuel system, fuel burn sequence, center-of-gravity, center-of-gravity position, fuel tank, fuel feed subsystem, fuel supply subsystem.*

Introduction

Fuel system of modern airplane is one of the most complicated and integrated with its all other systems. Fuel system provides naturally fuel storage and feed to engines at all foreseen flight modes of airplane. In addition it influences substantially airplane stability, controllability, efficiency and service life. Really, as all fuel tanks could not be arranged in airplane center-of-gravity (CG), then airplane CG position will shift with fuel burn. As it is known, relative position of CG and center of pressure determines stability and controllability properties, and, naturally, airplane flight safety. Accounting modern trends of commercial airplanes flight range increase and corresponding increase of relative fuel mass onboard (more than 50 %), CG shift can be rather considerable.

In spite of temporal oil price abatement, the fuel efficiency increase problem remains actual. One of the ways to solve it is the airplane trim drag decrease, which is also determined by the relative position of CG and center-of-pressure. If there are some fuel tanks onboard, then the fuel burn schedule also influences considerably CG position.

The base CG calculation algorithm for airplane with single tank in each wing accounting fuel migration and specified pitch angle was considered in publication [1]. This base algorithm was updated in publication [2] for the purpose of ribs with baffle check valves (RBCV) accounting. Their arrangement optimization under condition of fuel accommodation only in single fuel tank per each wing was considered ibid.

The aim of this publication is development of center-of-gravity position calculation algorithm for airplane with swept-back wings, which carries fuel in both wings, wing central section and fuselage tanks, in the process of fuel utilization at specified pitch angles, accounting specified number and arrangement of RBCV and fuel burn schedule.

Statement of Research Problem

To calculate mass of fuel, located in the integral wing tanks, it is necessary to describe wing shape with enough accuracy.

Analyzing wing shapes of actual passenger and transport airplanes (Fig. 1), it is possible to conclude than they consist of several (from one till four) trapezoidal sections. Taking into account breaks of spars, the number of sections can increase up to five. Leading edge swept-back angle χ_0 and wing anhedral/dihedral angle ψ can change stepwise on the boundaries of the sections. Wing chord $b(z)$, airfoil thickness ratio $\bar{c}(z)$, airfoil setting angle (twisting) $\alpha(z)$, forward $\bar{x}_I(z)$ and aft $\bar{x}_{II}(z)$ spar positions can change linearly within each section. In addition, fuel is usually arranged in cylindrical wing center section, which base shape corresponds to the shape of root rib.

Basing on this analysis, it is possible to propose design model shown in Fig. 2 to describe shape of various wings.

So, to describe wing surfaces, the following expressions can be used

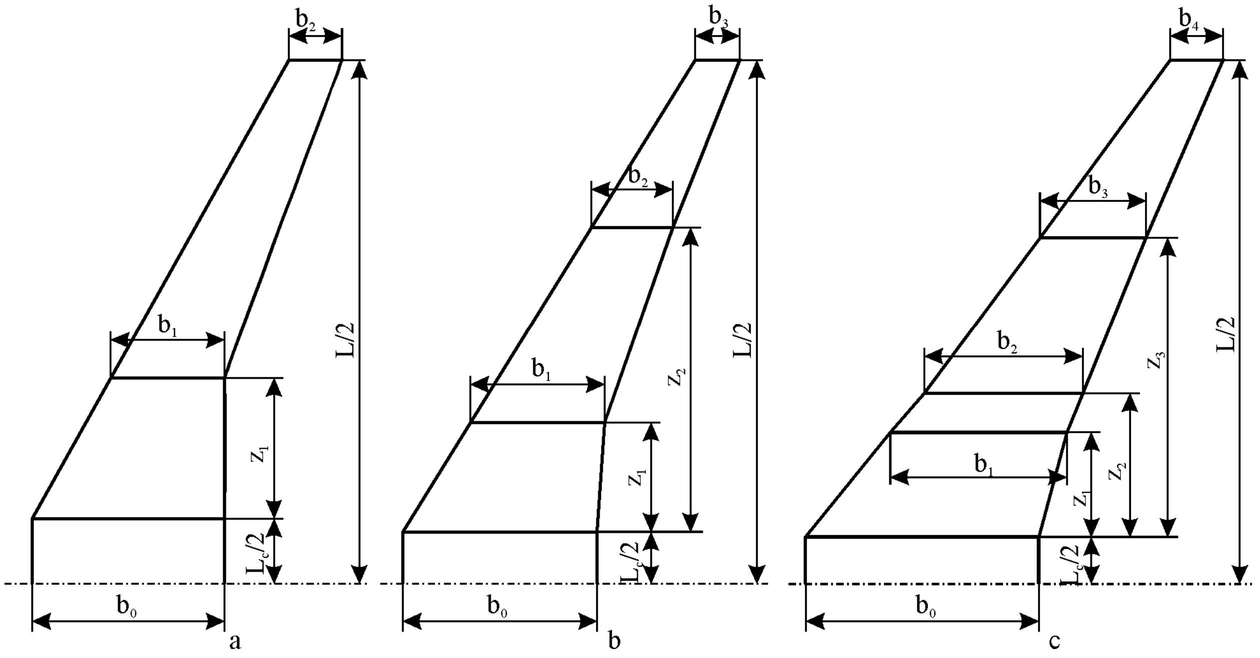


Fig. 1. Examples of wing shape for various airplanes:
a – A-300, A-310, A-320, DC-10; b – A-330, A-340, A-350, B-747; c – A-380

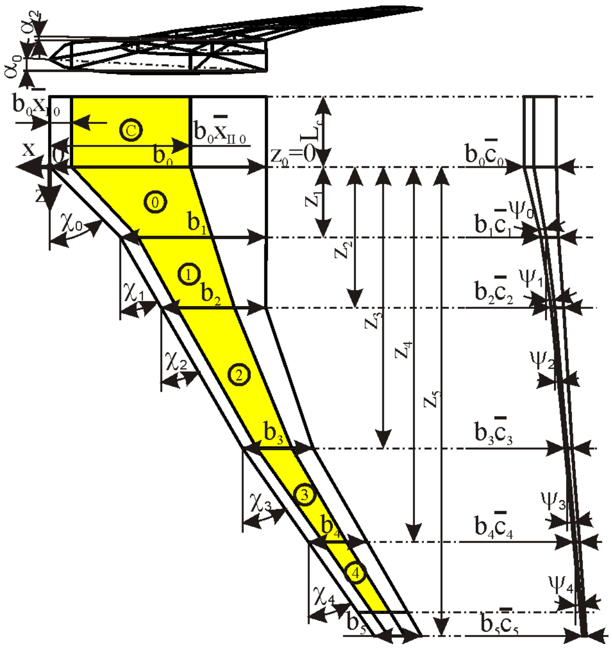


Fig. 2. Design model for wing shape

$$y_{low}(z,x)=y_{mid}(z)-(x-x_0(z))\sin(\alpha(z))+$$
$$+b(z)\bar{y}_{low}\left(\frac{x-x_0(z)}{b(z)}\right)\frac{\bar{c}(z)}{\bar{c}_{type}};$$
$$y_{top}(z,x)=y_{mid}(z)-(x-x_0(z))\sin(\alpha(z))+$$
$$+b(z)\bar{y}_{top}\left(\frac{x-x_0(z)}{b(z)}\right)\frac{\bar{c}(z)}{\bar{c}_{type}}; \qquad (1)$$
$$y_{mid}(z)=\sum_{i=0}^{k}(z_{i+1}-z_i)\tan(\psi_i)+(z-z_k)\tan(\psi_k).$$

where $y_{low}(z,x)$ and $y_{top}(z,x)$ – point coordinates on the top and low wing surfaces; $y_{mid}(z)$ – coordinate of wing middle line without twisting; $x_0(z)$ – coordinate of wing leading edge; $\bar{y}_{low}(\bar{x})$, $\bar{y}_{top}(\bar{x})$ – relative coordinates of specified airfoil points; $\bar{c}_{type}$ – thickness ratio of specified airfoil; k – the section number, in which coordinate hits $z\in[z_k,z_{k+1}]$.

