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TRANSPORT CATEGORY AIRPLANE CENTER-OF-GRAVITY SHIFT MATHEMATICAL SIMULATION ACCOUNTING FUEL TRIM TRANSFER

Introduction

One of the main issues being in front of world commercial aviation and practically determining marketability of a transport category airplane, is operating expenses decrease. Fuel expenses make the best part of them; and their decrease results in fuel efficiency increase.

There are some ways to increase the fuel efficiency of an airplane: decrease of fuel flow rate in cruising flight mode by means of engines improvement and their properties compliance with airplane performance; decrease of structural mass ratio by means of more advanced structural materials application in terms of specific strength; increase of lift-to-drag ratio by means of rational choice of airplane geometrical parameters etc.

The first way relates to the theory, structure and technology of engine designing. Airplane designers are forced to use existing engines or wait for development of new engines during uncertain time.

The second way now is expressed in wide application of composite materials wide application in airframe load-carrying structures. This way is rather advanced, although it has such disadvantages as: complicated and expensive repair and recovery of these structures. But the main constraint is necessity of manufacturing complete rebuilding, requiring huge investment, that makes it unacceptable for domestic practice now.

The third way is lift-to-drag ratio increase. It seems that, reserves of this direction are completely depleted. Really, considering the schematics of the first generation jet liners (DC-8, B-707), they distinguish a little from modern ones (A-340, A-380). But that is not actually so. Nowadays, to increase lift-to-drag ratio in cruising mode, designers use airplane center-of-gravity (CG) position control by means of fuel trim transfer (FTT) all the more. This method is already used in some foreign liners (A-310, A-330, A-340, A-380, B-747), but is not applied in domestic practice probably due to insufficient methodological instructions.

The base algorithm of CG position calculation for an airplane with one tank in each wing taking into account fuel migration and given pitch attitude was considered in publication [1]. Ribs with baffle check valves (RBCV) influence on the airplane CG shift caused by pitch attitude variation was taken into account in paper [2]. Ways to take into account different tank connection schemes and feed methods were given in publication [3]. Wing geometry influence, fuel burn and transfer schedule were taken into account in paper [4].

The aim of this publication is development of the method to calculate CG position of airplane with swept-back wing, carrying fuel tanks in both wings and fuselage, in the process of fuel utilization at specified pitch angles, accounting specified number and arrangement of RBCV, fuel burn schedule and fuel trim transfer.

1. Analysis of Foreign Fuel Trim Transfer Subsystems

As it was mentioned, some modifications of foreign passenger airplanes [5 -10] were equipped with FTT subsystem between wing tanks and trim tank in horizontal stabilizer. It is possible to distinguish three versions of FTT subsystem. The first of them (implemented in A-310) corresponds to the parallel fuel usage subsystem (Fig. 1) and allows aft fuel transfer from wing central section tank (WCS) or inner wing tanks and forward fuel transfer into WCS tank only (pumps, valves and pipeline sections used in each case are marked out by bold lines in schematics). In this version, eight control valves and two pumps are installed for FTT operation.

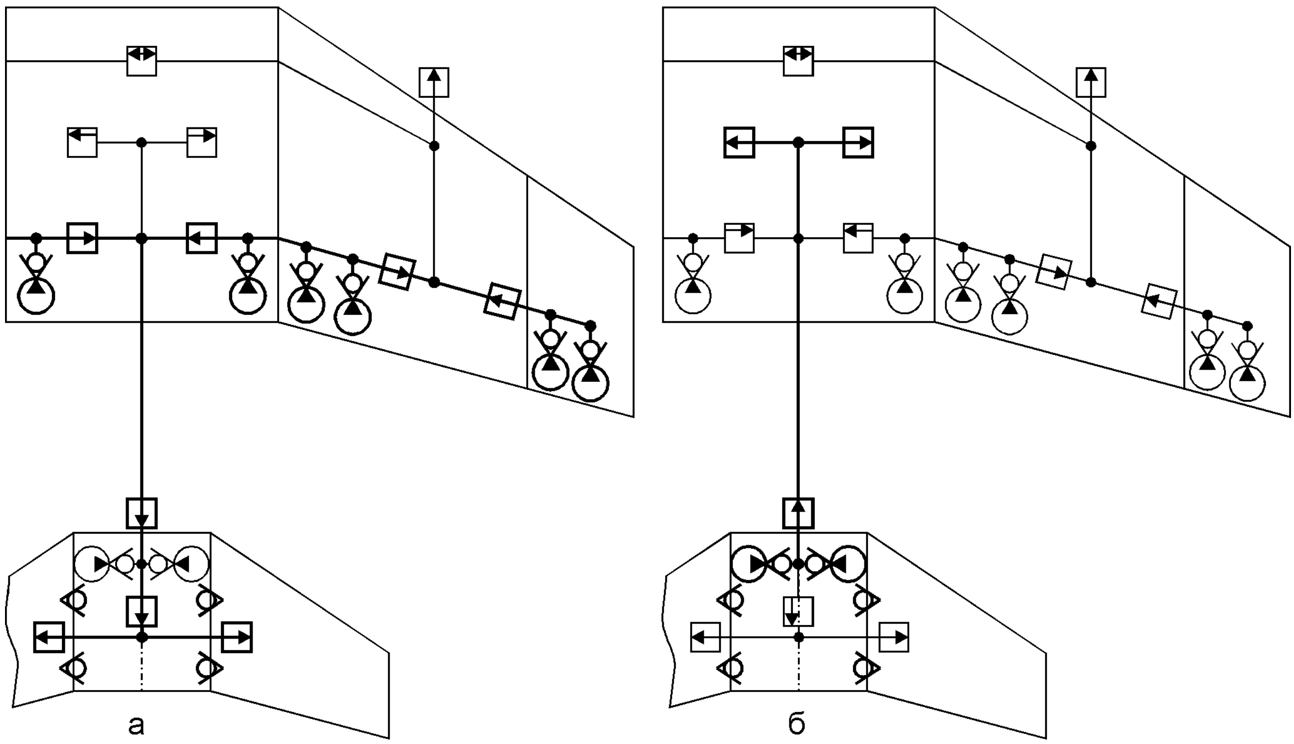

Figure 1 – First version of FTT subsystem (A-310):
a – Aft transfer; b – Forward transfer

