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ENERGY-SAVING FORMATION FLIGHT:
A REVIEW OF THE PAST, PRESENT, AND FUTURE

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Abstract

Formation flight was first observed in the long-distance migration of bird flocks. After the invention of airplanes, formation flight of aircraft was initially utilized as attractions in airshows. Back then, the benefits of formation flight were not well understood and great challenges were faced by pilots to overcome the turbulence generated by the nearby airplanes. With the development of aerodynamics and fluid mechanics, the benefits of formation flight have been well studied. Theories, simulations, and experiments have started to reveal the possible energy savings in formation flight for various purposes.
This paper reviews the practice and research of the formation flight of airplanes to increase flight and fuel efficiency. It briefly covers some of the most important progress into the human understanding of formation flight. Both military and commercial related outcomes are also investigated.

Keywords - Formation Flight, Bio-inspired, Aerodynamics, Fuel Saving, Flight Efficiency, Multiple Robot Cooperation

Early Days

It is particularly common to see large groups of migrating birds such as geese or ducks flying in formation, especially during the seasons when they move to another habitat with warmer climate. However, the mystery of the fascinating V formation flight of birds had not been revealed until the aerodynamics of airplanes were well understood.
Formation flight was first utilized by humans during the dawn of winged aviation for various reasons. In the early 20th century, the airplane was still in its infancy. To promote the new concept of aviation, airplanes were flying in air shows all over the world. Due to its spectacular nature, formation flight was one of the main attractions in the air shows of the time, and it is still utilized in airshows today. One example is the Belmont Park air show in 1910, as shown in Figure 1.

During wartime, military airplanes often flew in formation for tactical reasons. Figure 2 shows aircraft during World War I flying in a V formation so that the following airplanes would have a clear view of the leading aircraft, as the aircraft communications at the time relied mainly on hand signals.

During World War II, heavy bombers, such as the famous B-17, would flying in a formation called the Combat Box, as shown in Figure 3. The Combat Box was used for the tactical purpose of massing firepower of the bombers' guns and the concentrated release of bombs on a target [1].

Figure 1. Belmont Park air show, New York, 1910. Courtesy of Library of Congress, Washington, D.C.

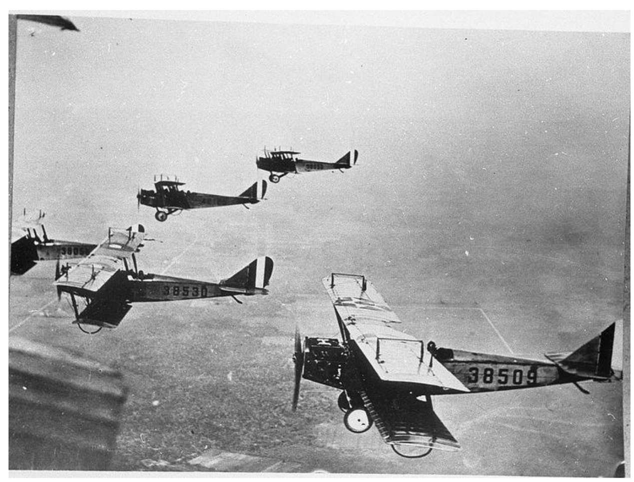

Figure 2. World War I Aircraft in V formation

Figure 3. World War II Combat Box consisting of a squadron of twelve B-17 bombers.

Theory Development

In the middle of the 20th century, due to the advent of the jet engine with particularly high fuel consumption, the focus started to shift to using formation flight to increase the range of airplanes [2, 3]. The basic idea was inspired by migratory birds flying in V formation as previously mentioned [3, 4].

In 1952, White [2] suggested that the field of flow about an airplane wing creates an upward induced velocity in a certain region that can partially support another airplane following it.

In 1970, Speer, et al, [5, 6] studied the stability of formation flight in a dynamic environment.

In 1977, Maskew [7] applied the quadrilateral vortex-lattice method to calculate the force and moment data for use in estimating potential benefits of flying aircraft in formation. The two formations investigated were echelon and double row formations, as shown in Figure 4.