As it is known, to calculate mean aerodynamic chord (MAC) b_a and its longitudinal coordinate x_a, counting from root chord leading edge, the following formulas are used:

$$b_a=\frac{2}{S}\int_0^{L/2}b^2(z)dz, \qquad x_a=\frac{2}{S}\int_0^{L/2}b(z)x_0(z)dz. \qquad (2)$$

where S – wing area; L – wing span.

According to the design model (See Fig. 2), wing chord in i -th section can be presented as follows:

$$b^{(i)}(z)=b_i+\frac{b_{i+1}-b_i}{z_{i+1}-z_i}(z-z_i). \qquad (3)$$

where b_i, b_{i+1} – wing chords in the section boundaries; z_i, z_{i+1} – coordinates of the section boundaries.

Substituting expressions for chord (3) into known formulas (2), we get expressions to calculate MAC and its leading edge coordinate for the considered design model:

$$b_a=\frac{2}{S}\left[\frac{b_0^2L_c}{2}+\frac{1}{3}\sum_{i=0}^{n_{seg}}(z_{i+1}-z_i)\left(b_{i+1}^2+b_{i+1}b_i+b_i^2\right)\right],$$

$$x_a = \frac{1}{3S}\sum_{i=0}^{n_{seg}} \frac{\tan\chi_{0i}}{z_{i+1}-z_i}\Big[b_{i+1}\left(2z_{i+1}^3 - 3z_{i+1}^2 z_i + z_i^3\right) + \\ + b_i\left(2z_i^3 - 3z_i^2 z_{i+1} + z_{i+1}^3\right)\Big]. \qquad (4)$$

where L_c – wing center section span; n_{seg} – number of sections in the considered wing.

Integral fuel tanks are used in majority of cases in wings of modern airplanes. I. e. fuel is placed in inter-spar part of wings. The boundaries of these tanks along airplane axis are usually forward and aft spars only. As the tanks are separated by middle spar in seldom cases only (Ан-22, Ан-124, C-5), it is possible to consider only forward and aft spars as these boundaries.

Spanwise, integral tanks are subdivided by pressurized ribs, which can be located both along air flow, and perpendicularly to one of the spars. As the tanks subdivision by ribs, arranged along air flow, considerably simplifies design model, just this version is considered. In case when the pressurized ribs are placed perpendicularly to a spar, inaccuracy appears which seems insignificant because of small distance from CG along x axis.

Number of integral tanks within one wing in actual wings does not exceed six. Wing center section as a rule includes only single tank or is subdivided into two tanks of equal volume along airplane axis (that does not influence on algorithm, as under airplane symmetry only one wing and a half of wing center section are considered). In some rather seldom cases (Ту-154М, Falcon-900) wing center section can be subdivided into two tanks by middle spar. These cases can be simulated using fuselage tanks.

In fuselages of passenger and transport airplanes, as a rule, bladder-type tanks are installed, which shape corresponds to the shape of standard containers. In seldom cases (usually in airplanes-tankers), rigid tanks in form of circular cylinder are used. Shape of both types tanks can be presented in the view, shown in Fig. 3.

To describe shape of these tanks, the following expressions are proposed:

$$y_{low}^f(z,x) = \\ = \begin{cases} 0; & \left(M \ge \frac{D}{2}\right) \vee \left[\left(M < \frac{D}{2}\right) \wedge \left(z \le \sqrt{MD - D^2}\right)\right] \\ \frac{D}{2} - M - \sqrt{\frac{D^2}{4} - z^2}; & \left(M < \frac{D}{2}\right) \wedge \left(z > \sqrt{MD - D^2}\right) \end{cases};$$

$$y_{top}^f(z,x) = \qquad (5)$$

$$= \begin{cases} H - M; & \left(H \le \frac{D}{2}\right) \vee \left[\left(H > \frac{D}{2}\right) \wedge \left(z \le \sqrt{HD - D^2}\right)\right] \\ \frac{D}{2} - M + \sqrt{\frac{D^2}{4} - z^2}; & \left(H > \frac{D}{2}\right) \wedge \left(z > \sqrt{HD - D^2}\right) \end{cases},$$

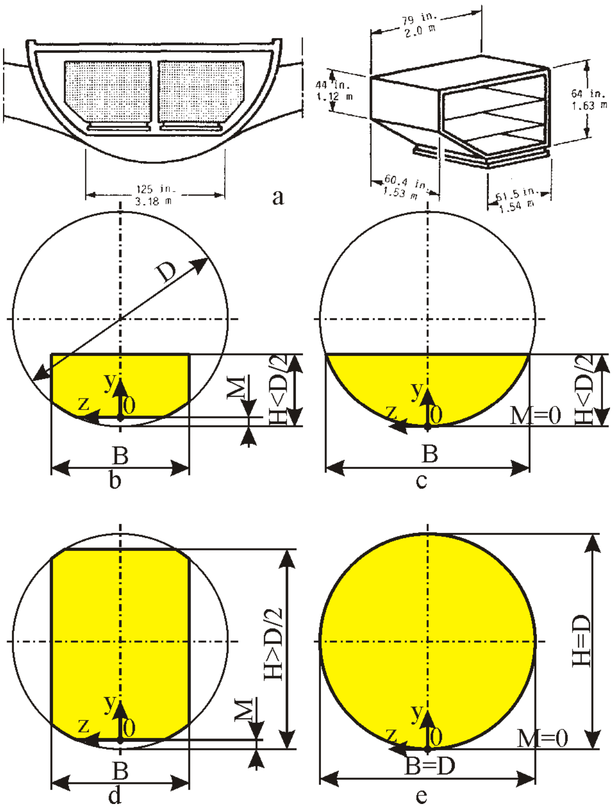


Fig. 3. Shape of fuselage tanks: a – Luggage containers, instead of which tanks are installed (A-310);
b-e – Possible versions of fuselage tank shape setting

where D – fuselage inner diameter; H, M – height of top and bottom tank flat surfaces; B – tank width. In addition, it is necessary to specify: L – tank length and X – coordinate of tank front wall relatively to fuselage nose.

Various schemes of fuel tank connection and fuel feed influence was analyzed in publication [3].

Center-of-Gravity Calculation Algorithm for Airplane with Several Tanks Accounting Specified Fuel Burn Schedule

In publication [2], it was shown that the algorithm should be subdivided into two parts: «components calculation» algorithm and fuel «usage» algorithm. The first one prepares arrays of levels, masses and static moments for each tank and tank section, separated by RBCH. In the second algorithm, total static moment is calculated and CG position is computed for current fuel mass in the process of fuel utilization.

When turning to calculation of several tanks, the «component calculation» algorithm [2] will be applied serially to each tank (in wing, in wing center section and in fuselage).

Main features of «usage» algorithm are: necessity to specify and account fuel burn schedule; to account fuel transfer schemes with preselected groups and with common tanks; and also to account dry bays and vent tanks. Let's consider them in turn.

Fuel burn schedule can be specified by two different ways. According to **the first method** (Fig. 4), definite order is specified to each fuel tank. Thus, zero order tanks are firstly used (if they were refueled); next – first order tanks etc. till last order tanks (which are feed tanks). When the tanks are connected serially, thus fuel is transferred from transfer tank of current order into the feed tank. This transfer keeps specified (usually maximal) fuel level in feed tank. To specify fuel burn schedule according to this method, it would be enough to specify only the number of order for each tank, thus feed tank would have the last number of order. This method was widely used in past and is still used in some A/C.

