CHAPTER 2. FORMATION FLIGHT

This chapter gives an overview of formation flight. First, the potential advantages and challenges of the introduction of formation flight in commercial aviation are discussed. Later, the most important studies on formation flight are surveyed. After that, the principles of formation flight are introduced. Finally, the main types of formation are described along with the influence of several parameters in fuel savings achieved in formation flight such as the longitudinal spacing between aircraft, the shape of the formation, the relative position of the heaviest aircraft, and the number of aircraft within a formation.

2.1. Introduction: Advantages and challenges of formation flight

As stated in Chapter 1, the current GHG emissions caused by civil aviation have become a priority at international level. Formation flight has the potential not only to mitigate the environmental impact of aviation but also to increase the capacity of the ATM. According to [ICAO, 1944], "*the formation operates as a single aircraft with regard to navigation and position reporting*," meaning that two or three aircraft flying in formation would be treated as a single aircraft for air traffic control purposes. This would help to reduce their workload. Furthermore, formation flight may even provide enhanced inter-aircraft communication, since the proximity between aircraft enables cost reductions and limits jamming sensitivity [Klavins, 2004].

Therefore, the question that naturally arises is what needs to be changed in the current paradigm to ensure effective implementation of formation flight in commercial aviation. Surprisingly, making today's aircraft appropriate to fly in formation does not require significant changes to the current aircraft appearance. However, the possibility of implementing formation flight in commercial aviation depends upon several factors, such as defining a new concept of operation for formation flight of commercial aircraft, changing the international airworthiness regulation, updating the ATM system in such a way that formation flights and solo flights can share the same airspace, creating alliances among airlines for sharing the benefit derived from formation flight, and developing the avionics systems for formation control. These complex issues will be discussed in the following sections.

2.1.1. Operational concept and airworthiness regulation for formation flight

Safety is the greatest concern in commercial flights, and the short longitudinal distances between aircraft needed for formation flight are not currently allowed.

However, both the european aviation safety agency (EASA) and the federal aviation Administration (FAA) have been considering formation flight for commercial aircraft in recent years [Durango et al., 2016]. In 2019, at the ICAO 40th Assembly [Abeyratne, 2020] [Assembly 40th, 2019], formation flight was presented as a strategic objective and the following challenges for the upcoming triennium were established:

- A new operational concept should be established, including new separation schemes, specific procedures, and reduced separations to allow the formation.

- International standards and recommended practices should be developed by a multidisciplinary technical panel in which industry groups should be included.

2.1.2. Sharing benefits among airlines

As mentioned in Chapter 1, not all the aircraft flying in an extended formation benefit individually from formation flight since only the trailing aircraft save fuel. Additionally, flying in formation requires a spatial and temporal modification to the optimal individual trajectories, which could correspond to higher DOC for some of the flights. This means that formation flight offers a reduction in the total cost of the formation mission, i.e, considering all aircraft in the formation, not in the costs of the individual flights.

Furthermore, it is improbable that two or three flights that are good candidates for inclusion in a formation mission belong to the same airline. This means that the actual implementation of formation flight for commercial aircraft requires the creation of alliances among airlines to share the costs and benefits derived from formation flight. In the ICAO standards and recommendations mentioned above, a special mention to actions on airline alliances should be included [Xu et al., 2014].

2.1.3. Avionic systems for formation control

As outlined in Chapter 1, fuel savings in formation flight are generated for the trailing aircraft flying in the upwash of the wake vortex generated by the leader aircraft. To optimize the fuel savings, the trailing aircraft has to be positioned with precision with respect to the wake vortex of the leader aircraft. Thus, achieving a better understanding of generation and evolution of the wake vortices is mandatory for the real implementation of formation flight, together with the creation of reliable technology for detecting them and positioning aircraft with respect them.

As shown in [Hallock and Holzapfel, 2018], a review of recent research on wake vortex research, characterizing them is highly complex, mostly because of the large number of parameters involved in the model. Some of them are related to the leader aircraft that generates the vortex, such as weight, wingspan, speed, high lift devices settings, and thrust. Other parameters are related to the trailing aircraft, such as the weight or the speed, which are also involved in the case of formation flight. Meteorological variables, such as wind field and turbulence, also come into play when modeling wake vortices. However, as pointed out in [Ning, 2011], considering typical atmospheric conditions, the wake vortex of the leader aircraft causes low turbulence disturbances for the trailing aircraft in those extended formations in which the streamwise distance between the leader and trailing aircraft is greater than 10 wingspans.

