An Optimization Method of Formation Flight for Minimizing Fuel Consumption

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Abstract: A method for formation flight trajectory optimization was established. This method aims at minimizing fuel consumption of a two-aircraft formation flight, without changing the original trajectory of the leader. Candidate flight pairs were selected from all international flights arriving at or departing from China in one day according to the requirement of the proposed method. Aircraft performance database Base of Aircraft Data (BADA) was employed in the trajectory computation. By assuming different fuel-saving percentages for the following aircraft, pre-flight plan trajectories of formation flight were optimized. The fuel consumption optimization effect under the influence of different trajectory optimization parameters was also analyzed. The results showed that the higher the fuel savings percentage, the longer the flight distance of formation flight, but the smaller the number of formation combinations that can be realized, which is limited by the aircraft performance. The following aircraft flying along the approximate actual flight trajectory can be benefited as well, and the optimal fuel-saving efficiency is related to the expected fuel-saving efficiency of formation flight.

Key words: formation flight; trajectory optimization; fuel-saving; Base of Aircraft Data (BADA)

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0 Introduction

Birds take advantage of formation flight to save energy, which has been known for many years. Studies have been carried out applying formation flight to commercial flight aiming at improving transportation capacity and reducing greenhouse gas emissions. Simulation and experimental tests have showed that formation flight can reduce fuel consumption by up to 20%[1-5]. Similar results were obtained in flight tests as well[6-10].

Research efforts have also been carried out applying formation flight to trajectory optimization. There have been several efforts related to aircraft trajectory optimization to reach a numerical solution, using heuristic optimization techniques[11], or to develop an analytical solution[12-13]. In very rare cases several flights were sharing similar flight plans including departure and arrival airport, and departure times[14]. Therefore, route optimization was analyzed with the same departure or arrival airport[15]. Based on previous results, a completely decentralized approach was established[16], which suppressed the occurrence of large detours in the assembly of flight formations. Recently, an optimization framework was also developed that relies on optimal control theory to solve the multiple-phase optimization problem[17].

Formation flight trajectory optimization has been a hot topic in the last decade. However, most of the studies, optimizing the total fuel consumption, were based on the assumption that both the

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leading aircraft (leader) and the following aircraft (follower) agree to change their original trajectories. In these methods, only the follower's fuel consumption is reduced and the leader's fuel consumption is increased because of the detour required to match both trajectories. This is unrealistic even when the two flights are operated by the same airline, because the pilot's performance evaluation is related to fuel consumption. This shortcoming makes it difficult to implement these algorithms into real-world operations. It is more practical if the leader's operation is not impeded and only the follower's trajectory is replanned to form the formation. Another factor constraining the application of current studies is that free-routing airspace is assumed while the airspace structure is not taken into consideration.

In order to address these two problems, a novel optimization method of formation flight for minimizing fuel consumption is proposed in this paper. We assume that only the follower's trajectory is revised to follow the leader while the leader's trajectory remains unimpeded. Under this assumption, the leader's trajectory follows the existing airspace structured, so that the availability of the path of the new formation is guaranteed. Therefore, the proposed method could potentially be achievable in the near future.

In the development of this method, this paper focuses on two key questions: Could the follower still be benefited by formation flight, when it follows the actual trajectory of the leader; and how much savings could be achieved? To answer these questions, we set constraints to candidate flight pairs selection and optimized the rendezvous and separation points for the follower. Then, the formation of flight trajectory and fuel consumption for the follower is optimized. Such trajectory optimization is not geometric optimization, but based on real trajectory. Consumption is estimated according to aircraft data. The numerical study results are closer to the actual fuel saving after the formation flight is put into effect.

In this study, historical trajectory data of the whole world on one day are taken as a sample dataset. Candidate flights are filtered for formation flight, and fuel consumption is estimated by each case. This paper is organized as follows: Section 1 describes the heuristics that acts as filters on the combinatorial set of all possible candidates. Section 2 describes trajectory computation methodology, including models for aircraft and trajectory constraints. Section 3 describes the methodology of trajectory optimization. Results analysis for China international flights are provided in section 4. Discussion and conclusions are given in sections 5.