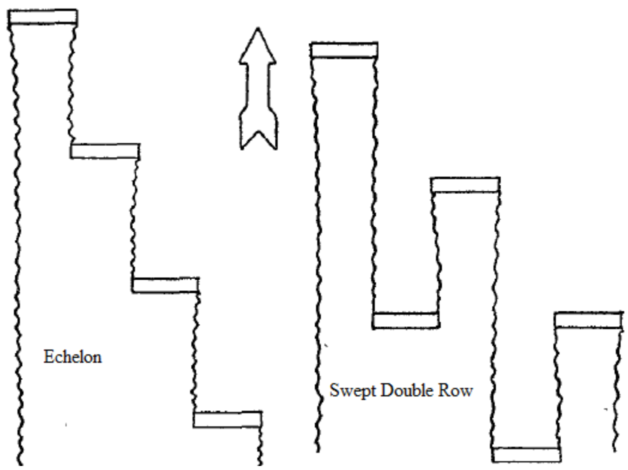

Figure 4. Echelon and double-row formations [7]

Since the turn of the 21st century, many researchers have studied the aerodynamics of formation flight. Their approaches include computational fluid dynamics (CFD) [8, 9], experimental work [10, 11], or the combination of simulation and experiments [12, 13].

The theory explaining the benefit of a trailing airplane flying in the vortex of the leading airplane has become well established. The leading airplane leaves behind regions of downwash inboard and upwash outboard of its wings [14], as shown in Figure 5. The trailing airplane that flies through the upwash can have its induced drag reduced. The research also extended from two airplane analysis to multiple airplanes [15]. Different three-airplane formations are shown in Figure 6 [16].

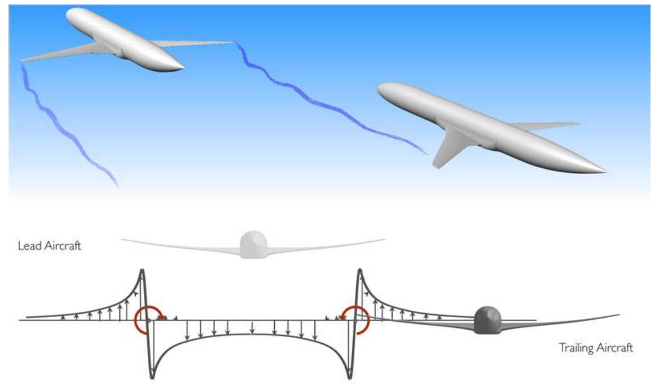

Figure 5. Wake downwash/upwash from a leading aircraft [14]

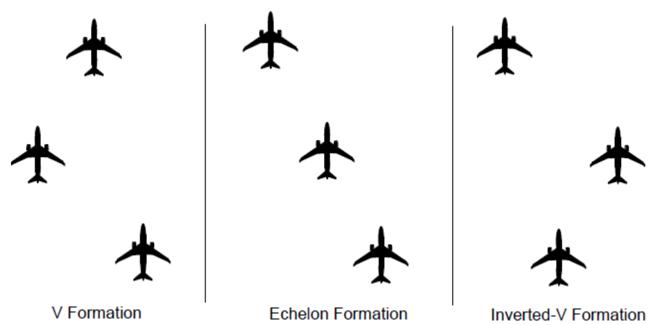

Figure 6. Three-airplane formations [16]

In 2010, Ning, et al, suggested an extended formation, extending the stream wise spacing between airplanes to at least ten spans or more which allows a safe separation distances between each airplane, while still benefiting from the upwash of the wingtip vortices of the leading aircraft [16-18].

Military Test Flights

In 2002, NASA Dryden's Autonomous Formation Flight (AFF) Project used a pair of F/A-18 research airplanes to perform a formation flight [19-22], as shown in Figure 6. The goal of this project was to demonstrate that the airflow from the wingtips of an airplane can help another airplane flying behind the leading aircraft.

Various positions of the trailing airplane in relation to the leader were tested to compare drag coefficients and fuel flows, among other parameters, as shown in Figure 7. The results showed that at an optimal position, a drag coefficient reduction of over 20% and maximum reductions in fuel flow of over 18% were achieved for the trailing airplane [22]. The leading airplane did not experimentally show any beneficial reduction in drag or fuel flow, despite the fact that some theory predicts the trailing airplane can influence the performance of the lead airplane [22].

Figure 6. Autonomous Formation Flight (AFF)

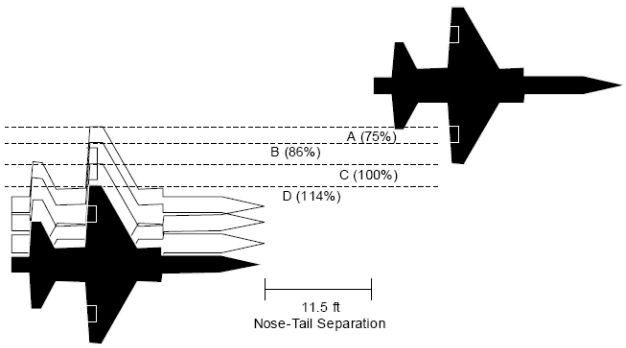

Figure 7. Lateral positions [21]

The Air Force Research Laboratory's (AFRL) Surfing Aircraft Vortices for Energy ($AVE) project aims to demonstrate that formation flight with C-17s enable the aircraft to fly inside the lead aircraft's vortex for long distances using autopilot and auto-throttle [23]. There have been several flight tests.