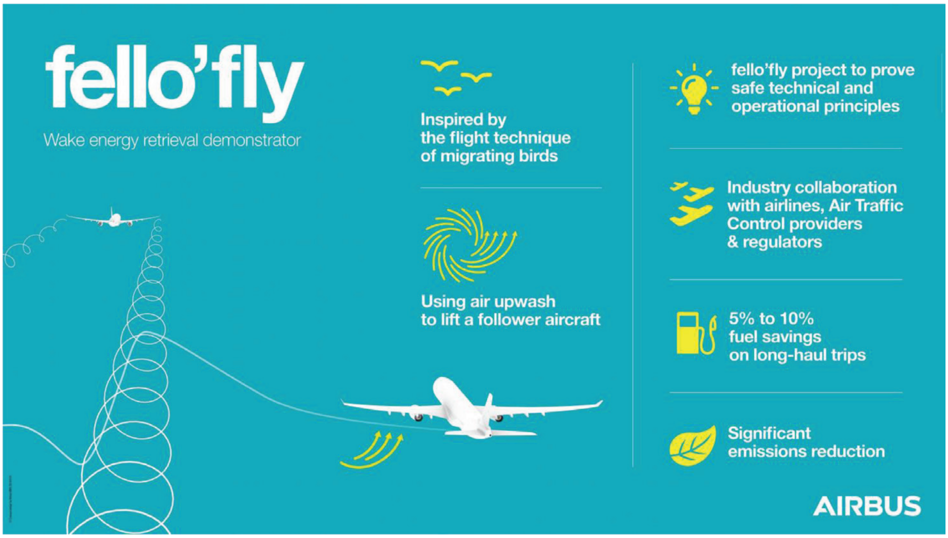
Several research studies have demonstrated the possibility of “visualizing” the wake vortices of the leader aircraft for accurate positioning of the trailing aircraft with respect to the leader’s wake vortex [Caprace et al., 2019]. This positioning system is based on the light detection and ranging (LiDAR) onboard technology [Michel et al., 2020], which allows the wake vortex generated by the leader aircraft to be accurately tracked by the trailing aircraft. Experimental flight tests have been conducted with an onboard LiDAR in the trailing aircraft providing real-time measurements of velocities of the wake vortex generated by the leader. Dynamic flight simulations described in [Vechtel et al., 2018] demonstrate that it is possible to maintain the position of the trailing aircraft in the wake vortex generated by the leader accurately using a regular autopilot.

These results demonstrate that formation control systems have been improved in recent years, permitting the trailing aircraft to position itself with precision in the optimal location while surfing the vortex generated by the leader aircraft.

The main aircraft manufacturers have begun developing the technology to implement formation flight. Airbus, the major European aircraft manufacturer, is undertaking an ambitious project called Fello’fly [Airbus, a] which aims to demonstrate the technical, operational, and commercial viability of formation flight for long-haul commercial flights. In this project, Airbus is collaborating with two European airlines, Frenchbee and scandinavian airlines system (SAS), as well as air navigation service providers such as France’s direction des services de la navigation aérienne (DSNA), the UK’s national air traffic services (NATS) and EUROCONTROL, NAVCANADA, and the irish aviation authority (IAA) in order to tackle the challenges of formation flight. The project also benefits from the support of the Direction Gènèrale de l’Aviation Civile (DGAC), the French Civil Aviation Authority. The objective of this project is not only to demonstrate the operational feasibility of the project but also to identify safety procedures and standards for transatlantic operations, enabling a controlled entry into service by 2025.

On November 9, 2021, the first formation flight test was carried out in the field of transoceanic flights.[1] Two wide-body Airbus aircraft, A350-900 and A350-1000, performed the first transatlantic formation flight from Toulouse–Blagnac Airport to Montréal–Trudeau International Airport. In this formation flight test, the observed reduction in fuel consumption was over 5% and 6 tons of CO_2 were saved.

Fig. 2.1. Fello'fly Airbus project [Airbus, a].



Boeing has also conducted research activity on formation flight involving flight tests on Boeing's ecoDemonstrator platform [Flanzer et al., 2020].