1 Candidate Search for Formation Flight

As fuel consumption estimation for the whole trajectory is very time-consuming. Aiming at tens of thousands of trajectories, it is impractical to estimate every trajectory. Hence, candidates selection is carried out only by the positions of the departure airport (A_D) and arrival airport (A_A), subscripts letters "l" and "f" are for leader and follower, respectively. As the leader's trajectory has not been changed, we assume the leader trajectory from A_{Dl} to A_{Al} is the great circle route (GCR) for filter candidates. And the spherical perpendicular from A_{Df} and A_{Af} to the leader's GCR is made. As shown in Fig.1, the red line is the trajectory of the leader; the upper green line is the trajectory of the follower for case 1; the lower green line is the trajectory of the follower for case 2.

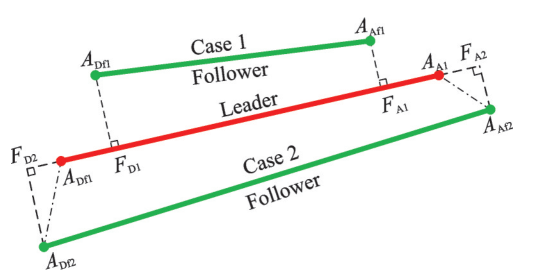

Fig.1 Geometric construction of two cases of two-aircraft formation mission

We take the two cases shown in Fig. 1 as samples. In both cases, the A_{Df} and A_{Af} have footpoint (F) on leader GCR or its extension line. As rendezvous point (P_R) and separation point (P_S) have not been set, we assume that the follower departs from

A_{Df} and passes F for departure (F_{D}) and F for arrival (F_{A}) sequentially, then arrives at A_{Af} finally. Therefore, F_{D} is P_{R}, and F_{A} is P_{S}. In case 1, both A_{Df1} and A_{Af1} have F on the leader's GCR as F_{D1} and F_{A1}, respectively. And in case 2, both A_{Df2} and A_{Af2} have F on the extension line of leader GCR. During filtering, we take A_{Dl} and A_{Al} as F_{D2} and F_{A2}, which means the follower flies along the dot-dash line in Fig.1. Between F_{D} and F_{A} is the overlapping trajectory, which is the part of the trajectory where formation flight will take place.

After the route is set, we require the flight direction of both aircraft are identical. Longitude is chosen as the indicator of direction. The east and the west are presented by positive and negative longitude, respectively, and International Date Change Line is simplified to be $\pm 180°$. To make sure two aircraft have the same flight direction, Eq.(1) needs to be met, where lng refers to longitude

$$(\ln g_{F_{\mathrm{D}}} - \ln g_{F_{\mathrm{A}}})(\ln g_{A_{\mathrm{D1}}} - \ln g_{A_{\mathrm{A1}}})(180 - |\mathrm{lng}_{F_{\mathrm{D}}} - \mathrm{lng}_{F_{\mathrm{A}}}|)(180 - |\mathrm{lng}_{A_{\mathrm{D1}}} - \mathrm{lng}_{A_{\mathrm{A1}}}|) > 0 \tag{1}$$

To ensure that the benefit of formation exceeds the cost of detouring, κ_d is introduced as the minimum ratio of overlapping. We divide the formation flight trajectory of the follower into three phases, $d_{D_{\mathrm{A}}F}$, $d_{A_{\mathrm{A}}F}$, and d_{FF}, where $d_{D_{\mathrm{A}}F}$ is the distance between A_{Df} and F_{D}, $d_{A_{\mathrm{A}}F}$ is the distance between A_{AF} and F_{A}, d_{FF} is the distance between F_{D} and F_{A}, or the distance of overlap trajectory, as shown in Fig.2.

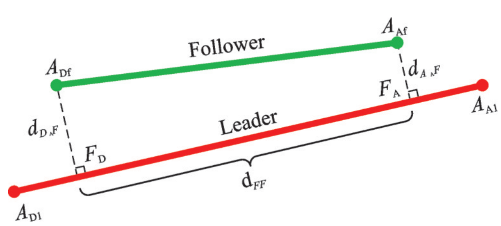

Fig.2 Geometric construction of overlap ratio estimation

$$\frac{d_{FF}}{d_{D_{\mathrm{A}}F} + d_{FF} + d_{A_{\mathrm{A}}F}} \geqslant \kappa_d \tag{2}$$

As presented by Eq.(2), the ratio of d_{FF} to the sum of $d_{D_{\mathrm{A}}F}$, $d_{A_{\mathrm{A}}F}$ and d_{FF} must be no less than κ_d, to ensure that the follower has sufficient formation flight distance. Obviously, the larger the overlap ratio, the more efficiency the follower can obtain.