In 2010 [24], under DARPA's Formation Flight for Aerodynamic Benefit program, the C-17 Globemaster III Squadron concluded several flight tests to evaluate modifications made to the formation flight system.

Pahle briefed the preliminary results in 2012 [25]. The two-airplane formation geometry is shown in Figure 8, and the test points are shown in Figure 9. The maximum average fuel flow reduction was approximately 7-8%. More detailed results can be found in reference [26].

More flight tests were conducted in September and October of 2012 at Edwards AFB with the trailing aircraft 4,000ft or more behind the lead aircraft. Data showed that the trailing aircraft could reduce its fuel consumption up to 10% by flying in the wingtip vortex of the lead aircraft [23].

During another test flight in 2013, two C-17s took off from Edwards Air Force Base in California, heading to Hawaii. In the two-airplane formation, the trailing C-17 was flown in various position 2000 to 6000 feet behind the lead airplane [27] in places where the vortices were fully formed and pushing air upward, unlike the close-formation F/A-18 flight flown a decade before. The trip to Hawaii reduced fuel by 6%. On the return trip, this formation flying offered a 10% fuel reduction.

Blake, et al, also summarized the C-17 test flights in a 2015 paper [28].

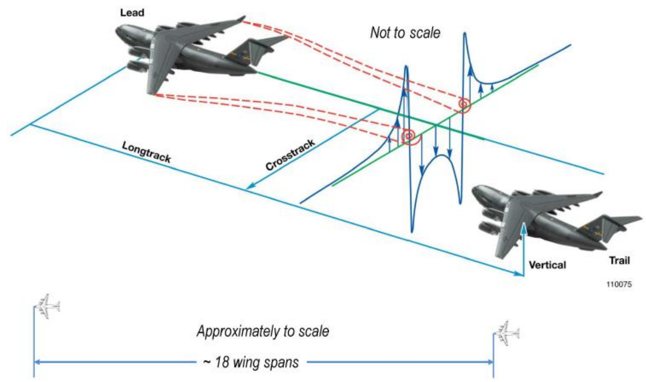

Figure 8. C-17 formation geometry [25]

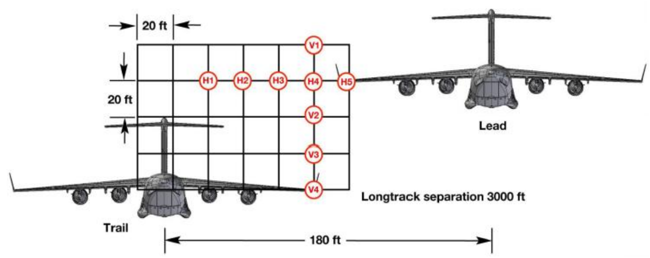

Figure 9. C-17 test points [25]

Commercial Flights

A group of researchers at Stanford University, led by Professor Ilan Kroos, have suggested route-optimized formation flights for commercial companies. In 2009, a hypothetical case study was published that examined the use of formation flight on five FedEx flights from the Pacific Northwest and Midwest to Memphis, TN [29]. One example is shown in Figure 10. Five airplanes departed from different cities then rendezvoused and formed two groups, a three-airplane and two-airplane formation, and then continued flying in formation until they arrived at their destination. The study concluded that with a tip-to-tip overlap of about 10% of the wingspan the overall fuel savings were about 11.5% if the schedule is unchanged. This translates to saving approximately 700,000 gallons of fuel per year with this route with this set of five flights.