2.2. Studies on formation flight

2.2.1. Studies on the aerodynamics of formation flight

Studying nature and trying to imitate it has often been a very effective way to find innovative solutions to human problems. Formation flight is undoubtedly a fine example of this. The concept of formation flight arose from the observation of nature, where many species of bird fly in formation during their migrations. In 1914, Wieselsberger established the aerodynamic aspects concerning the power savings which may give birds flying in formation an aerodynamic benefit [Wieselsberger, 1914]. Over the next halfcentury, this

[1] https://simpleflying.com/airbus-a350s-bird-like-flight/

aerodynamic theory was developed including less simplified analysis. In [Lissaman and Shollenberger, 1970], the authors theoretically affirm that a flock of 25 birds flying in V-formation could achieve a range increase of over 70% with respect to solo flight. Additionally, the aerodynamic benefit achieved by birds in a formation can also be obtained by any body immersed in a fluid, including fishes, airplanes, and submarines.

At a later point in time, the efficiency obtained in flock formations was therefore extended to aircraft formations. These initial studies mainly focused on the aerodynamics of formation flight to assess the potential benefits in terms of induced drag reductions and, consequently, potential fuel burn reductions [Ning et al., 2011, Kless et al., 2013, Slotnick, 2014]. Experimental studies on formation flight have also been carried out. One of the most exhaustive works was conducted within the Surfing Aircraft Vortices for Energy ($AVE) project [Bieniawski et al., 2014]. The results obtained using two C-17 aircraft, at longitudinal distances of between 18 and 70 wingspans, revealed fuel savings of up to 11% [Haalas et al., 2014, Flanzer et al., 2014] for the trailing aircraft. The results of another experimental study [Vachon et al., 2002], obtained using two F/A-18 flying closer, at a longitudinal distance of up to 6.6 wingspans, returned fuel savings of just over 18% for the trailing aircraft.

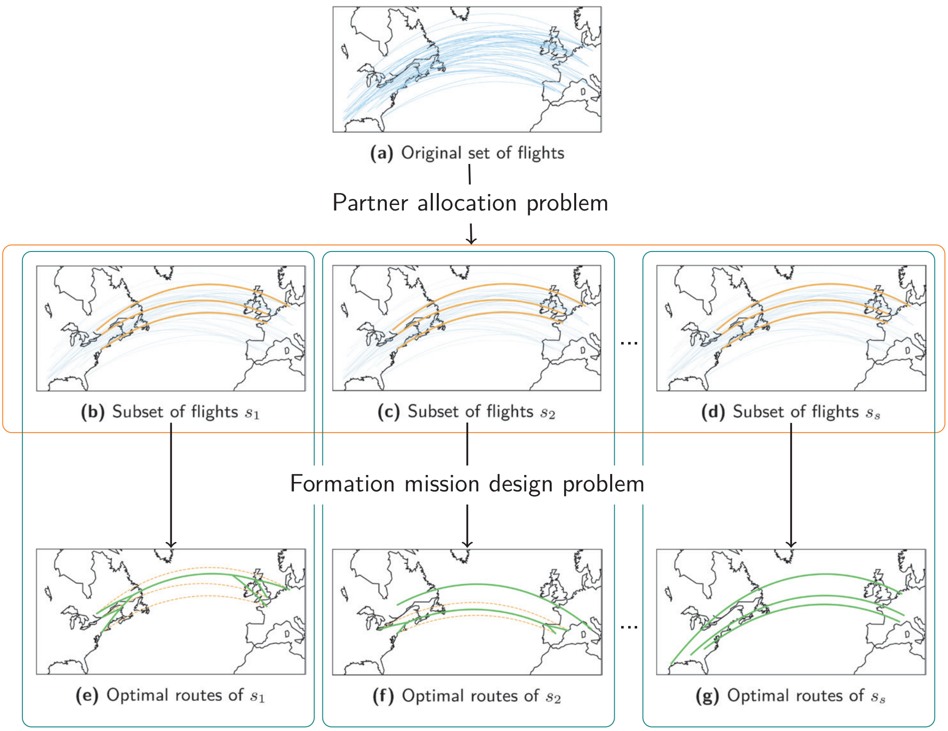
In addition to these studies on the aerodynamics of formation flight focused on estimating the potential induced drag and fuel burn reductions, other research activities have been conducted to study different practical aspects of formation flight, such as the formation control problem under actuator and sensor faults [Liu et al., 2019] and the collision avoidance in formation flight [Seo et al., 2017].