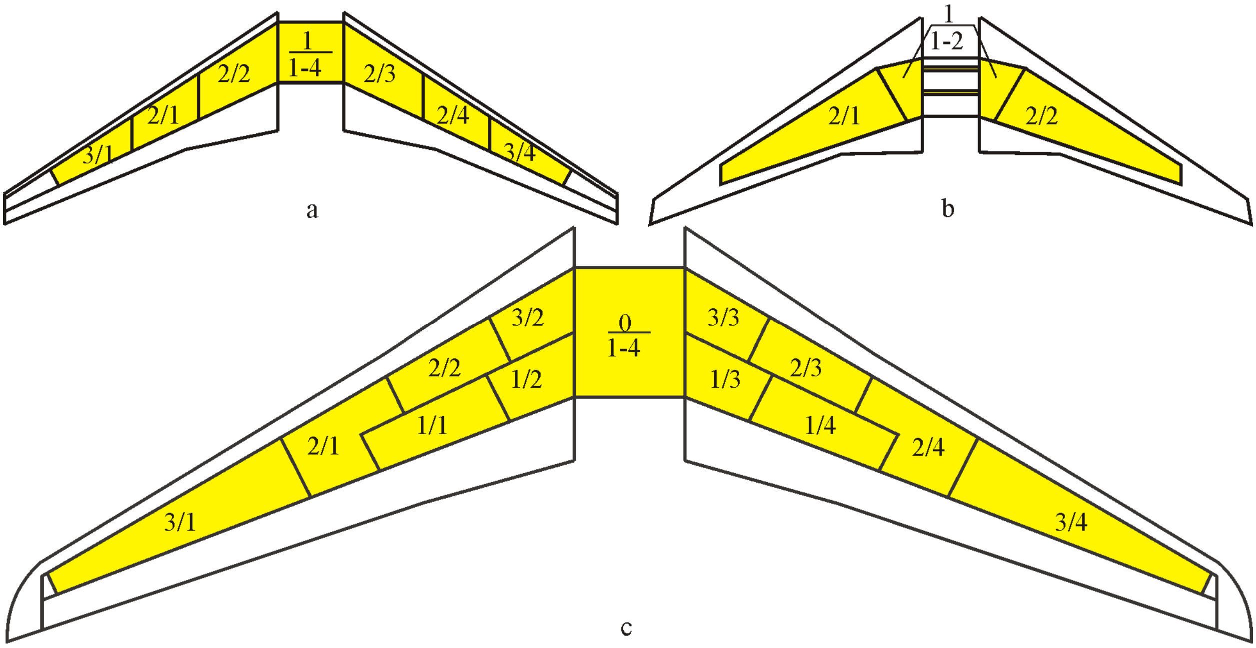


Fig. 4. Fuel bur schedule specified by number of order:
a – Ил-96; b – B-777; c – Ан-124; (top figure – number of order,
bottom figure – number of engine where the fuel from this tank is burned)

According to **the second method**, fuel burn schedule is specified by mass of fuel remaining in feed tank, at which fuel transfer into this feed tank begins from the following transfer tank (Fig. 5). In this case, number of order (which can formally exist) is not already enough to specify fuel burn schedule. Thus, the table of remaining fuel mass is required (for each feed tank); when fuel quantity in this feed tank drops down to these values, fuel transfer activates from corresponding transfer tank. As majority of modern airplanes uses just this method, and because it is more common, it is used in the mathematical model.

Example of fuel burn schedule setting for twinjet airplane A-310 is shown in Fig. 5, a. In this airplane, parallel fuel tank connection scheme is used (which turns to mixed one in case of stabilizer trim tank utilization). There are two tanks inside each wing and one tank in wing center section. Initial data is specified as follows. As there are two tank groups in airplane, then only one group is considered under symmetry. Tank inclusion into the group is provided by depressing the buttons, corresponding to the tank arrangement. In this case: 0 – inner tank; 1 – outer tank; C – wing central section (WCS) tank; S – stabilizer tank. Feed tank is specified by the second column of buttons (from the tanks included in this group). In this case, tank No. 0 was selected. Fuel burn schedule is specified for all tanks of the group except feed tank. Wing center section tank (No. 6) begins to use first – therefore full fuel mass in feed tank (m[0][6]=11160 kg) is specified to start fuel transfer from it (i. e. transfer from this tank begins at full feed tank). After the WCS tank depletion, fuel usage begins from feed tank until its remaining fuel drops down to m[0][1]=1000 kg. In this moment, fuel transfer from outer tank (No. 1) starts. When the outer tank is depleted, fuel usage from feed tank begins until remaining fuel m[0][7]=500 kg. From this moment, forward transfer begins from stabilizer trim tank (No. 7). When it is depleted, the fuel remaining in feed tank is used.

Example of fuel burn schedule setting for three-engined airplane DC-10 is shown in Fig. 5, b. Serial fuel tank connection scheme is used here. There are three tanks and a dry bay inside each wing, and also one tank in WCS. There are three groups of tanks onboard the airplane, therefore under symmetry, the group of central engine and the group of wing engine are considered. Tank inclusion into the group is provided by depressing the buttons, corresponding to the tank arrangement. In this case for the group of central engine: 0 – inner tank; C – WCS tank. For the group of wing engine: 1 – middle wing tank; 3 – outer tank; C – WCS tank. Note that, tank No. 2 (dry bay) is not included in any group. Feed tank is specified by the second column of buttons for each group. For the group of central engine, the tank No. 0 is set. For the group of wing engine, the tank No. 1 is set. Fuel burn schedule is specified for all tanks of the group except feed tank. As WCS tank is common for all groups, then two masses of remaining fuel are specified for it: to start fuel transfer in each of the groups.

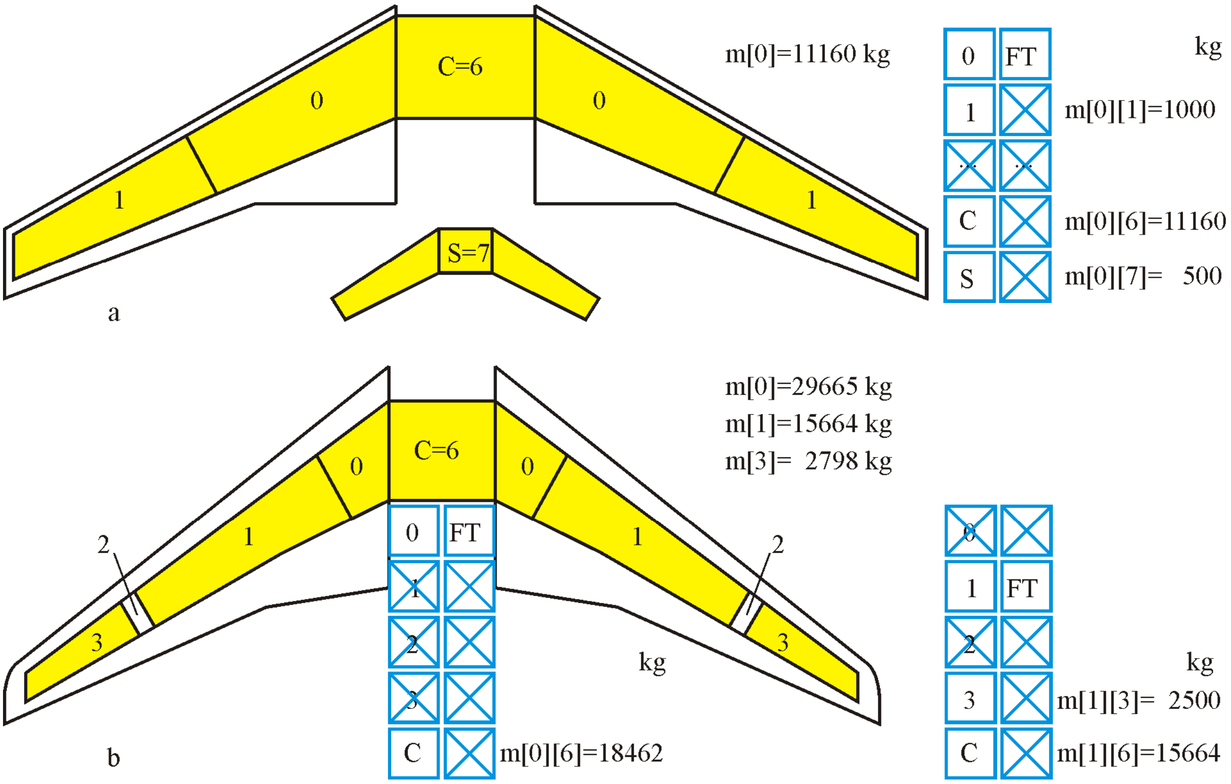


Fig. 5. Fuel burn schedule specifying by fuel remaining in feed tanks (FT):
a – A-310; b – DC-10; (the first column of buttons specifies fuel tanks included in the group of this engine; the second column of buttons sets feed tank for this group; right column specifies fuel mass remaining in feed tank of this group, at which fuel transfer starts from this transfer tank)

For the group of central engine, feed tank starts to use the first. Next, fuel transfer from WCS tank (No. 6) begins – at fuel remaining in feed tank (m[0][6]=18462 kg). After the WCS tank depletion, fuel usage from feed tank (No. 0) continues until its complete depletion.