The second version (implemented in A-330, A-340, A-380) corresponds to the serial fuel usage subsystem (Fig. 2) and allows fuel trim transfer in both directions between WCS tank or wing tanks and trim tank in horizontal stabilizer. In this version, eight control valves and a pump are installed for FTT operation.

The third version (implemented in B-747) corresponds to the mixed fuel usage subsystem (Fig. 3) and allows fuel trim transfer in both directions between WCS tank and trim tank in horizontal stabilizer only. In this version, nine control valves and two pumps are installed for FTT operation.

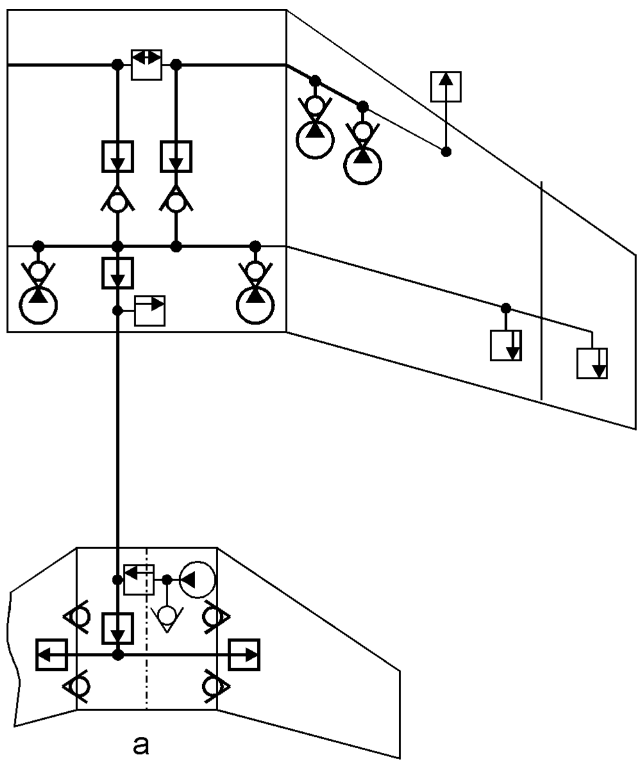

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Figure 2 – Second version of FTT subsystem (A-330, A-340, A-380):
a – Aft transfer; b – Forward transfer

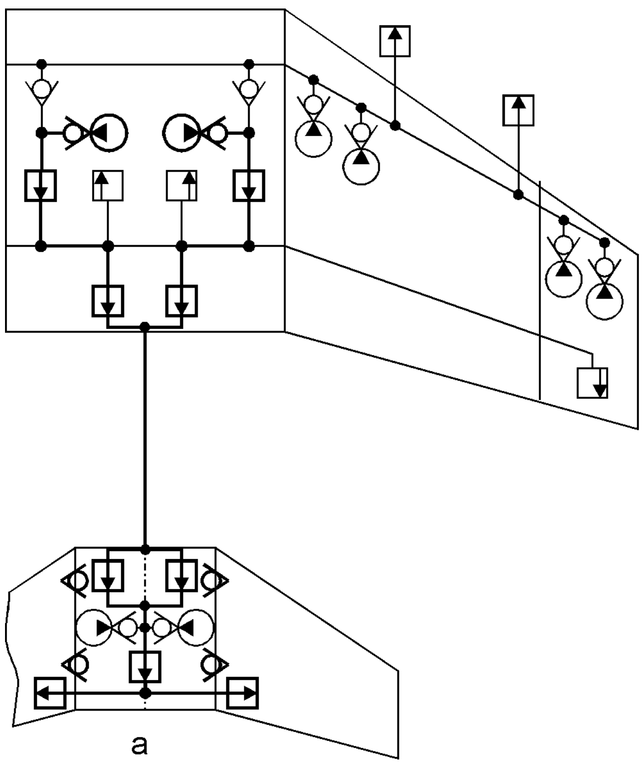

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Figure 3 – Third version of FTT subsystem (B-747):
a – Aft transfer; b – Forward transfer

It is clear, that mass expenses for the valves and pumps installation are approximately equal in all three schemes and could not be an optimality criterion. In the author's opinion, the second version of FTT subsystem is the most applicable of three existing systems for implementation in domestic practice. Because, firstly, it corresponds to the serial fuel usage subsystem (which is conventional in domestic airplane designing). And, secondly, it provides the most flexible fuel transfer control.

Thus, during development of airplane center-of-gravity calculation algorithm, it is necessary to take into account forward fuel transfer possibility in WCS tank or into wing tanks, and a number of other FTT system operation features.

Fuel trim transfer usually means (Fig. 4): one-time (per flight) transfer of the definite fuel quantity from wing tanks into the trim tank in horizontal stabilizer to reach the target CG position (aft transfer), and next – in the process of fuel utilization from wing tanks – multiple transfer of small fuel portions back to keep the target CG position (forward transfer). In the Airbus company airplanes, target CG position is specified depending on the current flight mass generally by bilinear function (Fig. 5).

