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Airplane Flight Center-of-Gravity Position Calculation Algorithm. Adaptation Features for Different Fuel Feed Schemes

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On the base of analysis of numerous real airplanes' fuel systems, fuel tank connection schemes, not described in academic books and methodological literature previously, are exposed i. e.: parallel connection without switching, mixed connection and convertible connection. Classification table has been developed, which allows to determine reasonable fuel feed scheme by correlation between the number of engines and the number of feed tanks taking into account wide experience of real airplanes' design. Fuel tank connection schemes and the number of engines fed from single feed tank influence are analyzed; and the ways to account them in airplane center-of-gravity calculation algorithm according to fuel burn sequence are proposed.
Key words: center-of-gravity, CG position, fuel tank, fuel system, fuel feed, feed tank, tank connection type, fuel feed method.

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. Accounting modern trends of commercial airplanes flight range increase and corresponding relative fuel mass increase onboard (more than 50 %), CG shift can be rather considerable.

But this shift becomes the most hazardous at pitch angle variation, when substantial fuel masses migrate along tank spanwise. As practically all modern commercial jet airplanes are equipped with swept-back wings, than this fuel migration along wing span is accompanied with CG shift along airplane axis. In these cases, it is necessary to estimate, if the airplane CG position is within acceptable limits from point of view of stability and controllability. In addition, CG position influences considerably on horizontal stabilizer trim lift, and, consequently, on the airplane fuel efficiency.

The aim of this publication is analysis of features and development of recommendations to adapt airplane center-of-gravity position calculation algorithm according to fuel burn sequence for various fuel tank connection schemes and number of engines fed from single feed tank. Thus, the determining factor is fuel system scheme selected accounting numerous considerations. To calculate it a designer must adapt general algorithm of calculation.

1. Tanks Connection Scheme Influence

As it is known, to arrange fuel onboard airplanes, designers try to use airframe payload volume as much as possible. In case of bladder-type or rigid tanks utilization, it forces to divide this volume into some tanks along airframe strong elements (spars, ribs, frames). For integral tanks, this partitioning into separate tanks can be caused by requirements of specified CG support, wing load alleviation, and also operational and battle survivability. In the sequel, these tanks are jointed in groups. There are feed tanks and transfer tanks. Feed (reservoir, sump) tank (FT) is a tank from which fuel is supplied to engines. Transfer tank (TT) is a tank from which fuel is transferred into FT.

In the literature [5–7], only two schemes of tanks connection are usually discussed: parallel and serial. More careful analysis of real fuel systems allows to distinguish five types of tanks connection (Fig. 1): the simplest, parallel, serial, mixed, and convertible schemes.