2.2.2. Studies on formation flight planning

Studies on the aerodynamics of formation flight have given way to studies on formation flight planning [Xu et al., 2014, Kent and Richards, 2015, Blake and Flanzer, 2016, Bower et al., 2009, Hartjes et al., 2018, Hartjes et al., 2019, Kent and Richards, 2021], most of which focus on extended formations. In these studies, the formation flight planning problem has been solved as a bilevel optimization problem, in which the higher level problem is the optimal partner allocation problem and the lower level problem is the mission design problem. A conceptual representation of these two problems is given in Fig. 2.2. Consider a set of transoceanic flights, represented in blue in Fig. 2.2(a). Solving the partner allocation problem for this set of flights consists in establishing how to group them into smaller subsets which contain potential partners of beneficial formation missions in terms of overall DOC. For instance, to solve the partner allocation problem for the eastbound set of flights, first the westbound flights are disregarded and then potential partners are selected based on the distance between the departure and arrival airports and the schedule of each flight. The subsets of flights with potential for profitable formations, $s_1, s_2, \ldots, s_s$, are shown in orange in Fig. 2.2(b), Fig. 2.2(c), and Fig. 2.2(d). Note that although these figures represent subsets of three flights, these sets can have cardinality two or three.

Once the subsets of flights that are potential candidates for profitable formation missions have been compiled, the formation mission design problem is solved for each subset of flights to determine the optimal trajectories of the aircraft. The optimal routes calculated solving the formation mission design problem for each group of flights are represented in green in Fig. 2.2(e), Fig. 2.2(f), and Fig. 2.2(g). They correspond to a three-aircraft formation mission, a two-aircraft formation flight plus one solo flight, and a three-aircraft solo flight mission, respectively. As can be seen in the figures, the flights of subsets s_2 and s_s do not result in three-aircraft formation missions. Therefore, better partners for these flights should be sought.

Fig. 2.2. Conceptual representation of the partner allocation and the formation mission design problems. (a) Original set of flights. (b), (c), and (d) groups of flights determined in the partner allocation problem. (e), (f), and (g) optimal routes obtained in the formation mission design problem.



Although the mission design and the partner allocation problems are intrinsically very different, the existing interconnection between them has resulted in their being addressed together in several studies such as [Xu et al., 2014] and [Kent and Richards, 2015], in which the Breguet range equation and the Fermat point extension problem were employed, respectively. [Kent and Richards, 2021] the most recent formation flight research at the time of writing this thesis, also investigated the potential for two commercial aircraft flying in formation for different cases using an analytical geometric method. Other examples are [Blake and Flanzer, 2016, Bower et al., 2009], in which geometric methods were also employed. In these approaches, the inherent combinatorial complexity of the partner allocation problem, which quickly grows with the number of flights, forced the introduction of simplifications such as using approximated dynamic models of the aircraft and neglecting the meteorological forecast.