Formation flight requires the follower to unite with the leader. To achieve this, normally, the followers need to adjust their departure time. A threshold must be set to the shift of departure time. As F_{D} is obtained already, we assume that the leader and the follower arrive at P_{R} simultaneously from F_{D} and $A_{\mathrm{D}F}$, respectively. From the actual trajectory of the leader, we can find the tracking point closest to F_{D}, and take the time when the leader passed it as t_{l}, and take the takeoff time of the follower as t_{f}. We define the time threshold as t_{lag} and therefore we impose the following constraint

$$|t_{\mathrm{l}} - t_{\mathrm{f}}| \leqslant t_{\mathrm{lag}} \tag{3}$$

Besides trajectory information, aircraft types are also contained in the dataset. The aerodynamic performances of aircraft are taken into consideration. The follower is not a match for the leader, if its upper limit of airspeed and flight altitude is lower than the corresponding value of the leader during its cruise phase.

In this paper, worldwide historical trajectory data of 20 January, 2017 are employed, including 140 000 flights of ADS-B record. Fourteen thousand flights that arrived at or departed from China are extracted as a sample dataset. Candidates for formation flight are selected from the dataset. Based on the above-mentioned requirements, we obtain the sensitiveness of the number of candidates to κ_d and t_{lap} as shown in Table 1.

Table 1 Number of formation flight candidates

κ_d	t_{lap}/s		
	1 800	3 600	5 400
0.9	298	567	807
0.8	640	1 233	1 773
0.7	936	1 797	2 606

The larger t_{lag} or the smaller κ_d, the more formation flight candidates. Smaller κ_d makes the candidates be excessive, and is time-consuming for further trajectory optimization. However, larger κ_d limit the number of candidates. t_{lag} depends on operational constraints, but longer than 1 h is probably unbearable. For trajectory optimization in this paper, we filter candidates by setting $\kappa_d = 0.8$, and

t_{lag} = 3 600 s. Thus 1 233 candidate flight pairs met the requirements.

2 Trajectory Computation Methodology

When computing the aircraft trajectory, several considerations must be taken into account. First, the aircraft performance model is needed, with the definition of a mathematical model representing aircraft dynamics and its performance. Second, in order to obtain operationally sound trajectories, flight envelope and air traffic management (ATM) constraints must also be specified, as detailed in "Trajectory constraints modeling"[18]. Finally, atmospheric variables, such as wind, temperature, and pressure, are also needed, since they have a significant influence on the trajectory.

A point-mass dynamic model, Eurocontrol's Base of Aircraft Data (BADA), and the International Standard Atmosphere (ISA) have been considered in this paper. More mathematical details on the formulation of this computation methodology can be found in Ref. [19].

2.1 Aircraft model

Accurate estimation of fuel consumption in formation flight needs to be in accord with reality. To obtain realistic results, an aircraft performance model (APM) is required to accurately represent aircraft behavior. BADA is an APM based on the kinetic approach developed and maintained by Eurocontrol, with the active cooperation of aircraft manufacturers and operating airlines. BADA was designed for trajectory prediction and simulation for purposes of ATM research and operations, and has a high reputation within the academic and research world. A multi-platform library, pyBADA designed for a rapid, easy and transparent integration in Python of the BADA APM for ATM research purposes, is used in this study. The applications of pyBada include aircraft performance modeling, trajectory prediction and optimization, and visualization[19].