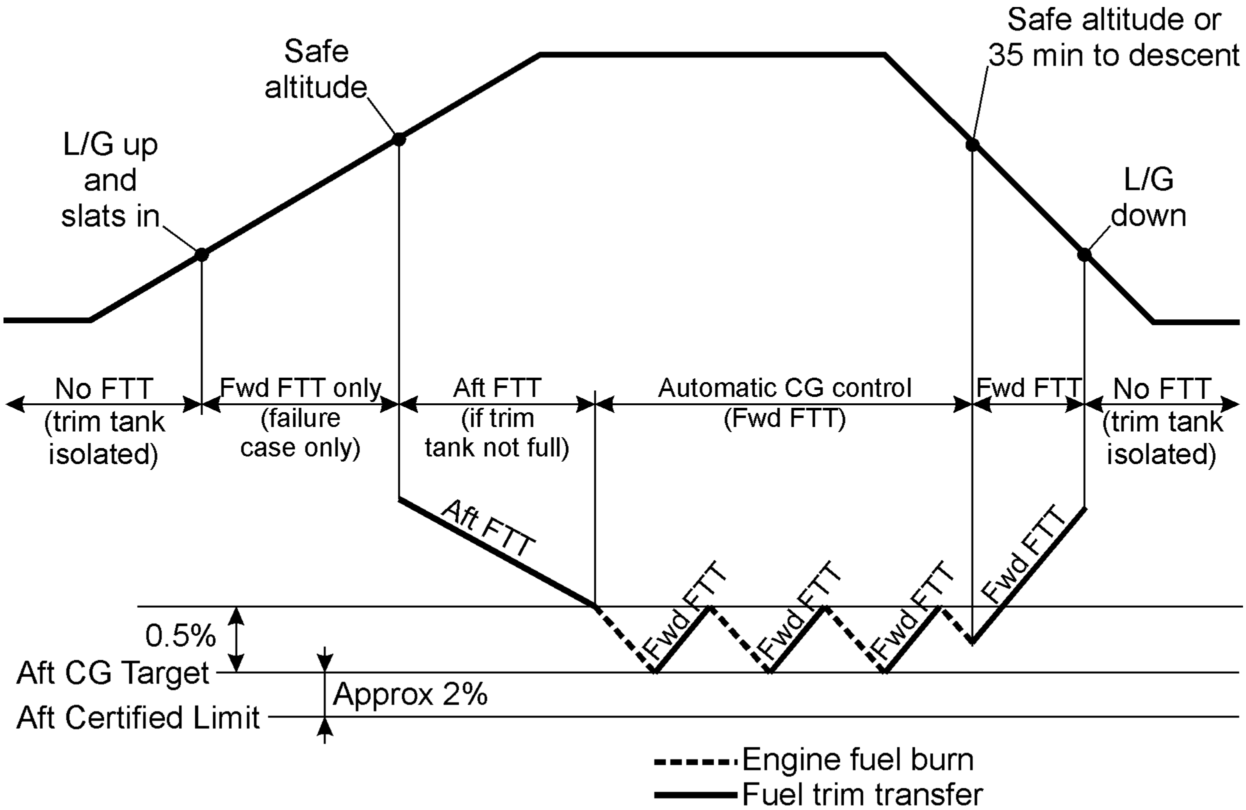


Figure 4 – FTT operation schematic

To provide acceptable stability performance at takeoff and landing, aft FTT can be provided after takeoff when reaching definite safe altitude, and forward FTT – after completing cruise flight during descent down to this altitude. In other cases, aft transfer is not used at all, if the airplane takes off with stabilizer tank filled. In addition, to provide safety (stability) before descent and landing, forward transfer is performed with increased rate. To avoid selfoscillation, tolerances for actual CG position in relation to the target are specified. So in the Airbus airplanes, tolerance for the aft transfer makes 2 %, and for the forward transfer is 0.5 %.

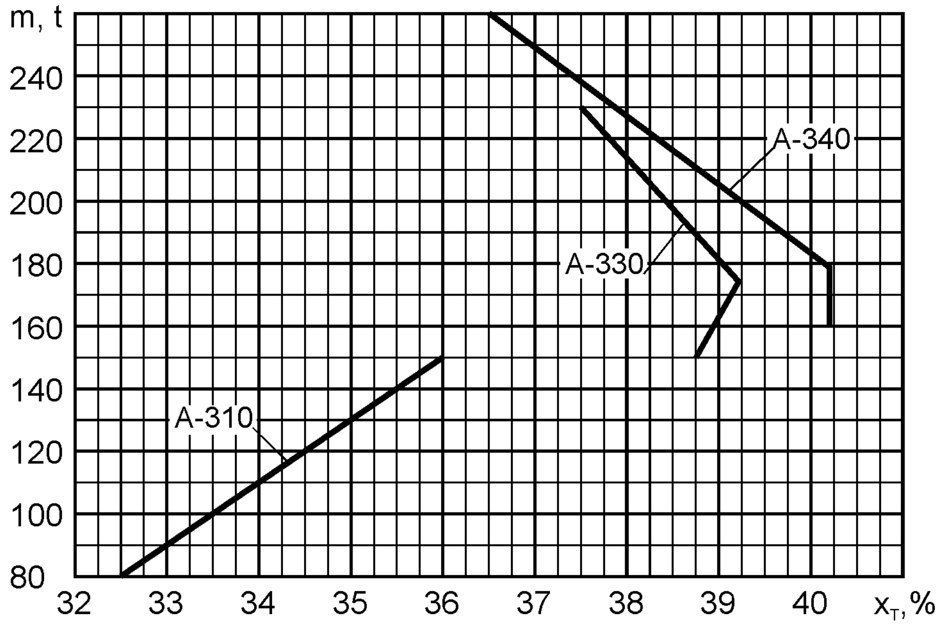


Figure 5 – Target CG positions

Aft trim transfer is usually used once per flight during climb. Aft trim transfer begins when all the following conditions are met: landing gear and slats are retracted; there is enough free space in the stabilizer trim tank (when the airplane takes off with filled trim tank, aft FTT is not required); the fuel quantity in feed tank is enough; the flight altitude is above specified one; actual CG position is less than target minus tolerance (2 %). If all these conditions are met again (for example, at pitch angle variation), an additional aft transfer will occur.