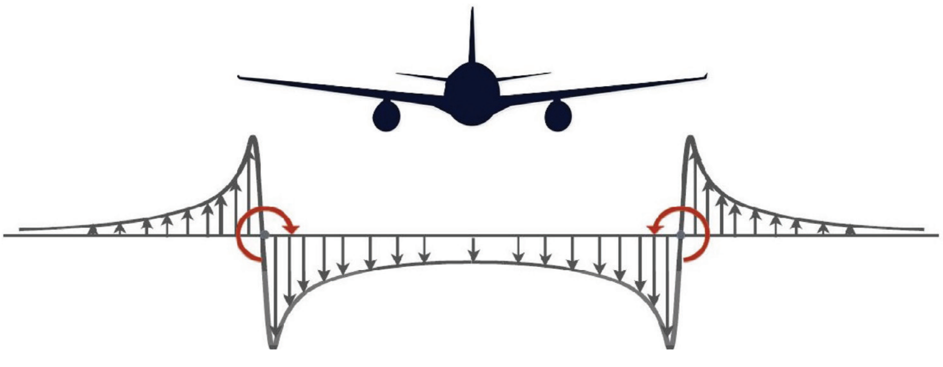
In [Hartjes et al., 2018], the mission design problem was studied for two-aircraft formations using a multiphase optimal control approach. In this case, the number of phases and the structure of the formation missions is unique and known in advance. There are five phases. The first two correspond to the flights from the departure locations to the rendezvous point, after which the formation flight, which corresponds to the third phase, starts. The other two flight phases correspond to the flights from the splitting point to the arrival locations. In this case, a solution is found using multiphase optimal control techniques and compared with the solution of a solo flight mission to establish which results in minimum DOC. The same framework used in [Hartjes et al., 2018] is extended in [Hartjes et al., 2019] to design three- aircraft formation missions. However, only in the latter was a wind field model, obtained from a weather database using a polynomial regression, taken into account. In contrast to two-aircraft formation missions, the structure of three-aircraft formation missions is not unique and, consequently, many different cases must be considered, including the case in which one or all the aircraft fly solo. The obtained solutions must be then compared to establish which corresponds to the minimum DOC. This drawback is due to the fact that the multiphase optimal control approach is only able to tackle optimal control problems with a fixed switching structure, in other words, with transitions among phases established in advance. This approach is feasible if the number of flights considered is low and the type of formation and the relative position of each aircraft in the formation are fixed. Otherwise, the number of combinations quickly increases with the number of flights, making the previous approach hardly scalable.

In this thesis, only the mission design problem has been addressed using optimal control techniques, including accurate dynamic models of the aircraft and the wind forecast. A new approach to this problem is proposed, which avoids the multiphase approach employed in [Hartjes et al., 2018, Hartjes et al., 2019].

2.3. Principles of formation flight

Formation flight is based on the fact that any aircraft moving through a fluid generates lift by imparting a swirling motion to the air. In particular, an aircraft flying in the cruise phase produces a vortex wake which mainly maintains its structure and intensity for several kilometers. This wake is characterized by a downwash region in the center of the wake and two similar upwash regions outside of the vortex core. A schematic representation of these upwash and downwash regions is given in Fig. 2.3. A second aircraft flying in either of these upwash regions, will increase its apparent angle of attack obtaining useful energy. The increment of the apparent angle of attack produces an effective forward rotation of the lift vector, $\vec{L}$, resulting in a lower lift-dependent component of drag, D_i. Thus, a significant decrease in induced drag is achieved [Ning et al., 2011]. For a better understanding, the apparent and induced angle of attack, α_e and α_i respectively, the local and induced velocities, u_i and w_i respectively, and the lift and induced drag vector for both solo and formation flight are given in Fig. 2.4, where sub-index $S\,F$ has been used to indicate "Solo Flight" and sub-index $F\,F$ indicates "Formation Flight". Additionally, the components related to $S\,F$ are represented in blue, whereas the components related to FF are represented in green. The total angle of attack, α, together with the free flowing fluid velocity, u_∞, have been represented in black. Notice that the total angle of attack is defined by the following sum of the apparent and the induced angle of attack,

Fig. 2.3. Vertical component of the induced air velocity field (not to scale). Figure adapted from [Ning, 2011].



$$\alpha = \alpha_{i,}SF + \alpha_{e,}SF = \alpha_{i,}FF + \alpha_{e,}FF \cdot \qquad (2.1)$$

From Eq. (2.1), it is easy to see that an increase of the apparent angle of attack is obtained due to the formation flight, which results in a decrease of the induced angle of attack. Consequently, both the induced velocity and the induced drag are reduced.