pyBADA assumes a nonlinear point-mass representation of the aircraft, where forces are applied at its center of gravity. It is reduced to what is commonly called a gamma-command model, where continuous vertical equilibrium is assumed. Gamma-command point-mass models have been reported to provide sufficient fidelity for ATM purposes. Aircraft dynamics are described in the air reference frame assuming flat nonrotating earth and neglecting wind components, yielding to the following set of differential equations

$$\begin{cases} \dfrac{\mathrm{d}v}{\mathrm{d}t} = \dot{v} = \dfrac{T-D}{m} - g\sin\gamma \\ \dfrac{\mathrm{d}s}{\mathrm{d}t} = \dot{s} = v\cos\gamma \\ \dfrac{\mathrm{d}h}{\mathrm{d}t} = \dot{h} = v\sin\gamma \\ \dfrac{\mathrm{d}m}{\mathrm{d}t} = \dot{m} = -F_{\mathrm{F}} \end{cases} \tag{4}$$

where $\boldsymbol{x} = [v, s, h, m]$ is the state vector, in which v is the true airspeed, s the along path distance, h the altitude and m the mass of the aircraft; T the total thrust; D the aerodynamic drag; g the gravity acceleration, assumed to be constant; γ the aerodynamic flight path angle and F_{F} the fuel flow. The control vector considered is $\boldsymbol{u} = [\gamma, \pi]$, where π is the throttle setting.

All aerodynamic and engine parameters are represented by continuous polynomials that use manufacturer performance data encoded in BADA. The ISA has also been considered in this model.

2.2 Trajectory constraints modeling

Besides the dynamics of Eq. (4), other constraints must be specified to model certain operational aspects or limits. In pyBADA, the initial and final conditions of the problem are taken. At the moment the slats are retracted after the take-off or extended before the landing. The remaining parts of the take-off and approach are not considered because the trajectory is heavily constrained by operational procedures. For the initial point of the trajectory, the mass of the aircraft is not fixed. All the remaining state variables are fixed to typical operational values.

Generic bounding constraints on certain variables are specified as follows

$$\begin{cases}\gamma_{\min}\leqslant\gamma\leqslant\gamma_{\max}\\0\leqslant\pi\leqslant1\\v_{\mathrm{CAS\,min}}\leqslant v_{\mathrm{CAS}}\leqslant v_{\max}\\Ma_{\min}\leqslant Ma\leqslant Ma_{\max}\end{cases}\tag{5}$$

where v_{CAS} is the calibrated airspeed (CAS) and $\gamma_{\min}$, $\gamma_{\max}$, $v_{\mathrm{CAS\,min}}$, $Ma_{\min}$ (minimum Mach number), $v_{\max}$ (velocity maximum in operations) and $Ma_{\max}$ (maximum Mach in operations) are aircraft dependent scalars.

3 Pre-flight Plan Trajectory Optimization

Horizontal and vertical pre-flight plan trajectory optimization was carried out based on the whole trajectory of the follower, including formation flight part and trajectories where the follower flied alone. Fuel flow was calculated by aircraft model, which is described in Section 2. As only one location for P_{R} or P_{S} of a minimum of fuel consumption was exist on the trajectory, we used a bubble sort algorithm to realize the optimization.

3.1 Horizontal route optimization

In this part, P_{R} and P_{S} location on the trajectory of the leader were optimized. The new trajectory of the follower from the initial position to P_{R} and from P_{S} to terminal position need to be built, if the leader and the follower do not have the same A_{D} or A_{A}. As shown in Fig.3, the blue line is the trajectory of the follower for formation flight.

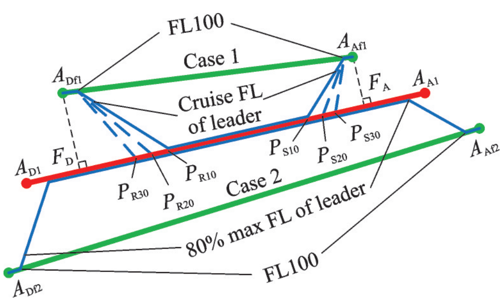

Fig.3 Horizontal route diagram

In case 1, the trajectory of the follower was shorter than that of the leader. The assumption was made that the trajectory below FL100 was governed by terminal airspace structures. So that the trajectory of the follower remained unchanged below FL100, presenting the taking off or landing phase. And we adjusted the time of those trajectories to ensure they could match the formation flight. The initial position was where the follower reached FL100, and the terminal position was where the follower descent under FL100. The trajectories that needed to be built were from initial position to P_{R} and from P_{S} to terminal position. When the follower passed P_{R}, it had an identical position with the leader, both horizontally and vertically. And they also should have performed at the same airspeed. A similar condition should be achieved when the follower leaved the leader at P_{S}. To allow the follower to unite with the leader, the follower and the leader passed P_{R} or P_{S} at the same time. Further description is expressed in vertical route optimization.