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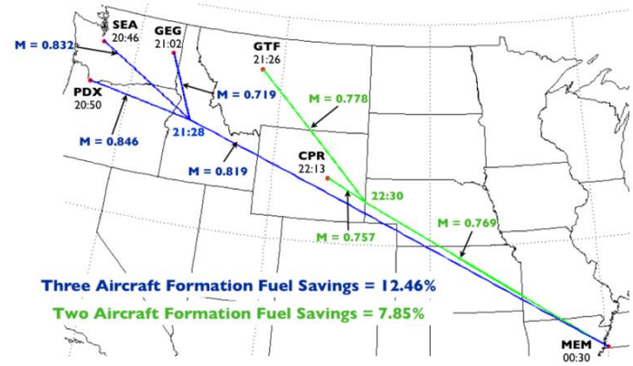

Figure 10. FedEx case study example [29]

In 2014, Xu, et al, from the Stanford group, also published a case study on a South African Airlines (SAA) route optimization [30]. Figure 11 shows the optimal direct operating cost (DOC) routes. A 31-flight South African Airlines long-haul schedule can reduce fuel consumption by over 5.8%, or reduce direct operating cost by 2.0% using formation flight. In the same paper, a collaborative multi-airline implementation was also studied, as shown in Figure 12.

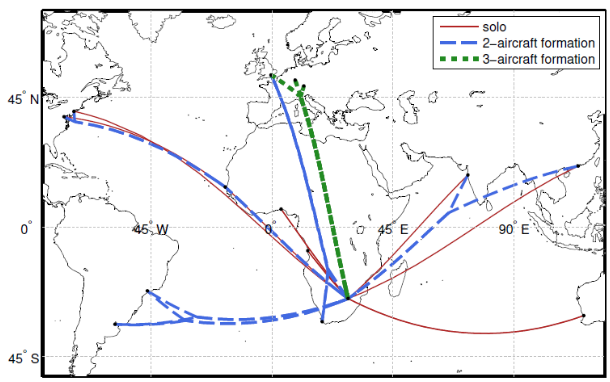

Figure 11. SAA optimal DOC routes [30]

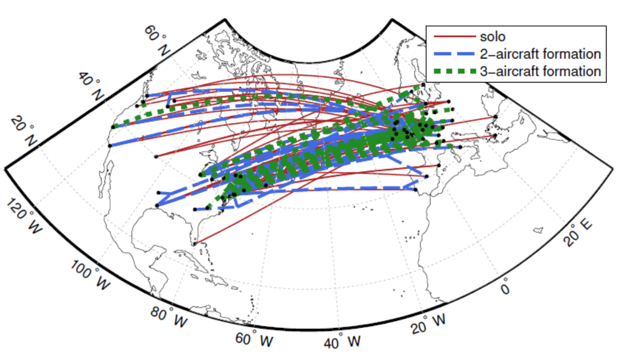

Figure 12. Star Alliance optimal DOC routes [30]

Star Alliance transatlantic flights optimal DOC routes, shown in Figure 12, include 150 airplanes. The minimum DOC network reduces fuel consumption and cost by 6.9% and 2.6%, respectively, as contrasted against the minimum cost solo-airplane flight network.

Airbus launched the inaugural Fly Your Ideas challenge in 2009. The Stanford University students' research discussed in the last section was in the proposal that reached the finals of the challenge [31]. Airbus since has been looking into cooperative flight scheduling and conducting research into aircraft stability and control.

In 2014, five Airbus A350 XWB airplanes took part in formation test flights. Videos are available on-line [32] and the formation is shown in Figure 13. On the Airbus website [33] it explains that "high-frequency routes would also allow aircraft to benefit from flying in formation like birds during cruise, bringing efficiency improvements due to drag reduction and lower energy use."

Figure 13. Airbus A350 XWB formation flight [32]

Richard Deakin, the former Chief Executive Officer of National Air Traffic Services, predicts that in the future airlines might fly their aircraft in formation like flocks of birds [34].

Future

Although much progress has been made toward understanding the benefits present in formation flight, there are many concerns that must be addressed before formation flight can be widely implemented. The primary concern stems from flight safety regulations. The Federal Aviation Administration (FAA) has detailed regulations about the minimum distance for commercial airplane operations. According to the regulations, commercial airplanes have to maintain a minimum lateral distance of 3 miles in terminal environment and 5 miles in the enroute environment and a minimum vertical distance of 1,000 feet for Instrument Flight Rules (IFR) air traffic and 500 feet for Visual Flight Rules (VFR) air traffic. These current restrictions do not allow for the relatively short distances needed for formation flight operations. The second concern is collaboration between airplanes and airline companies, which include task allocations and cooperative route planning. The third concern comes from the additional stress on the pilots themselves. Flight in formations requires the pilots to have more experience in flying under complex airflow conditions. In addition, the current flight facilities, such as flight instruments and airport facilities, do not fully support formation flight and group operations. More studies are still needed to address these concerns and other related problems, however, formation flight in both military and commercial airplane operations has a bright future.

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