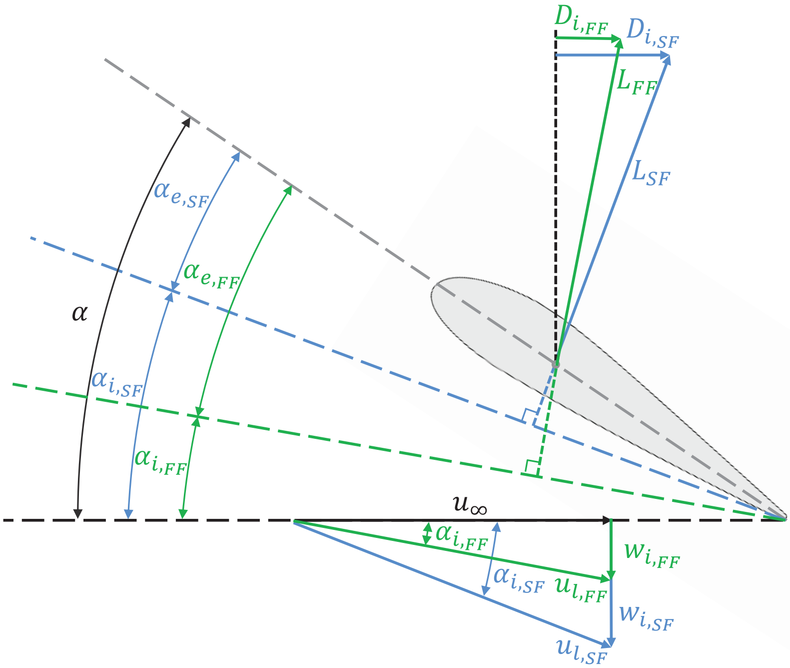
2.4. Types of formations

Formations can be classified based on the longitudinal distance between aircraft in close and extended formations or based on their relative positions in V, inverted-V, and echelon formations.

2.4.1. Close and extended formations

Regarding the optimal positioning, the lateral and the streamwise distance gain significance. In particular, the longitudinal spacing between aircraft, usually expressed in terms of wingspans, is used to classify formations. In the literature, the formations in which the longitudinal distance between the leader and trailing aircraft is less than 10 wingspans are called close formations, whereas those in which this distance is between 10 and 40 wingspans are called extended formations [Durango et al., 2016]. Close formations provide the greatest benefits in terms of induced drag reduction while the potential induced drag reduction is lower in extended formations, especially in separations of more than 20 wingspans. However, extended formations are intrinsically safer than close formations - a crucial aspect in commercial flights. Therefore, in this thesis, only extended formations are permitted. In particular, a conservative approach in which the formation benefits are negligible for separations of more than 20 wingspans is considered, and longitudinal distances lower than 10 wingspans are prohibited.

Fig. 2.4. Impact of the formation flight on the induced velocity, on the apparent angle of attack and on the induced drag.

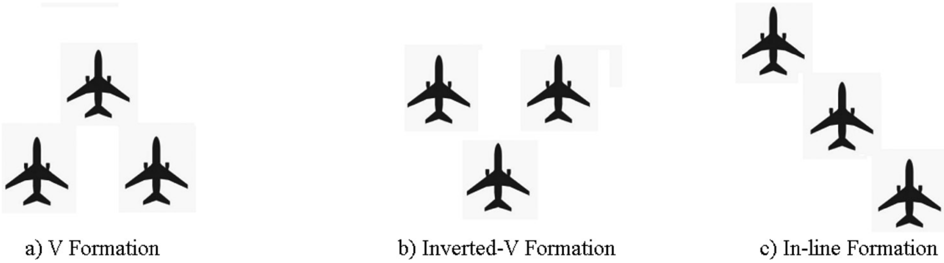


2.4.2. V, Inverted-V, and in-line formations

Furthermore, if three or more aircraft are involved in the formation, a second classification can be made according to the shape of the formation. In this case, three types of formations can be distinguished: the V formation, the inverted V formation and the in-line or echelon formation. These different types of formation are represented in Fig. 2.5.

The V formation is the most common in the nature, being that chosen by birds to fly in formation. Considering three-aircraft formation flights, in a V formation, one aircraft is the leader, and the two trailing aircraft fly in the upwash regions of the two wake vortices generated by the leader aircraft. In the inverted-V formation, as its name suggests, the configuration is the opposite: there are two leaders and one trailing aircraft, which, flying in the upwash regions of the wake vortices generated by the two leader aircraft, benefits twice

Fig. 2.5. three-aircraft formation configurations: V, inverted-V, and in-line formation (not to scale).



from formation flight. Finally, in the in-line formation, there is one leader aircraft followed by one first trailing aircraft, usually referred to as the intermediate aircraft, which is followed by another trailing aircraft.

In both the V formation and in-line formation, two aircraft benefit from the formation, while in the inverted-V formation, just one of them benefits. In the inverted-V formation, the trailing aircraft has a more symmetric load condition, which is clearly an advantage for the stability and control of the aircraft. However, in the inverted-V formation, finding the optimal position of the trailing aircraft is more challenging because it must be determined with respect to two aircraft at the same time, making this type of formation difficult to implement and the fuel savings more sensitive to position errors. As shown in [Ning et al., 2011], inverted-V formation offers lower benefits when compared to other types of formation.