In case 2, as above mentioned in Section 1, P_{S} and P_{R} were close to A_{D} and A_{A}. The new trajectory of the follower followed the original trajectory below FL100 as above mentioned in case 1. In ideal conditions, the follower unites with the leader from A_{D} to A_{A}. But the follower needs to wait until the leader achieves the cruise altitude, or holds an altitude before it arrives A_{Af}. As the actual flight trajectory is not ideal, it is hard to predict the cruising altitude of the leader. We assumed the follower needed to achieve 80% max altitude of the leader at first, then maintained the altitude until the follower united with the leader at P_{R}. The P_{S} must be above 80% max altitude of the leader also.

The mass of aircraft is a key factor in trajectory modeling. We took the nominal mass in BADA as the mass when the follower passed the initial position, and we took 90% of the maximum landing mass as the mass when the follower passed the terminal position, for every type of aircraft.

For horizontal route optimization, the position of P_{R} and P_{S} were optimized depending on assumed fuel-saving percentage (AFS). AFS is the difference between estimate fuel consumption and original fuel consumption as a percentage of original fuel consumption. As estimating fuel consumption for each trajectory for optimization is too time-consuming, we presented the fuel-saving effect as the reduction of distance during formation flight. $d_{A_D P_R}$ is the distance between A_{Df} and P_R, $d_{P_R P_S}$ is the distance between P_R and P_S, and $d_{P_S A_A}$ is the distance between P_S and A_{Af}. d_{total} is the total flying distance of the follower. We optimize P_R and P_S by minimizing the d_{total}, and take the position reporting point as the results

$$d_{total} = d_{A_D P_R} + d_{P_R P_S}(1 - \text{AFS}) + d_{P_S A_A} \quad (6)$$

Three values of AFS, 10%, 20% and 30%, were used to analyze the sensitiveness of the position of P_R and P_S to AFS. As the trend of position change can be explained explicitly, other values of AFS are not listed here. Subscript 10, 20, 30 represent AFS = 10%, 20%, 30%. Each pair of P_R and P_S are shown in Fig.3 as a schematic. P_{R10} and P_{S10} is the closest pair, P_{R20} and P_{S20} is the further one, and P_{R30} and P_{S30} is the farthest. In other words, pair with AFS = 10% has the shortest formation flight distance, and AFS = 30% has the longest. With higher AFS, the follower prefers to follow the leader for a longer distance, which also means the follower can obtain more benefit from formation flight.

3.2 Vertical profile optimization

The whole flight trajectory has three phases, namely climb, cruise and descend. According to altitude, there are four segments in both climb and descent, as shown in Fig.4[20]. Formation flight needs precise relative position control. The follower needs to maintain a fixed horizontal position relative to the leader. Getting too close will be risky for the follower to be involved in the wake vortex of the leader, but getting too far will make the follower lose the benefit of formation flight. Therefore, formation flight is maintained in the cruise phase mostly, when the leader is in the cruise phase.

As described for the horizontal route optimization, both cases have the original trajectory that is performed below FL100 by the follower before the formation flight starts, as shown in Fig.5. The blue dashed line is the trajectory which is the same as the original trajectory of the follower. When the follower cannot unite with the leader directly, as in case 2, it achieves 80% max altitude of the leader at first, and unite with the leader at P_R. After P_S, which is at 80% max altitude of the leader, the follower maintains the altitude until it starts descending.