For the group of wing engine, WCS tank (No. 6) starts to use first – therefore to start fuel transfer from it, full fuel mass in feed tank (m[1][6]=15664 kg) is set (i. e. fuel transfer from it begins at full feed tank). After the WCS tank depletion, fuel usage from feed tank (No. 1) begins until the fuel remaining inside it drops down to m[1][1]=2500 kg. At that moment, fuel transfer from outer tank (No. 3) starts. When it is depleted, the fuel remaining in feed tank is used.

Equality of fuel volumes intended for each engine is provided by correct setting of the burn schedule. In this case, in the moment when fuel transfer begins from WCS tank (No. 6) into feed tank of central engine (No. 0); as much fuel quantity must remain in the last tank, as totally in tanks No. 1 and No. 3, i. e. m[0][6]=m[1]+m[3]=15664+2798=18462 kg.

As it is known, main fuel transfer schemes: radial (Fig. 6) and collector (Fig. 7) have two versions: with preselected transfer tank groups (with direct transfer) and with common transfer tanks (with cross transfer). Cascading transfer scheme (Fig. 8) is used only with preselected transfer tanks groups.

In **schemes with preselected transfer tanks groups** (See Fig. 6, a; Fig. 7, a and Fig. 8), total volume of each tanks group (feed tank plus all transfer tanks of the group) must be equal; as normally, these groups are isolated (although their interconnection is always foreseen by the cross-feed line). Experience shows, that calculation of these systems does not present any difficulties, if the volume equality condition is met. So, for each transfer tank of the group, such fuel mass remaining in corresponding feed tank is set, under which fuel transfer from that transfer tank to the given feed tank begins.

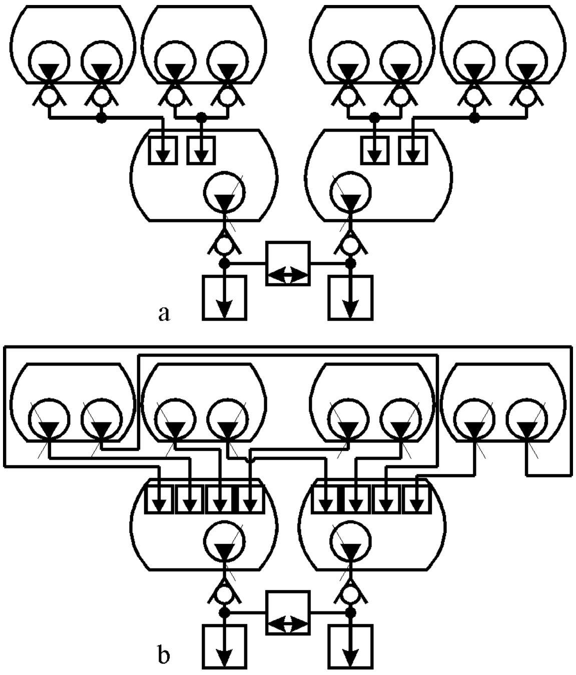


Fig. 6. Radial transfer schemes

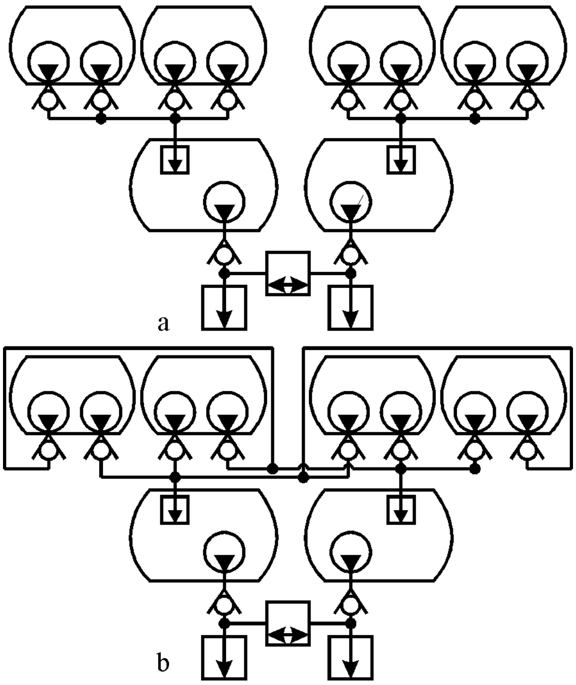


Fig. 7. Collector transfer schemes

In **schemes with common transfer tanks** (See Fig. 6, b; Fig. 7, b), it is not necessary to meet the transfer tank volume equality condition. But fuel transfer schedule must be selected so, that all engines are provided with fuel until it remains onboard. Practically, it slightly complicates initial data setting procedure for these systems.

Such cases, when there are **dry bays** or vent (surge) tanks (See Fig. 5) inside wing fuel compartments between the fuel tanks, are encountered (but rather seldom) in practice of airplane designing. These dry bays can be arranged in fire hazardous zones close to engine. Vent tanks, as a rule, are placed near to wing tips; but in some cases (A-380, C-141, DC/KC-10) to decrease explosion probability under the lightning stroke; vent tanks are located in the middle parts of each wing. When calculating «usage», these compartments can be simulated as dummy transfer tanks, which are not included in any of the groups.

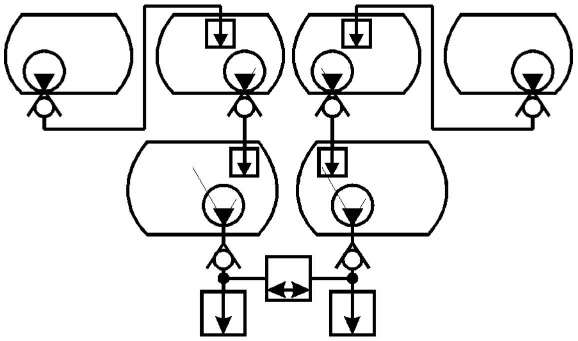
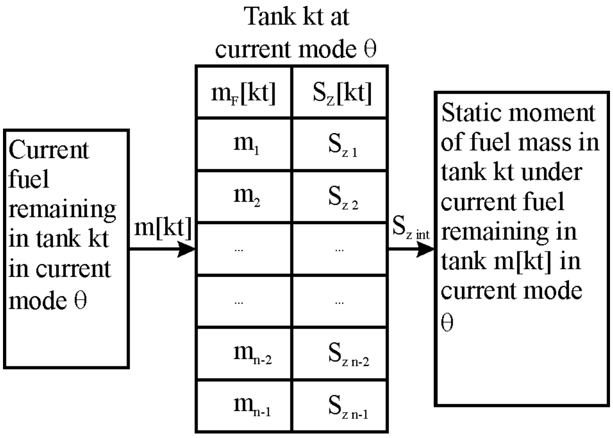


Fig. 8. Cascading transfer scheme

Without RBCV, computation of static moment of fuel mass in separate tank does not present any difficulties; and it is performed by interpolation according to current fuel remaining in this tank (Fig. 9).



m_F[kt]	S_Z[kt]
m_1	$S_{z\,1}$
m_2	$S_{z\,2}$
...	...
...	...
m_{n-2}	$S_{z\,n-2}$
m_{n-1}	$S_{z\,n-1}$

Fig. 9. Fuel mass static moment computation for tank kt

When RBCV exist, they must be taken into account only in «extreme» pitch angle θ, i. e. for high-wing/anhedral monoplanes – for $\theta_{\min}$; for low-wing/dihedral monoplanes – for $\theta_{\max}$. In other cases even when RBCV are installed, static moment calculation is provided by the same scheme.