The aft transfer terminates at any of the following conditions: actual CG position becomes equal to the target minus tolerance (0.5 %); trim tank high level sensor becomes wet; feed tank's fuel quantity decreases down to the specified level; manual trim transfer is selected.

Forward trim transfer is performed during cruise flight periodically in the process of fuel utilization. Forward transfer begins if one of the following conditions are met: the actual CG position becomes equal to the target; the fuel content in one of the feed tanks decreases to predetermined value (in this case the forward transfer stops when the fuel quantity in feed tank reaches the other specified valve); airplane descents below specified altitude (in this case, transfer terminates only by feed tank high level sensors); fuel jettison subsystem activation; in electrical emergency configuration.

Forward transfer terminates when any of the following conditions are met: actual CG position becomes equal to the target minus tolerance (0.5 %); stabilizer trim tank depletion. To provide forward transfer reliability, forward

FTT pump in stabilizer starts to operate, when both the landing gear and slats are retracted, but stops when trim tank becomes empty. In the event of the pump failure, forward FTT occurs by gravity through the trim tank check valve. In addition to the considered automatic transfer, there is manual forward transfer used by crew in emergencies.

2. CG Calculation Algorithm With Consideration of Fuel Trim Transfer

In publication [2], it was shown that the airplane CG calculation algorithm should be subdivided into two parts: «components calculation» algorithm and fuel «usage» algorithm (Fig. 6).

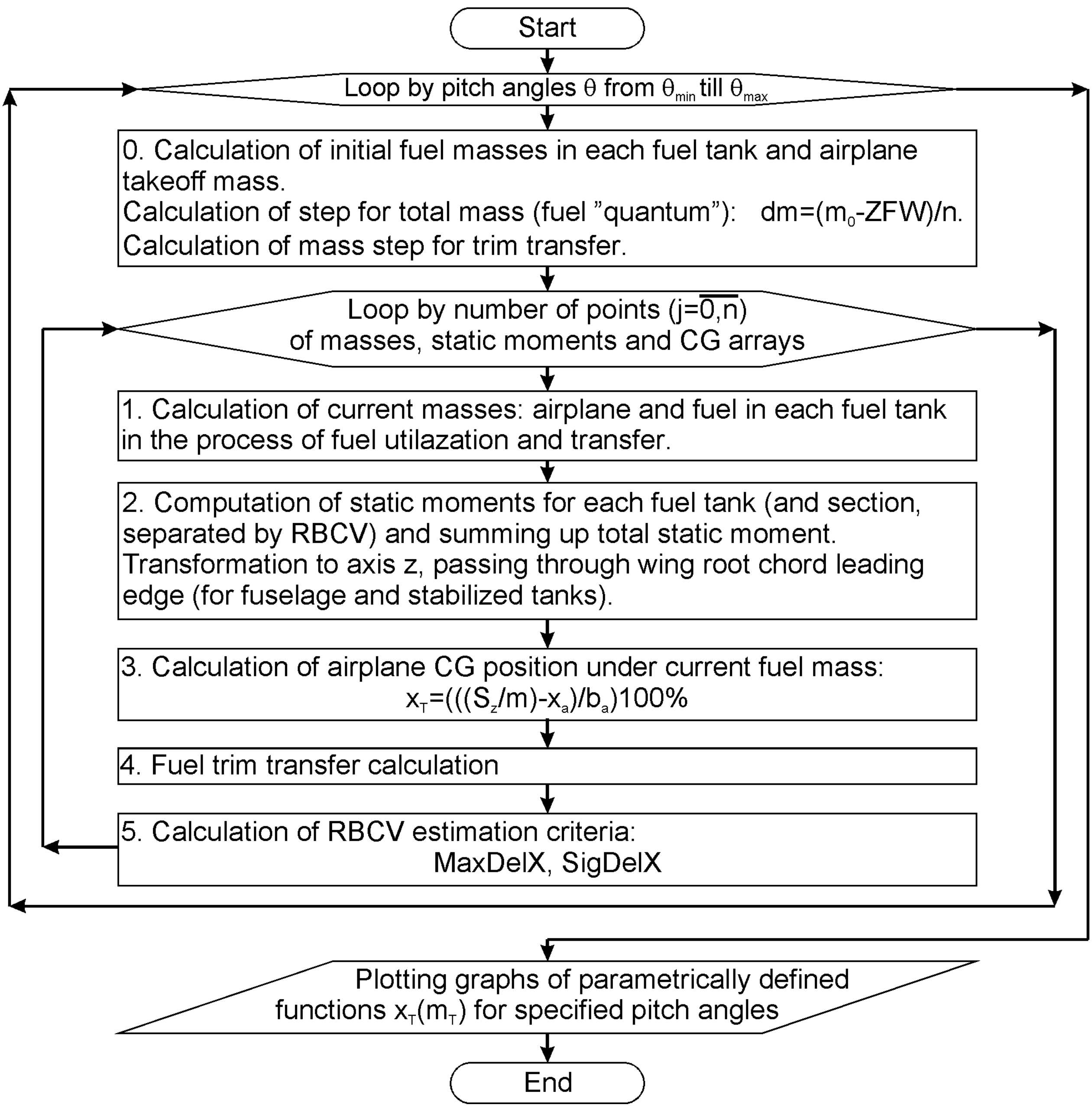


Figure 6 – Aggregated «usage» algorithm

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. The first algorithm was shown in the same publication. FTT algorithm (Fig. 7) formalizes all conditions listed earlier.