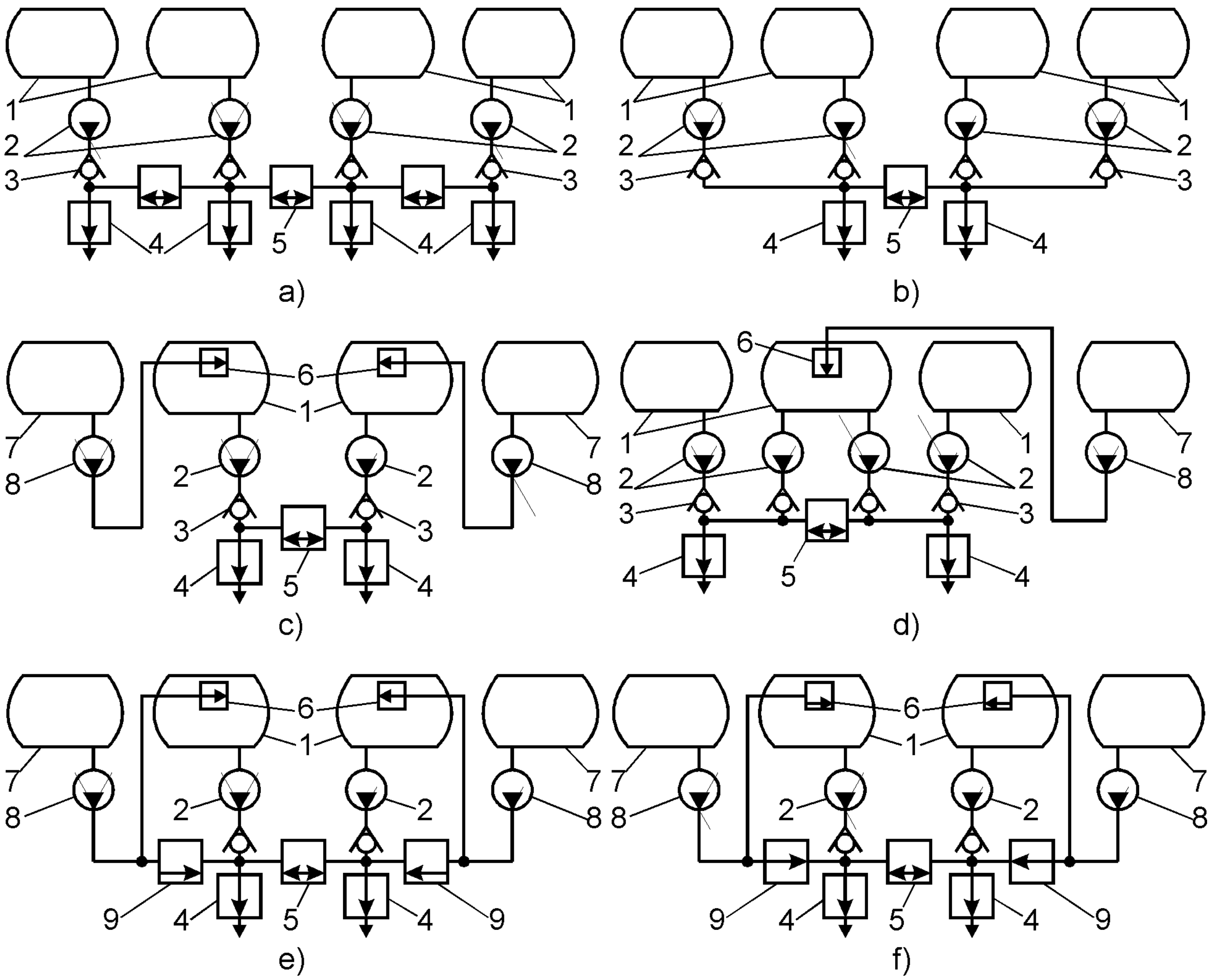

Fig. 1. Tanks connection types:
a — Simplest; b — Parallel; c — Serial; d — Mixed; e — Convertible in serial mode; f — Convertible in parallel mode; 1 — Feed tanks; 2 — Boost pumps of airplane; 3 — Check valves; 4 — Engine low pressure valves; 5 — Cross-feed valves; 6 — Transfer valves; 7 — Transfer tanks; 8 — Transfer pumps; 9 — Control valves

In the **simplest** (parallel without switching) connection type, total number of fuel tanks (n_T) is equal to number of feed tanks (n_{FT}) and does not exceed the number of engines (n_{en}) ($n_T = n_{FT} \le n_{en}$). In other words, all tanks are feed tanks and of equal volume; fuel is supplied to engines simultaneously from all tanks. There is no fuel transfer or switching among the tanks. Advantages of this connection type are minimal quantity of control devices, absence of problems with switching between the tanks, survivability due to fuel supply from any one tank directly into any one engine. This connection type is used for short-range airplanes only (Бе-200, Ил-114, Як-40, Як-42, ATR-42, DHC-4, X-22, YC-15), because big amount of fuel, intended for one engine, is seldom possible to arrange in single FT.

In **parallel** (parallel with switching) connection type, total number of fuel tanks is equal to number of feed tanks and exceeds a number of engines ($n_T = n_{FT} > n_{en}$). In other words, all tanks are feed ones, but fuel is supplied to engines not from all tanks simultaneously. On depletion of these tanks, system switches to the other tanks. There is still no fuel transfer among the tanks. Advantages of this connection type are relatively small quantity of control devices, high survivability because fuel can be supplied from any tank directly into any engine, possibility to control the engine fuel feed by using any program. Disadvantages are necessity to install boost pumps and recuperators inside each tank, that increases mass, and also problems related to switching among the tanks. This connection type is widely used in foreign passenger and transport airplanes (DC-9, B-727 / 737 / 757 / 767 / 777 / 787, A-310, C-160, C-27, C-130, C-141), and is sometimes used in military purpose aircraft (A/C) (A-10, SR-71). In domestic practice, it is assumed obsolete.

To provide uninterruptible engine fuel feed while switching between the tanks, four methods are used. In the **first method**, tree-mode direct current (DC) pumps are used capable to create different pressure (Ан-10, Ил-18, Ту-114). So, the pump of a tank from which fuel is supplied in that moment works in nominal rating; but before the tank depletion, it is turned to high rating. In the same time, the pump of tank being the following in order works in standby rating; and it is turned to nominal rating while switching to this tank. In modern A/C, this method is not used because of high power DC pumps low efficiency, high complexity and low reliability of the pump rating control system. The **second method** uses single-mode alternative current (AC) pumps of different power. In this case, more powerful pumps are installed in tanks which should be depleted in the first order. It simplifies control system, increases system efficiency and reliability; but requires different type pumps application in the same A/C. This method is used in practically all passenger airplanes of Boeing company.