Computation of the static moment of fuel mass in tank section, separated by RBCV in «extreme» mode θ, is impossible to perform directly by mass of fuel remaining in the tank; as fuel mass in the section separated by RBCV is not known beforehand in this mode [2]. For these cases, three consecutive steps are performed (Fig. 10). In the first step, fuel level in the tank is computed, which is equal for all its sections in cruising mode θ, by the current fuel mass remaining in the tank in extreme mode θ. In the second step, fuel mass in the considered tank section is calculated, which is equal for both modes, by this level. And only in the third step, static moment of fuel mass in this tank section in «extreme» mode is computed, by this mass.

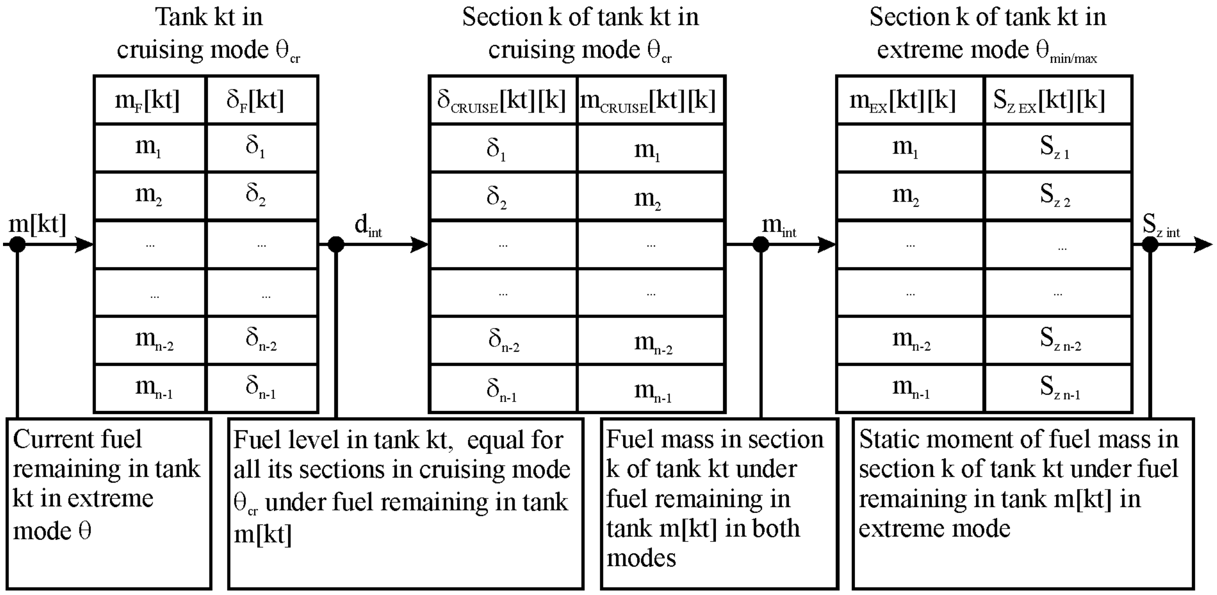


Fig. 10. Computation of static moment of fuel mass for section k of tank kt, separated by RBCV

Summing up all stated above, aggregative fuel «usage» algorithm for the case of several tanks can be presented consisting of some blocks (Fig. 11). The most important of them are blocks of mass and static moments calculation.

Calculation Results

The considered algorithms were implemented by R. U. Tsukanov in computation module of the Power Unit 11.6 software; the following calculations were performed by means of this software.

All calculations were carried out for three pitch angles: minimal, cruising and maximal ones.

CG position calculation was performed for twin-engined low-wing/dihedral monoplane and single fuel tank in each wing (**B-737-400**), but now with WCS tank, which is used in the first order into both engines (Fig. 12). Here, parallel fuel feed system is used.

Calculation was carried out for twin-engined high-wing/anhedral monoplane (**Ан-148**), but now with four tanks in each wing and WCS tank (Fig. 13). In this airplane, there is serial fuel feed system and cascade fuel transfer from common WCS tank and three wing tanks into feed tank in the wing tip. The following fuel burn schedule was set: WCS tank is used in the first order into both engines; next – the first tank from root, the second tank from root, the third tank from root and the outer tank are consequently used in proper engines. For comparison in the figure, graphs are shown for standby gravity fuel transfer (when intank transfer system is failed). In this case, fuel migrates through three RBCV, subdividing wing tanks.

As clear from the graphs, first-order fuel utilization from the wing center section considerably shifts CG aft (in the examples 2.7...3.3 %). In the same time, fuel migration in wing center section tank insignificantly influences on CG position (CG position difference at minimal and maximal pitch angles is 0.9...1.2 %).

Wing tanks utilization causes more complicated influence on CG position, which is defined in the first order by sign of wing anhedral/dihedral angle.

Let's initially consider low-wing/dihedral monoplane (See Fig. 12). Firstly, here in cruising mode, initially, CG shifts forward, but next it shifts aft. Secondly, maximal CG shift is rather big (in example 2.2 %). Thirdly, fuel migration has big value for wing tanks. But in this case, owning to rational arrangement of two RBCV, CG shift range under pitch angle variation makes only 1.3 %.

Let's now consider high-wing/anhedral monoplane. Firstly, here in cruising mode, initially, CG position shifts aft, but next it shifts forward. Secondly, maximal CG shift is even more (in the example 6.5 %). Thirdly, fuel migration causes considerable influence (CG shift range makes 1.9 %).

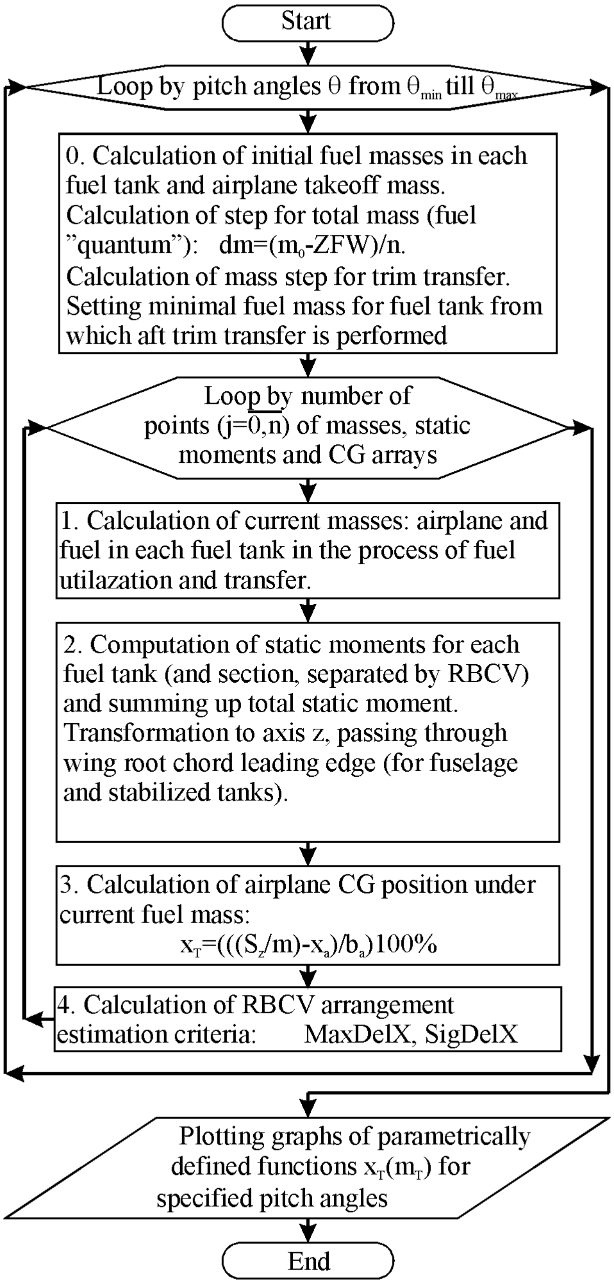


Fig. 11. Aggregated «usage» algorithm

The main **conclusion**, which can be done basing on these graphs, is the following: CG position of low-wing/dihedral monoplane in cruising mode is unfavorable from point of view of aerodynamic drag minimization and requires correction by means of fuel trim transfer (FTT). In the same time, for high-wing/anhedral monoplane – CG shifts in the desirable direction by «natural» way (initially aft, next forward). So, FTT application is the most advance in low-wing/dihedral monoplanes; practically all passenger airplanes with turbofans are related to which.