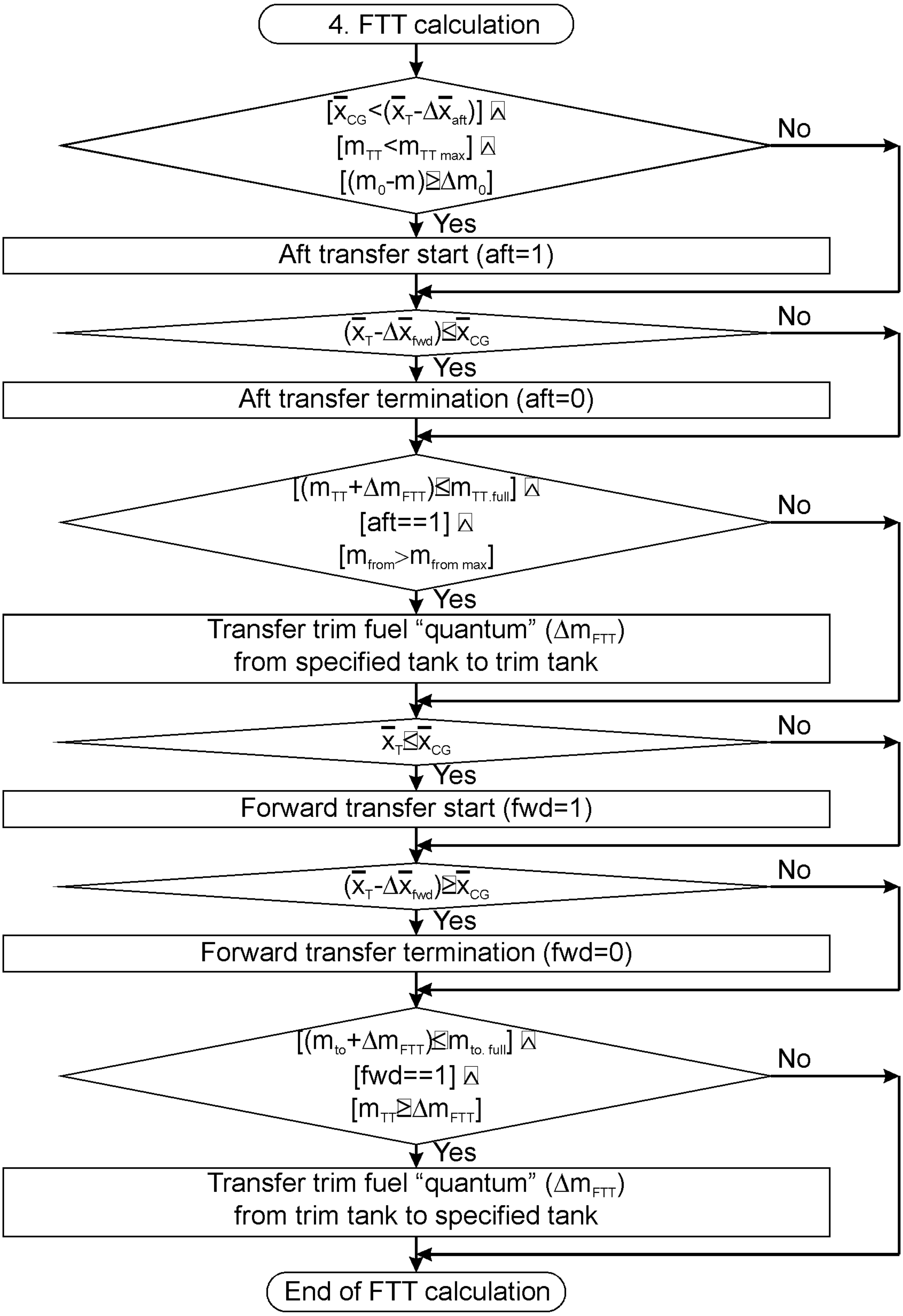


Figure 7 – FTT calculation algorithm

Aggregative fuel «usage» algorithm (see Fig. 6) was given in publication [4]. FTT calculation is performed just after CG position calculation in the loop for number of points of «usage» algorithm.

3. Calculation Results

The considered algorithm was implemented by the author in computation module of the Power Unit 11.6 software. The A-310 airplane was chosen as an example for FTT operation simulation. The CG position graphs for the airplane (calculated by the author) without fuselage tanks are shown in Fig. 8, and with fuselage tanks are given in Fig. 9. The CG position graphs taken from Flight Manual [5] are shown in Figs 10, 11.