In the **third method**, identical single-mode pumps are used; but in the first order tank, two pumps are connected serially (DC-9, MD-80), that increases overpressure generated by the pumps. The advantage of this method is single pump type utilization; disadvantage is reliability decrease of serially connected pumps. According to the **fourth method**, identical single-mode pumps are also used; but less rigid springs are installed inside check valves of the first order tanks (KC-135, B-737-900), that provides their first order depletion.

In **serial** (with feed tanks) connection type, total number of fuel tanks is more than number of feed tanks, which, in turn, does not exceed number of engines ($n_T > n_{FT} \le n_{en}$). In this case, fuel from transfer tanks is transferred into the feed tanks, and then is supplied to engines. This connection type decreases mass of fuel system, because the pumps transferring fuel from tank to tank generate less overpressure and have less mass. In addition, recuperators are placed in feed tanks only. This connection type provides temperature equalization of fuel going to engine; and also ensures fuel reserve. Disadvantages of this connection type are low survivability and big quantity of control devices. Now, this connection type is used the most widely (Ан-14 / 28 / 38 / 140 / 148, Ил-62 / 76 / 86 / 96, МиГ-19 / 21 / 23 / 25 / 27 / 29, Су-25 / 27 / 39, Ту-134 / 144 / 154 / 214 / 334, RRJ, A-330 / 340 / 380, KC-10, A-3 / 4 / 5 / 6 / 7, AV-8, XB-70, B-1, F-4 / 14 / 15 / 16 / 18 / 117 / 23 / 35, S-3, Tornado, EF-2000).

Mixed connection type is a combination of serial and parallel types. In this case, total number of fuel tanks is more than number of feed tanks, which exceeds the number of engines ($n_T > n_{FT} > n_{en}$). As a rule, designers come to this connection type on the base of initial parallel scheme, by means of additional fuselage tanks installation (B-727, MD-80, A-310) or by using outer fuel tanks for wing load alleviation (B-707 / 747, A-320). As it is far easier to make additional tanks as transfer tanks, then transferring from them into feed tanks is added, and it results in mixed connection type.

Convertible (multimode) connection type distinguishes by operation capability in some different modes: as serial connection type (with different FT) or as parallel one. Advantages of convertible connection type are maximum possible survivability and reliability. Its disadvantages are the biggest mass and complexity of the system, and also the greatest number of control devices. This connection type is used in different purpose A/C (Ан-26 / 74 / 70 / 124, A-340, A-7, B-1, C-5 / 130 / 141, F-105).

Practically, during center-of-gravity calculation, it is necessary to consider specified fuel burn sequence, at any type of tanks connection. For the simplest scheme, no additional actions required. The parallel scheme can be reduced to serial one: the last order fuel tanks are considered as feed tanks; but for the previous orders, transfer beginning into feed tanks shall be specified conventionally at full FT. The serial scheme requires special algorithm development, which is a subject of separate publication. The mixed scheme can also be simulated conventionally: by specifying conditions for fuel transfer for both serial and parallel tank connections. For convertible scheme, a set of calculations is required: for serial mode operation with specified fuel burn sequence, and for parallel (emergency) mode operation, when some different fuel burn sequences are possible.

2. Influence of Number of Engines Fed From Single Feed Tank

Depending on a number of engines fed from single feed tank, they usually distinguish: centralized, centralized-independent, partial and independent feed (listed in the reliability increase order). In addition, excessive feed is sometimes used to provide the highest reliability, but it is not mentioned in the domestic literature.

At **centralized feed**, fuel from single feed tank ($n_{FT} = 1$) is supplied to all A/C engines (Fig. 2, a). Advantages of this feed are minimal mass and maximum simplicity. Disadvantages are minimal reliability and survivability. This feed type was widely used in military aviation, until survivability became one of the main requirements for A/C.

At **centralized-independent feed**, fuel from each feed tank is supplied to definite group of engines, and usually $n_{en}/n_{FT} = 2$ (for example, to engines located under one wing) (Fig. 2, b). Here, advantages and disadvantages are the same, but expressed weakly. This feed type is used extremely seldom.