In the low-wing monoplane CG position graph (See Fig. 13), it is also possible to estimate influence of fuel transfer method (normal – by jet pumps or emergency – by gravity). It is clear that, graphs for cruising and maximal pitch angles practically coincide at both transfer methods. The graphs for minimal pitch angle differ only in narrow range of flight masses: notably before and after depletion the first tank from root.

CG position graphs for three-engined low-wing/dihedral monoplane (**DC-10**) are shown in Fig. 14. Here, serial fuel feed system and radial fuel transfer system with common WCS tank differs by certain complication because of presence of three engines and four feed tanks. In this airplane, it was possible to provide initial CG shift aft, and next forward, as in high-wing/anhedral monoplanes, that promotes trim drag decrease and fuel efficiency increase; by means of rational fuel burn schedule (firstly wing center section tank and partially – inner tanks are used, see Fig. 5, b).

CG position graph for the **A-310** airplane without fuselage tanks is shown in Fig. 15. In this airplane, there is parallel fuel feed system with common WCS tank.

In this case, the airplane takes off with empty tank in stabilizer. CG position graphs for this airplane without FTT utilization (1, 2, 3, 4) include two breaks, which are determined by assumed fuel burn schedule. The first break 6 (at current mass 130 t) matches to WCS tank depletion and inner wing tanks utilization start. The second break 7 (at mass 108 t) corresponds to fuel utilization start from outer wing tanks.

It is clear that, wing tanks subdivision into two ones leads to considerable decrease of CG shift range (in addition to the main task – wing load alleviation). But, it is necessary to remember that, increase in number of tanks, firstly, complicates fuel system, and, secondly, increases its cost and mass (due to additional pumps, pipelines and valves).

In this case, CG shift caused by fuel migration during fuel utilization from wing tanks is considerably less, than in the first example for low-wing monoplane, also due to wing subdivision into two tanks.

CG position graphs for four-engined low-wing/dihedral monoplane (**B-747**) are shown in Fig. 16. This airplane distinguishes by mixed fuel feed system with rather complicated fuel burn schedule.

In the first stage (5-6), fuel is used from WCS tank into outer engines, and from inner tanks into inner engines. From definite fuel mass (18200 kg) remaining in the inner tanks (6), fuel transfer starts from outer tanks into inner tanks.

After depletion of the outer tanks (7), fuel is fed from WCS tank into outer engines, and fuel from inner tanks is still fed into inner engines.

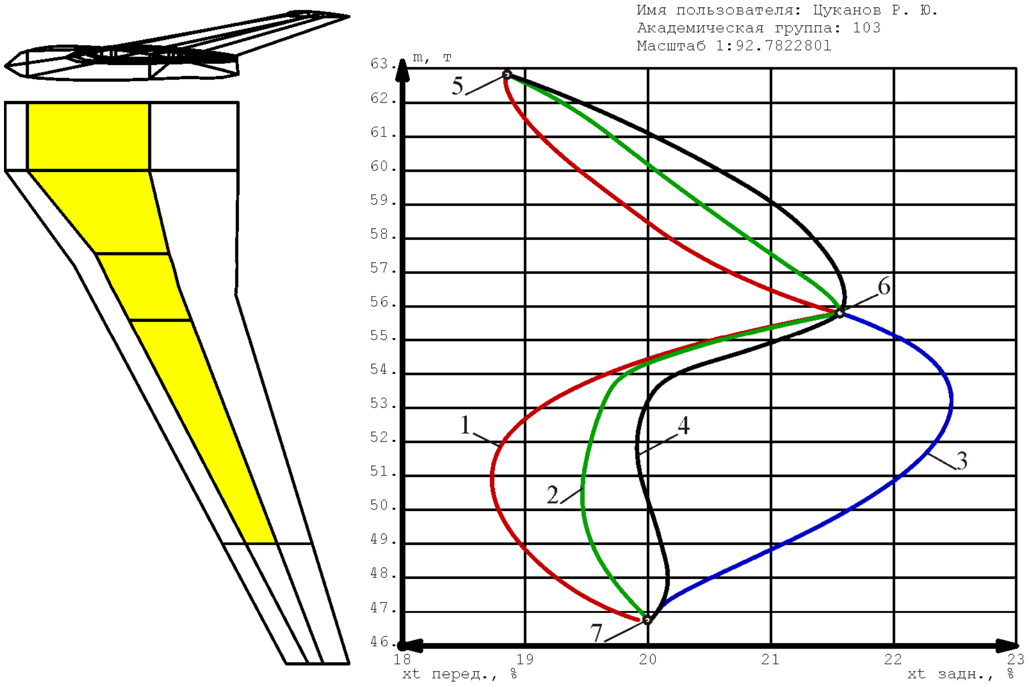


Fig. 12. CG position graph for twin-engined low-wing/dihedral monoplane with single fuel tank in each wing and a tank in wing center section (B-737-400): 1 – In minimal pitch angle; 2 – In cruising pitch angle; 3 – In maximal pitch angle without RBCV; 4 – In maximal pitch angle with two RBCV as in airplane (see scheme); 5 – Fuel feed start from WCS into both engines; 6 – WCS tank depletion and feed start from wing tanks; 7 – Wing tanks depletion