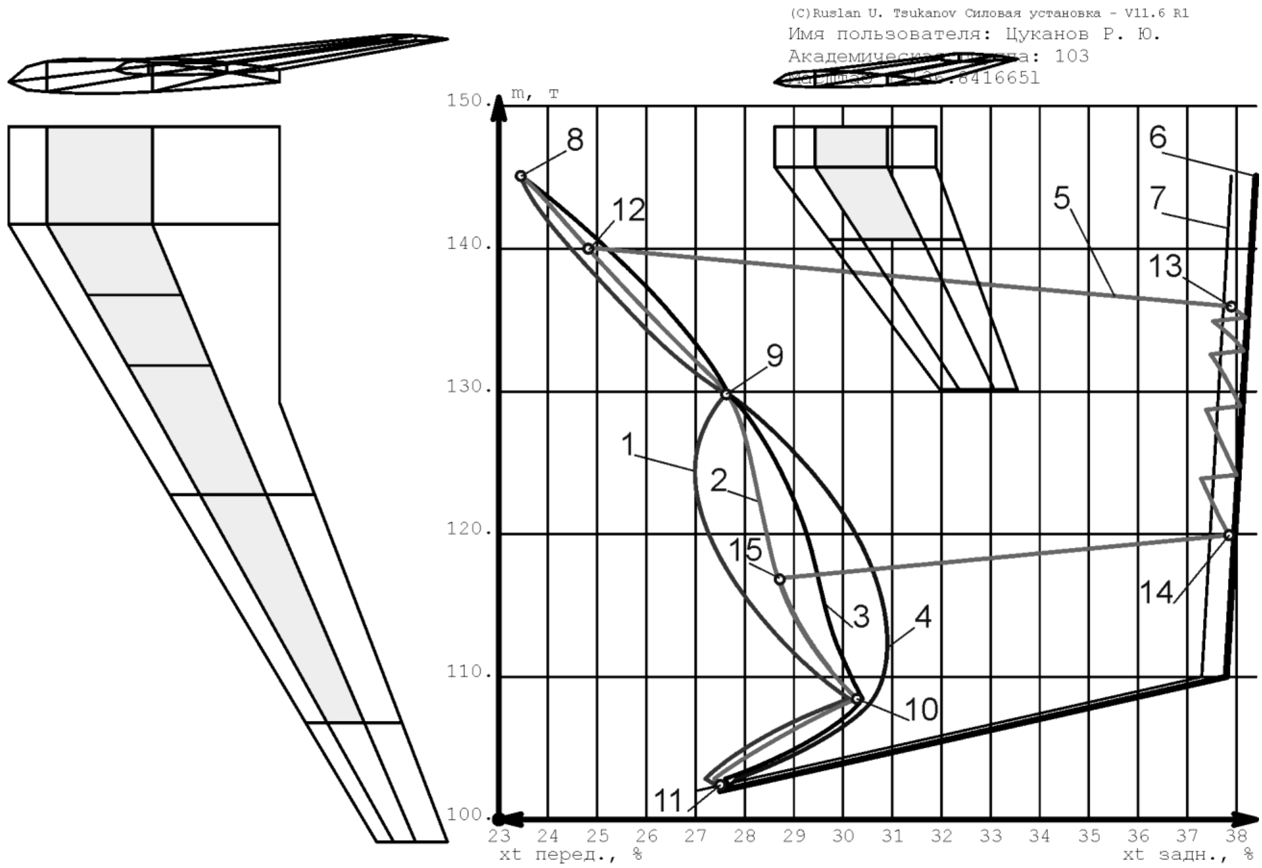


Figure 8 – CG position graph for A-310 airplane without fuselage tanks: 1 – In minimal pitch angle; 2 – In cruise pitch angle without FTT; 3 – In maximum pitch angle with RBCV; 4 – In maximum pitch angle without RBCV; 5 – In cruise pitch angle with FTT; 6 – Target CG position; 7 – Target CG position minus tolerance; 8 – Fuel utilization start from wing central section (WCS) tank; 9 – WCS tank depletion and fuel utilization start from inner tanks; 10 – Inner tanks depletion and fuel utilization start from outer tanks; 11 – Outer tanks depletion; 12 – Aft FTT start; 13 – Aft FTT termination; 14 – Forward FTT start before decent; 15 – Forward FTT termination before descent

In the first case (see Fig. 8), the airplane takes off with empty stabilizer tank. Its CG position graphs without FTT (1, 2, 3, 4) include two breaks, which are determined by fuel usage schedule adopted in the airplane. The first break 9 (at current mass of 130 t) corresponds to WCS tank depletion and inner wing tanks utilization beginning. The second break 10 (at current mass of 108 t) corresponds to the outer wing tanks utilization beginning.