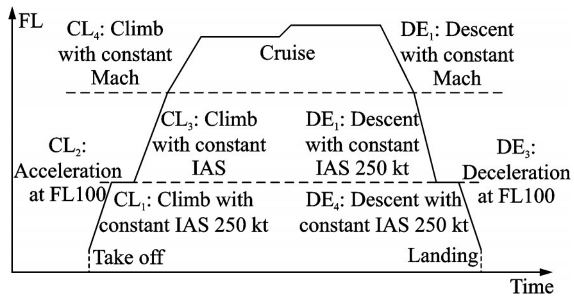

Fig.4 Model for the vertical profile

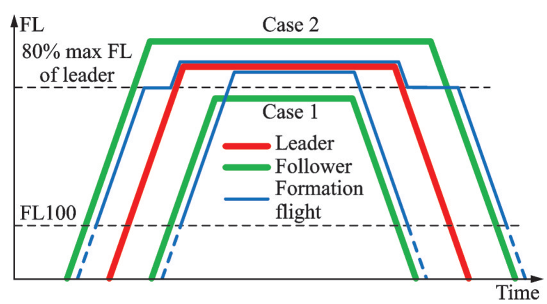

Fig.5 Vertical profile optimization

In both horizontal route optimization and vertical profile optimization, the constraint of waypoint and altitude restriction from air traffic control for the climb and descent phase of the follower was not considered, because they are relatively minor parts of the whole flight operation.

4 Numerical Study of International Flights of China

Based on the optimization method described, 1 233 pairs of flights were selected from historical trajectory data of the whole world on one day to form a sample dataset.

By setting different fuel-saving percentages, different numbers of pairs can be obtained. According to the previous section, the higher the fuel-saving percentage, the closer P_R and P_S are to departure and arrival airport, the shorter the climb and descent distance of the follower. In some cases, due to the shortened climb or descent distance, the follower cannot achieve the altitude of the leader within the climb phase or get ground within the descent phase within the maximum performance range. It is shown in Table 2 that a higher fuel efficiency results in a smaller number of candidate flight pairs.

Table 2 Number of formation flight pairs

AFS/%	10	20	30	40
Formation flight pairs	409	369	352	339

A pair of flights that was suitable for all parameters was chosen for demonstration. The leader departed from London Heathrow International Airport, to Shanghai Pudong International Airport, and its type was B777. The follower departed from Helsinki-Vantaa Airport, to Beijing Capital International Airport, and its type was A333.

The horizontal trajectory is shown in Fig.6. The red line is the trajectory of the leader; the green line is the original trajectory of the follower; and the blue line is the optimized trajectory with formation for the follower. It can be seen from Fig.6 that the trajectories of the leader and the follower basically conformed to the GCR, and the trajectories almost coincided in a relatively long-range. This is because during long-distance flights, international flights need to fly through various waypoints, and the number of routes that can be passed is limited. Most international routes in the same direction will pass the same waypoints and routes. It is for this reason that international flights are more convenient for formation flight.

The vertical profile is shown in Fig.7. It can be seen that during the cruise phase, the altitude of the

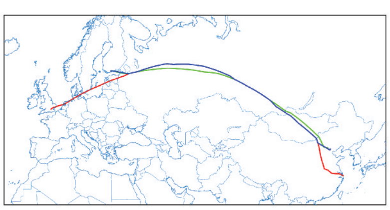

Fig.6 Horizontal route sample

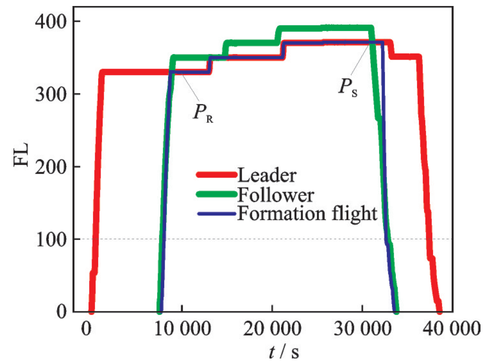

Fig.7 Vertical profile sample

follower's original trajectory was higher than the leader's. However, to achieve formation flight, the follower maintained the same altitude as the leader from P_R, and descended after it passed P_S. The optimized trajectory of the follower below FL100 was the same original trajectory. Trajectory optimization was performed only for the trajectory from FL100 to the P_R, and from the P_S to FL100. After the follower climbed to the altitude of P_S, it maintained the altitude until it passed P_S to unite with the leader. After the follower passed P_S, it maintained the altitude for a while, then descent directly.