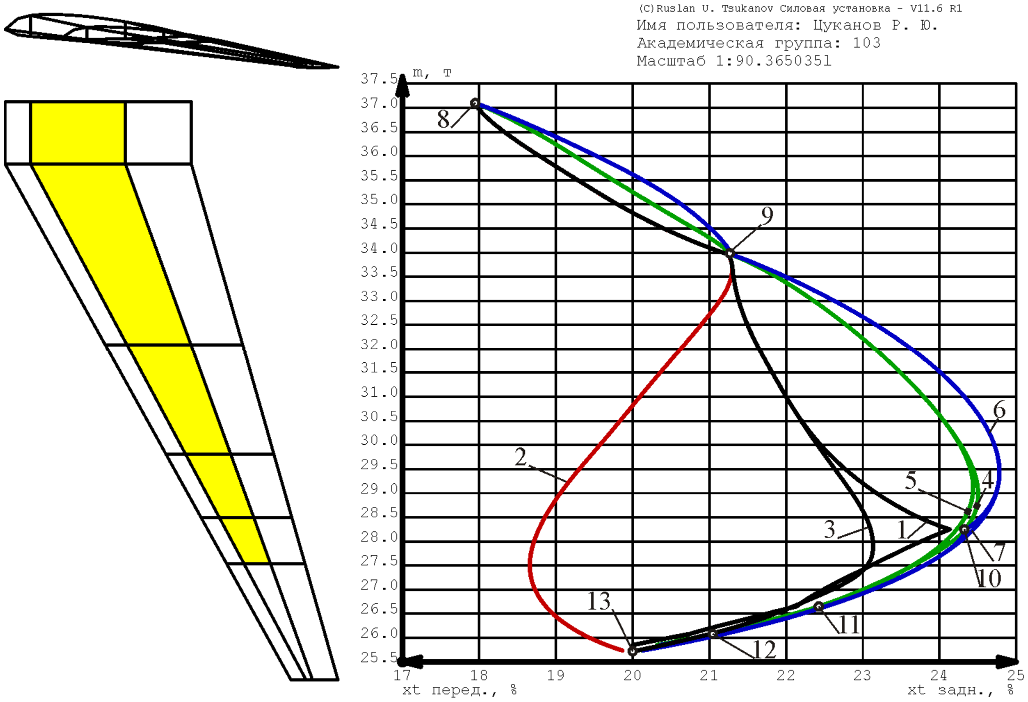


Fig. 13. CG position graph for twin-engined high-wing/anhedral monoplane, with four fuel tanks in each wing and a wing center section tank (Ан-148): 1 – In minimal pitch angle with fuel transfer as in airplane (see scheme); 2 – In minimal pitch angle with gravity transfer without RBCV; 3 – In minimal pitch angle with gravity transfer with three RBCV; 4 – In cruising pitch angle with fuel transfer; 5 – In cruising pitch angle with gravity transfer; 6 – In maximal pitch angle with transfer; 7 – In maximal pitch angle with gravity transfer; 8 – Fuel transfer start from WCS tank into both feed tanks; 9 – WCS tank depletion and transfer start from the first tank; 10 – First tank depletion and transfer start from the second tank; 11 – Second tank depletion and transfer start from the third tank; 12 – Third tank depletion and utilization start from feed tank; 13 – Feed tank depletion

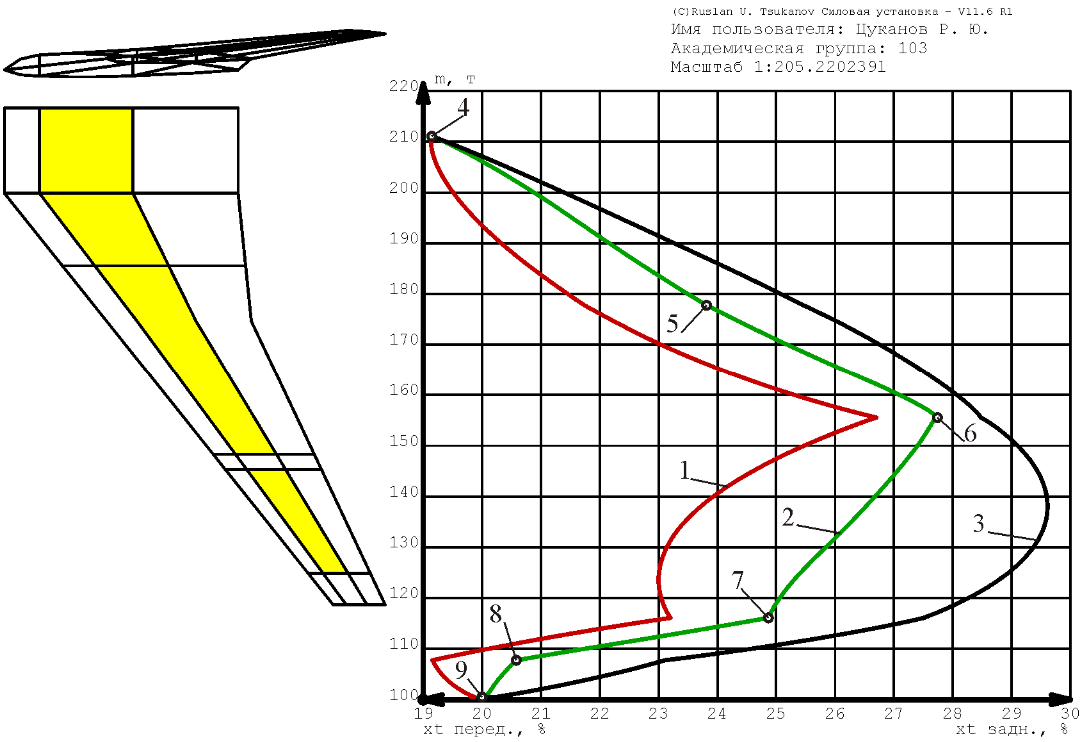


Fig. 14. CG position graph for three-engined low-wing/dihedral monoplane with three tanks in each wing and a wing center section tank (DC-10): 1 – In minimal pitch angle; 2 – In cruising pitch angle; 3 – In maximal pitch angle; 4 – Fuel feed start into central engine from inner tank, and fuel transfer start from WCS tank into middle tanks (from which wing engines are fed); 5 – Fuel transfer start from WCS tank to inner tanks; 6 – WCS tank depletion; 7 – Fuel transfer start from outer tanks to middle ones; 8 – Outer tanks depletion; 9 – Simultaneous depletion of inner tanks in central engine and middle tanks in wing engines

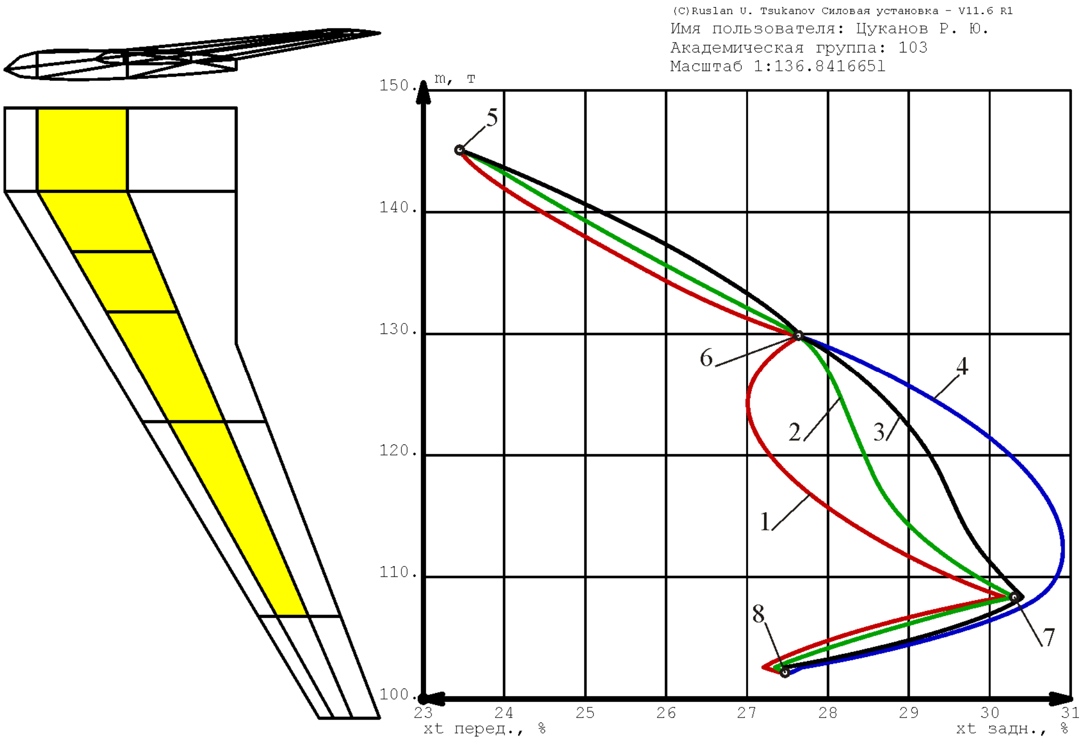


Fig. 15. CG position graph for A-310 airplane without fuselage tanks: 1 – In minimal pitch angle; 2 – In cruising pitch angle; 3 – In maximal pitch angle with RBCV; 4 – In maximal pitch angle without RBCV; 5 – Fuel utilization start from WCS tank; 6 – WCS tank depletion and fuel utilization start from inner tanks; 7 – Inner tanks depletion and fuel utilization start from outer tanks; 8 – Outer tanks depletion