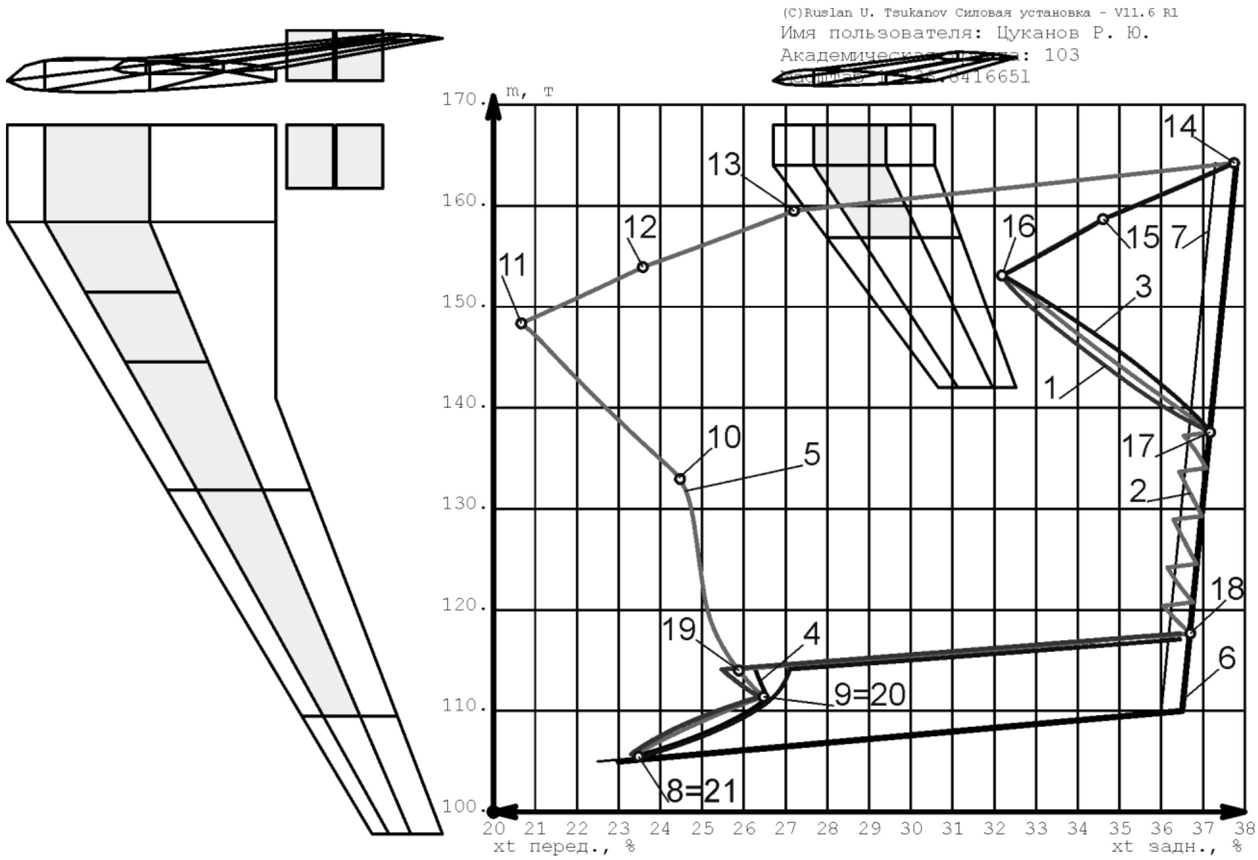
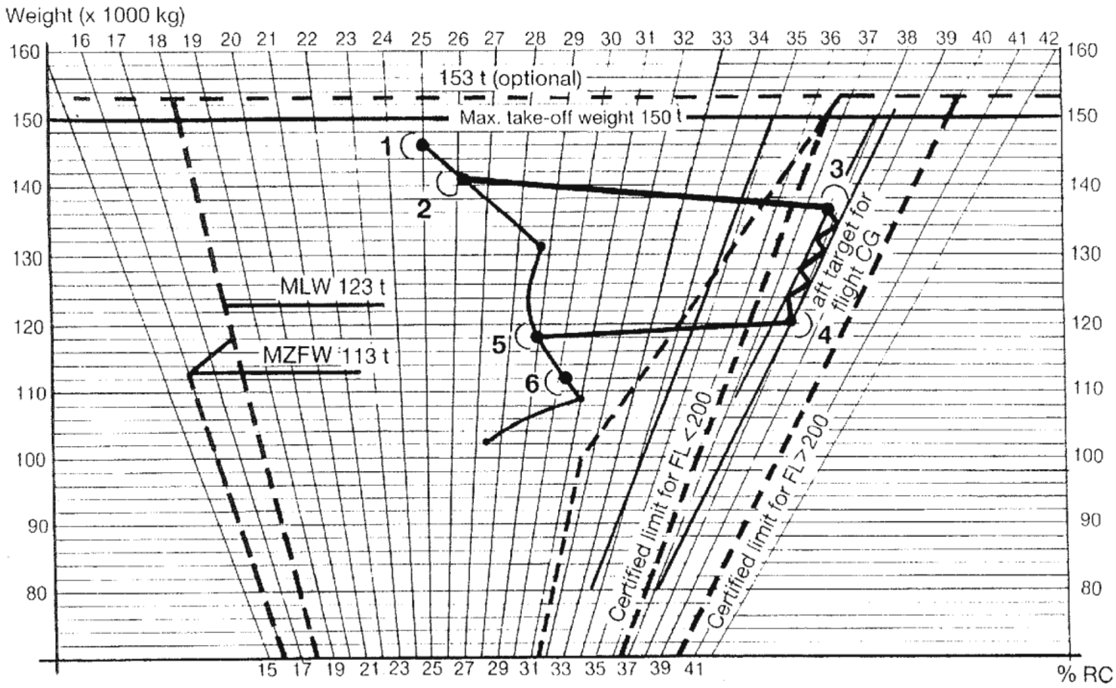


Figure 9 – CG position graphs for A-310 airplane with fuselage tanks:
1 – In minimal pitch angle; 2 – In cruise pitch angle with FTT; 3 – In maximum pitch angle; 4 – In maximum pitch angle with RBCV; 5 – Refueling schedule; 6 – Target CG position; 7 – Target CG position minus tolerance; 8 – Airplane without fuel; 9 – Outer tanks are refueled; 10 – Inner tanks are refueled; 11 – WCS tank is refueled; 12 – Forward fuselage tank is refueled; 13 – Aft fuselage tank is refueled; 14 – Stabilizer tank is refueled, fuel transfer start from aft fuselage tank; 15 – Aft fuselage tank depletion and forward fuselage tank transfer start; 16 – Forward fuselage tank depletion and WCS tank utilization start; 17 – WCS tank depletion and inner tanks utilization start; 18 – Forward transfer start before descent; 19 – Forward transfer termination before descent; 20 – Inner tanks depletion and outer tanks utilization start; 21 – Outer tanks depletion

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



Example for CG Control

1 - **Take-off** with no fuel in trim tank
2 - **Flight level 200** fuel being pumped into the trim tank
3 - **CG is at target** fuel being pumped forward in "packages" to keep CG at target
4 - **Flight level 200** remaining fuel in trim tank being pumped forward
5 - **Trim tank empty**
6 - **Landing**

Figure 10 – CG position graph for A-310 airplane without fuselage tanks from Flight Manual [5]

Aft FTT starts after definite (5 t) fuel mass utilization. Thus, fuel is transferred into stabilizer tank only from WCS tank. When the target CG position minus tolerance is reached (7), aft transfer terminates. In what follows in the process of fuel utilization from wing tanks, CG continuously shifts aft. When it reaches the target position (6), periodical forward FTT start occurs. So in cruise mode, CG is artificially kept within specified limits (band is equal to 0.5 %). During descent before landing, fuel remaining in stabilizer tank is transferred back into wing tanks. The following CG position variation is analogous to considered without FTT utilization. CG shift due to FTT application makes 9...13 %.