Different formation flight routes were built based on different AFS. But AFS is just an assumed value. The actual flight may not achieve this fuel-saving percentage. To analyze the sensitiveness of the actual fuel saving percentage to the AFS, four optimized trajectories were achieved with different AFS, named case 10, case 20, case 30 and case 40, referring to AFS = 10%, 20%, 30%, 40%, respectively.

The original and the four cases fuel consumption for followers were estimated with different actual fuel saving percentage of formation flight (AFSFF). Comparing with original fuel consumption, the actual fuel saving percentage was obtained. For each case, the average actual fuel saving percentages (actual percentage) are shown in Table 3.

When AFSFF is 0%, the follower united with the leader and flied longer than the original trajectory, but obtained no benefits from formation flight, which made its actual percentage all below 0. With the increase of AFSFF, the actual percentage is increasing, but still lower than AFSFF. This is be-

Table 3 Average actual fuel saving percentage for follower %

Case	AFSFF						
	0%	5%	10%	15%	20%	30%	40%
10	−0.18	3.38	6.96	10.57	14.21	21.56	29.03
20	−0.52	3.33	7.22	11.13	15.07	23.05	31.16
30	−0.97	3.04	7.08	11.15	15.25	23.56	32
40	−1.32	2.76	6.87	11.01	15.18	23.64	32.23

cause the follower could not follow the leader for the whole flight, and we took several constraints into account, including the trajectory below FL100 and the altitude changing of the follower. Flying along the original trajectory below FL100 and following the leader at nonoptimal altitude reduced its fuel saving. The case with the maximum actual percentage changed as the AFS change. The case 10 were the best at AFSFF = 0% and 5%, case 20 at AFSFF = 10%, case 30 at AFSFF = 15% and 20%, case 40 at AFSFF = 30% and 40%. The AFSFF of the optimized trajectory was not consistent with the actual percentage, which was always lower than the AFSFF. The reason is P_R and P_S were optimized only by AFS and distance, as shown in Eq.(6). The difference between climb, cruise and descent phases were omitted in such method. The higher the AFS, the further P_R and P_S, as shown in Fig.3. In a hypothetical condition, the extra flight segment would lead to lower fuel-saving, But the extra flight segment has a high probability that it exists during the climb or descent phase, which results in the follower saves more fuel if it chooses the trajectory with higher AFS.

5 Conclusions

Recent developments of formation flight were reviewed. Focusing on actual trajectories, we propose a new method for trajectory optimization of formation flight. Based on trajectory computation methodology and trajectory optimization, the results show that the follower can be benefitted if it does not follow the geometric optimal route, but follows the actual trajectory of the leader. Assumed fuel-saving percentage has an effect on trajectory optimization and actual fuel-saving efficiency affects the trajectory selection. The higher the actual fuel saving percentage, the more benefitted the formation flight trajectory with a higher assumed fuel-saving percentage will be. Nevertheless, there are still several future developments that could be expected. Firstly, during the climb and descent phase, the trajectory optimization of the follower does not take the constraints of waypoint and air control into account. Secondly, the actual fuel saving percentage depends a lot on the relative position of the follower to the leader, which is difficult to be maintained during the formation flight, and further affects the trajectory selection.

Finally, human factors are not in the scope of this article. However, formation flight is certainly against current separation standards, which leads to very different operational requirements for pilots and controllers involved. The work introduced in this paper is just a preliminary study of a new concept of formation flight operation, and is still far from application in the civil aviation industry.

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编队飞行低油耗优化方法研究

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摘要: 建立了编队飞行轨迹优化方法。该方法在不改变前机原轨迹的前提下,优化双机编队飞行的燃油消耗。根据该方法,从一天内进出中国的所有国际航班中选取候选航班对。利用飞机性能数据库(Base of Aircraft Data, BADA)进行轨迹油耗计算。通过为后机设定不同的节油百分比,优化编队飞行的飞行前计划轨迹。分析了不同轨迹优化参数影响下的节油效果。结果表明,节油百分比越高,编队飞行的伴飞距离越长;受飞机性能的限制,可以实现的编队组合数量越少。沿近似实际飞行轨迹飞行的后机能够产生节油效果,且最佳节油效率与编队飞行的预期节油效率有关。

关键词: 编队飞行;轨迹优化;节省燃油;飞机性能数据库