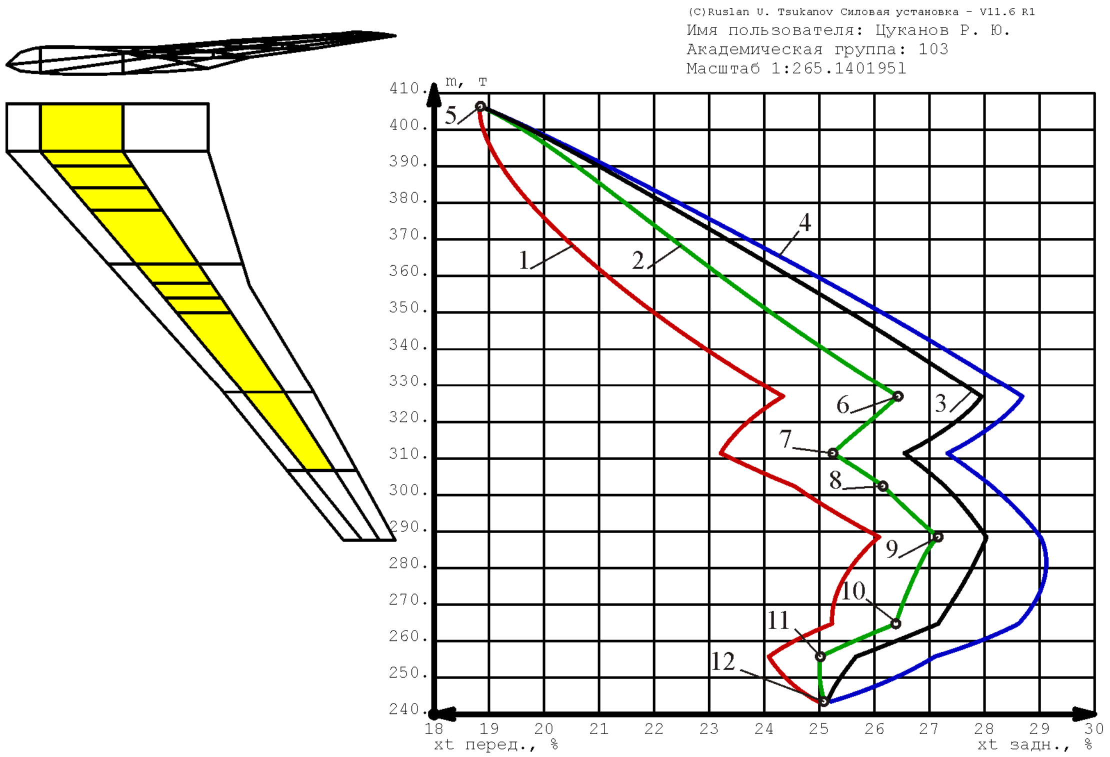


Fig. 16. CG position graphs for four-engined low-wing/dihedral monoplane with three tanks in each wing and a WCS tank (B-747): 1 – In minimal pitch angle; 2 – In cruising pitch angle; 3 – In maximal pitch angle with RBCV; 4 – In maximal pitch angle without RBCV; 5 – Fuel utilization start from WCS tank to outer engines, and from inner tanks to inner engines; 6 – Fuel transfer start from outer tanks to inner tanks; 7 – Outer tanks depletion; 8 – WCS tank depletion; 9 – Fuel transfer start from middle tanks to inner tanks; 10 – Transfer termination from middle tanks to inner tanks; 11 – Transfer termination from inner tanks to middle tanks; 12 – Simultaneous depletion of inner tanks to inner engines and middle tanks to outer engines

After depletion of the WCS tank (8), fuel feed starts from inner tanks in both inner and outer engines.

From definite fuel mass (9072 kg) remaining in inner tanks (9), fuel transfer starts from middle tanks into inner tanks. In the same time, both engines placed in one wing go on feeding from each inner tank.

At definite fuel mass (3200 kg) remaining in inner tanks (10), outer engines start to feed from middle tanks. Inner engines go on feeding from inner tanks with fuel transfer in them from middle tanks.

At the same fuel mass (3200 kg) remaining in middle tanks (11), fuel transfer from middle tanks into inner tanks terminates. After that, inner engines go on feeding from inner tanks, but outer engines are fed from middle tanks.

Conclusion

1. On the base of information analysis known from public information sources about shapes of wing and fuselage tanks; mathematical model of their shape has been developed.

2. Mathematical model (algorithm and its program implementation using C language in Power Unit 11.6 system) has been developed for CG position numerical simulation of airplane with swept-back wing, which keeps fuel both in wings, and in fuselage tanks, in the process of fuel utilization at specified pitch angles, taking into account specified number and arrangement of ribs with baffle check valves, and also specified fuel burn schedule.

3. Features of fuel burn schedule setting, fuel transfer schemes and dry bays arrangement used in modern aviation are analyzed and taken into account in the mathematical model.

4. On the base of mathematical simulation (in Power Unit 11.6 system), conclusion is done about greater rationality of fuel trim transfer utilization for low-wing /dihedral monoplanes.

5. For the mathematical model following development, it is necessary to account current flight mass and CG position influence on required pitch angle.

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Поступила в редакцию 03.02.2016, рассмотрена на редколлегии 15.02.2016

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ВЛИЯНИЯ ПОРЯДКА ВЫРАБОТКИ ТОПЛИВА НА ЦЕНТРОВКУ САМОЛЁТА

Р. Ю. Цуканов

На основе анализа форм крыльев существующих самолётов транспортной категории, предложены формулы для описания формы топливных баков, расположенных в консолях крыла, центроплане и фюзеляже. Проанализированы способы задания порядка выработки топлива и схемы перекачки топлива. Рассмотрен способ, позволяющий учесть влияние противоотливных нервюр на положение центра масс самолёта. Предложен алгоритм расчёта положения центра масс самолёта транспортной категории в зависимости от текущего уровня топлива в баках и угла тангажа, учитывающий заданное количество и расположение топливных баков в консолях крыла, центроплане и фюзеляже, порядок выработки топлива, а также количество и расположение противоотливных нервюр. На основе этого алгоритма и его программной реализации выполнены расчёты положения центра масс по мере выработки топлива для ряда пассажирских самолётов (Ан-148, B-737-400, A-310, DC-10, B-747). Предложенный алгоритм может быть использован для определения рационального количества и расположения противоотливных нервюр, построения более сложных математических моделей, а также при выполнении курсовых и дипломных проектов.

Ключевые слова: топливная система самолёта, порядок выработки топлива, центр масс, центровка, топливный бак, подсистема подачи топлива, подсистема выработки топлива.

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ВПЛИВУ ПОРЯДКУ ВИРОБЛЕННЯ ПАЛИВА НА ЦЕНТРУВАННЯ ЛІТАКА

Р. Ю. Цуканов

На основі аналізу форм крил існуючих літаків транспортної категорії запропоновано формули для опису форми паливних баків, що розміщено у консолях крила, центроплані та фюзеляжі. Проаналізовано способи задання порядку вироблення палива та схеми перекачування палива. Розглянуто спосіб, що дозволяє врахувати вплив противідливних нервюр на положення центру мас літака. Запропоновано алгоритм розрахунку положення центру мас літака транспортної категорії у залежності від поточного рівня палива у баках та кута тангажу, що враховує задану кількість та розміщення паливних баків у консолях крила, центроплані та фюзеляжі, порядок вироблення палива, а також кількість та розміщення противідливних нервюр. На основі цього алгоритму та його програмної реалізації виконано розрахунки положення центру мас відповідно до вироблення палива для низки пасажирських літаків (Ан-148, B-737-400, A-310, DC-10, B-747). Запропонований алгоритм може бути використано для визначення раціональної кількості та розміщення противідливних нервюр, побудови складніших математичних моделей, а також при виконанні курсових та дипломних проектів.

Ключові слова: паливна система літака, порядок вироблення палива, центр мас, центрування, паливний бак, підсистема подавання палива, підсистема вироблення палива.

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