In the second graph for A-310 with fuselage tanks (see Fig. 9), airplane refueling process (curve 5) and flight with the other fuel burn schedule (curves 1, 2, 3, 4) are simulated. Note that in this case, the airplane takes off with stabilizer tank filled with fuel, and airplane CG is on the target. Fuselage tanks are used first (initially – aft, next – forward); then – WCS tank; after that, the CG again is on the target. Further, fuel usage from inner tanks starts, which shifts CG aft, that causes forward FTT periodical activation (curve 2). After the cruise flight completion (point 18), forward FTT with increase rate is activated. The following utilization process is analogous to one considered in the previous example.

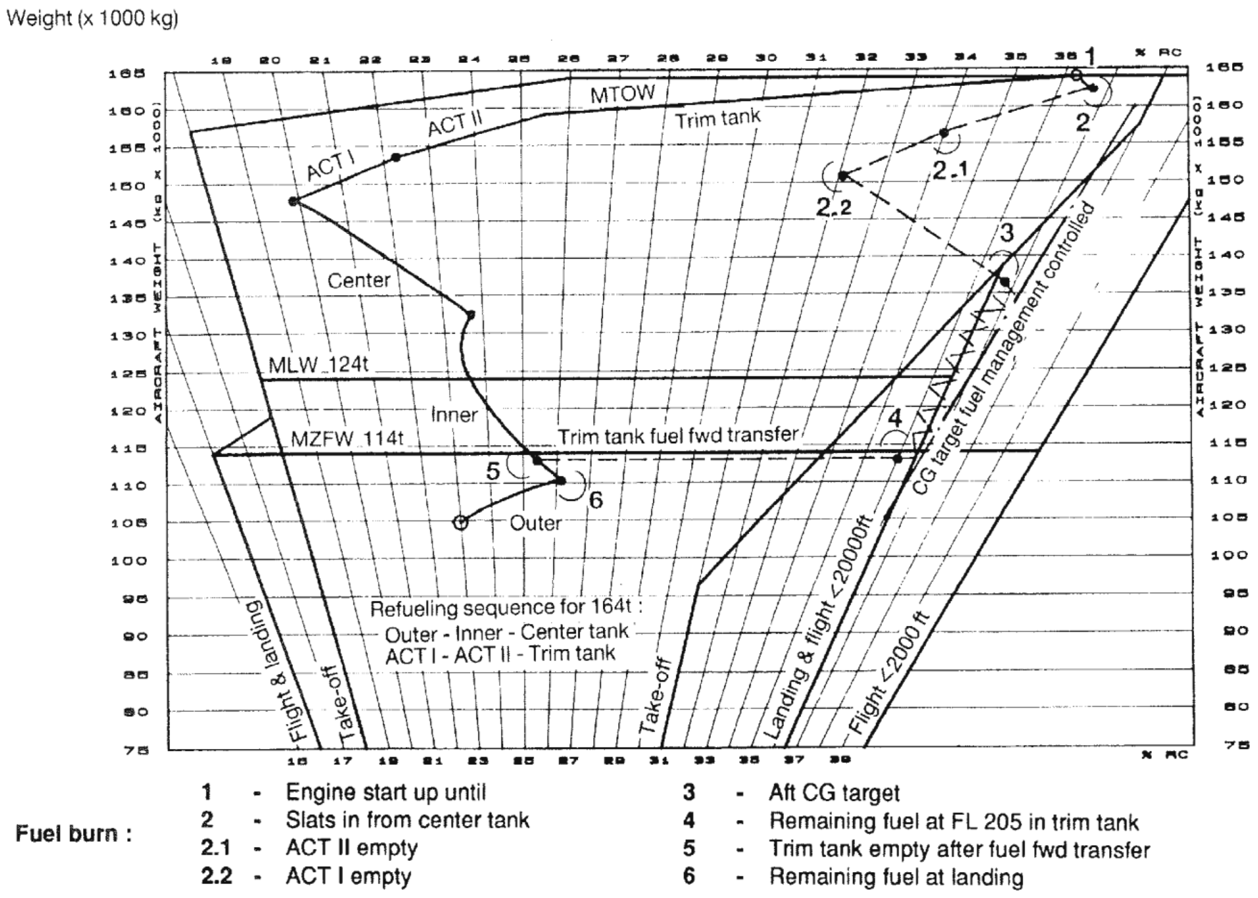


Figure 11 – CG position graph for A-310 airplane with fuselage tanks from Flight Manual [5]

As it is clear, CG position graphs for A-310 airplane got by calculation way according to the described algorithm are conformed well to the graphs from Flight Manual (see Fig. 10, 11).

Conclusions

1. Fuel trim transfer schemes known from the foreign practice are analyzed; and recommendations are given to choose the most reasonable among them for implementation in domestic aviation.

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 wings, 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, specified fuel burn schedule and its trim transfer.

3. By means of comparison with known CG position graphs (of A-310 airplane), adequacy of developed mathematical model is shown.

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