At **partial feed**, fuel from definite feed tank is supplied in addition to corresponding engine to some more engines ($n_{en}/n_{FT} = 1.5$). Author knows only one airplane with three engines and two FT. But practically any other feed type can turn in partial feed in emergency mode.

At **independent feed**, fuel from each group of tanks is supplied to single definite engine, $n_{en}/n_{FT} = 1$ (See Fig. 1, a, b, c, e, f). This feed type in majority of cases provides enough reliability and survivability, that is confirmed by its widest application. Disadvantages of this feed type are increase of mass and complexity.

At **excessive feed**, fuel is supplied from two groups of tanks to single engine through proportioner ($n_{en}/n_{FT} = 0.5$). Advantages of this feed type are the highest reliability and survivability. Disadvantages are big mass and complexity, and also necessity to provide equal fuel feed from two groups of tanks. The last is usually ensured by installation of fuel proportioner, that is displacement pump, providing equal fuel volumes supply from two FT. This feed type is used in single-engine A/C of military purpose.

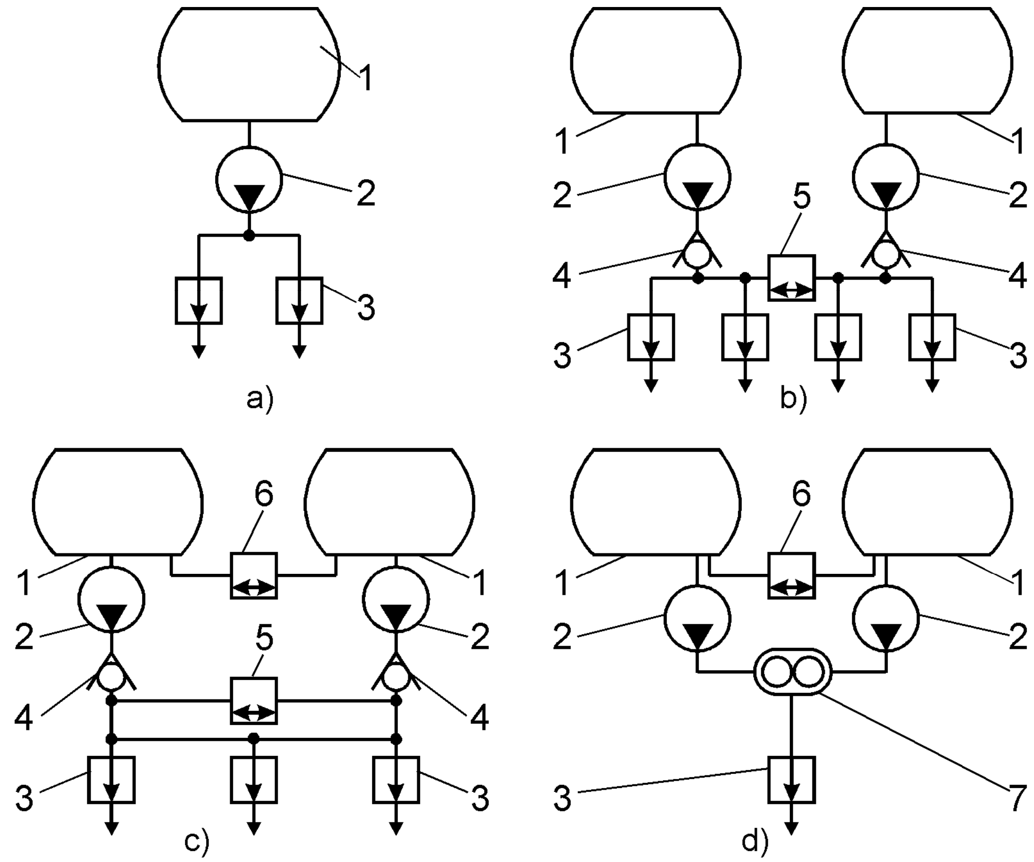

Fig. 2. Feed schematic:
a — Centralized; b — Centralized-independent; c — Partial; d — Excessive; 1 — Feed tanks; 2 — Boost pumps of airplane; 3 — Low pressure valves; 4 — Check valves; 5 — Cross-feed valves; 6 — Feed tank interconnect valves; 7 — Proportioner

Statistical data shown in the table 1 allow to make more common conclusions.

The first line of the table (below the head) corresponds to centralized feed. The diagonal corresponds to independent feed. The cells lying above the diagonal but below the first line correspond to partial or centralized-independent feeds. The cells lying below the diagonal correspond to excessive feed. The parallel tank connection scheme is placed into separate line, as in this case all tanks are feed ones. Airplane models which fuel system can work at partial failures in different mode (convertible scheme) are given in parentheses.