In [Ning et al., 2011], other aerodynamic aspects of formation flight were studied, particularly for extended formations. The obtained results show that inverted-V formations would be less affected by viscous and compressibility effects due to a more symmetric loading compared with the others types of formation. Even though it is possible, choosing the type of formation and the relative position of each aircraft in the formation have not been included in the formulation of the formation mission design problem proposed in this thesis. Thus, in the numerical experiments conducted in this thesis, the in-line formation has been chosen and the relative position of each aircraft in the formation has been established in advance.

2.4.3. Choice of the leader aircraft of a formation

This section discusses the choice of the leader aircraft of a formation based on the relative weight of the aircraft.

By definition, the overall drag *D* can be expressed by the sum of two terms: the zero-lift drag, $D_0 = \frac{1}{2}\rho V^2 S C_{D0}$, and the induced drag, $D_i = \frac{1}{2}\rho V^2 S K C_L^2$, therefore

$$D = D_0 + D_i = \frac{1}{2}\rho V^2 S\left(C_{D0} + K{C_L}^2\right), \tag{2.2}$$

where *ρ* is the air density, *S* is the reference wing surface area, *V* is the aircraft airspeed, and *W* is the aircraft weight.

In straight and level flight, the induced drag can be expressed in terms of the weight of the aircraft as:

$$D_i = \frac{KW^2}{\frac{1}{2}\rho V^2 S}. \tag{2.3}$$

According to Eq. (2.3), placing the heavy aircraft as the trailing aircraft would lead to greater benefits. The heavier the trailing aircraft, the higher induced drag D_i will be and, consequently, higher benefits will be achieved from the formation flight for the same rate of induced drag reduction. Some studies on formation flight planning such as [Hartjes et al., 2018, Hartjes et al., 2019] are based on this statement.

However, the weight of the leader aircraft also has an impact on the wake intensity. The heavier the leader aircraft, the stronger the wake vortex intensity will be and therefore greater rates of induced drag reduction could be achieved [Marks and Gollnick, 2016]. This runs contrary to the above statement, leading to the conclusion that, depending on the particular conditions of the formation flight, the ideal relative position of the heaviest aircraft within a formation may change. [Voskuijl, 2017], addressed a comparison between different scenarios for two-aircraft formations, pre-establishing the heavy aircraft as both, the leader and the trailing aircraft, in each scenario. According to the results obtained, the authors conclude that, in the proposed scenarios, the total fuel burn reduction is higher when the heaviest aircraft is flying as the trailing one.

In this thesis, following [Voskuijl, 2017] and [Ning, 2011], it will be assumed that the leader vortex is not significantly influenced by the weight of the aircraft and, therefore, that the highest fuel savings are obtained by positioning the heaviest aircraft as the trailing one.

2.4.4. Influence of the number of aircraft on the fuel savings

In [Lissaman and Shollenberger, 1970], formations composed by different numbers of birds were analyzed, concluding that the more birds involved, the better drag savings were obtained, up to a theoretical limit. In this aspect, formation flight differs between birds and aircraft. Indeed, it has been proven in [Ning et al., 2011] that increasing the number of aircraft in the formation asymptotically reduces the benefits obtained from the formation flight. Additionally, the difficulty in synchronizing more than three flights makes formations of more than three aircraft operationally impractical [Durango et al., 2016, Ning et al., 2011]. For these reasons, only formations of up to three aircraft have been considered in this thesis.

2.5. Conclusions

Formation flight has great potential to contribute significantly to reducing fuel consumption and the environmental impact of the air transport sector while increasing its capacity. These advantages can be achieved by updating aircraft avionics and air traffic management technologies and procedures. Its potentialities have been widely demonstrated from the aerodynamic point of view via numerical simulations and flight tests. Flight safety aspects have been also addressed, leading to the proposal of extended formations for commercial formation flight, which are intrinsically safer than close formations. Although formation flight is still not a reality for commercial aviation, international aviation organizations, aircraft manufacturers, airlines, air traffic service providers, and researchers are collaborating to make formation flight for commercial aircraft possible in the near future. The challenging Fello'fly Airbus project is a great indication of this.