Influence of number of engines fed from single feed tank should be taken into account when determining fuel flow from this FT. Thus, fuel flow from the considered FT is defined as a product of fuel consumption for single engine by number of engines fed from this FT. Note, that for excessive and partial schemes, this number is fractional. For

TT, fuel transfer flow shall be determined by number of fuel tank groups, in which this TT is included.

Table 1

Correlation between number of engines and feed tanks

Number of engines / FT number	1	2	3	4	6 and more
1 FT	A-4, A-7, F-104, МиГ-21, МиГ-23/27	A-3, A-5, A-6, F-4, F-101, МиГ-19, МиГ-25, МиГ-29, Су-25, Су-27	Ту-154	X-22	XB-70
2 FT	(A-7), AV-8, F-16, F-35	A-330, ATR-42, BAC-111, C-123, DHC-4, F-5, F-14, F-15, F-18, F-111, F-117, RRJ, Tornado, YF-23, Ан-14, Ан-28/38, Ан-74, Ан-140, Ан-148, Бе-200, Ил-114, Су-39, Ту-134, Ту-204, Ту-334,	Як-40	A-340, B-1, Ил-18	
3 FT			DC-10, KC-10, Falcon 900, Як-42		(ТВ-47)
4 FT				(A-340), A-380, YC-15, C-5, Concorde, DC-8, Ан-70, Ан-124, Ил-62, Ил-76, Ил-86, Ил-96, Ту-144	
Parallel	Ан-2/3, F-20	A-10, A-310, A-320, B-737, B-757, B-767, B-777, B-787, C-160, C-27, DC-9, MD-80, SR-71, Ан-24/26, Ту-104, Ту-114	B-727	B-58, B-747, (C-5), C-141, (DC-8), KC-130, KC-135, Ан-10/12, Ан-22, (Ан-70), (Ан-124)	B-36, B-47

Thus, compliance with the recommendations given above allows to adapt and to use effectively the general algorithm for airplane center-of-gravity position calculation according to fuel burn sequence for computation of practically any fuel tank connection scheme used nowadays and the number of engines, fed from single feed tank.

Conclusions

1. On the base of analysis of great quantity of actual airplanes' fuel systems, the following fuel tank connection schemes are exposed, not described in literature previously: parallel without switching, mixed and convertible.

2. The developed classification table allows to determine reasonable fuel feed scheme by correlation between the number of engines and the number of feed tanks taking into account wide experience of various purposes real airplanes' designing, both domestic and foreign.

3. Influence of fuel tank connection schemes and the number of engines fed from single feed tank are analyzed and recommendations are given to account them in airplane center-of-gravity calculation algorithm according to fuel burn sequence.

4. Serial fuel feed scheme has specific set of features and requires to develop the special algorithm in what follows.

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Особливості адаптації алгоритму розрахунку польотного центрування літака для різноманітних схем подачі палива

На основі аналізу великої кількості паливних систем реальних літаків виявлено раніше не описані у навчальній та методичній літературі схеми об’єднання паливних баків, а саме: паралельна без переключення, змішана та конвертована. Розроблено класифікаційну таблицю, що дозволяє за співвідношенням між кількістю двигунів і витратних баків визначити раціональну схему подачі палива з урахуванням великого досвіду створення реальних літаків. Проаналізовано вплив і запропоновано шляхи урахування способів об’єднання паливних баків і кількості двигунів, що живляться з одного витратного бака, в алгоритмі розрахунку центрування літака відповідно до витрати палива.

Ключові слова: центр мас, центрування, паливний бак, паливна система, витрата палива, витратний бак, спосіб об'єднання баків, спосіб живлення.

Особенности адаптации алгоритма расчёта полетной центровки самолёта для различных схем подачи топлива

На основе анализа многочисленных топливных систем реальных самолётов выявлены ранее не описанные в учебной и методической литературе схемы объединения топливных баков, а именно: параллельная без переключения, смешанная и конвертируемая. Разработана классификационная таблица, позволяющая по соотношению между количеством двигателей и расходных баков определить рациональную схему подачи топлива с учетом обширного опыта создания реальных самолетов. Проанализировано влияние и предложены пути учёта способов объединения топливных баков и количества двигателей, питаемых из одного расходного бака, в алгоритме расчёта центровки самолёта по мере выработки топлива.

Ключевые слова: центр масс, центровка, топливный бак, топливная система, выработка топлива, расходный бак, способ объединения баков, способ подачи.