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Formation Flight Mechanics and its Integrated Logistics

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Abstract

This paper presents an investigation of the fuel cost reduction effects of formation flight when applied to two different type aircraft. The first case is a general aviation case with a Cessna 152 and a Cessna 182 in staggered formation. The second case is a commercial transport with two Bombardier Dash-8 in staggered formation. The method used to analyze the induced drag is a vortex lattice method which keeps both aircraft in trim throughout the simulation. The total drag reduction for the trailing aircraft was found to be 4.4 % and 8 % for the two cases respectively this would reflect in fuel consumption and CO_2 emissions. In order to assess the effects of the cost of setting up the formation, a trade study in operational logistics was made for a sample route where flights between Stockholm/London and Linkoping/Amsterdam joined up mid-flight for a fractional formation flight. Formation flying with its integrated logistics can be optimized and sustained for this route, assuming fuel represent about 50 % of the direct operating costs of air cargo freight transportation.

Keywords: Formation flight; operational logistics; integrated logistics; fuel saving; air cargo.

Nomenclature

AR	Aspect Ratio, [-]
C_D	Drag Coefficient, [-]
C_{D0}	Zero Lift Drag Coefficient, [-]
Cf	Cost fraction, [-]
C_L	Lift Coefficient, [-]
C_m	Pitching moment coefficient, [-]
FL	Flight level, [ft]
Ff	Formation fraction, [-]

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L/D	Glide Slope, [-]
M	Mach number, [-]
NM	Nautical mile, [NM]
dcts	dcts, [-]
e	Oswald efficiency factor, [-]
h	hour, [h]
i	induced
kts	knots, [NM/h]

1. Introduction

1.1. Background

The use of formation flight for commercial air transport as a procedure to obtain increased fuel efficiency and a higher capacity in the air transport system has received some attention in the last couple of years. The time sensitive air transportation has seen an increased demand for it and subsequently its related activities like integrated logistics. Using existing aircraft in formation flight would enable large fuel savings, but at the cost of requiring changes to the operations side of air transport. The air transport system is a highly complex organization and any changes to the system rather than design changes to the individual aircraft, is a challenge. This paper covers a numerical investigation of the flight mechanics involved in close-coupled formation flight of commercial aircraft. Two cases are presented. The first is a two ship formation of general aviation aircraft: A Cessna 182 together with a Cessna 152. The second case is a two ship formation consisting of two Bombardier Dash-8, series 200. An artists impression of the Dash-8 in formation flight is shown in fig. 1. The method used in this paper was presented at the CEAS 2013 conference, Melin (2013) , where the numerical results of the formation flight simulation was compared with flight test data from NASA, Vachon, et.al. (2002). The comparison showed good correlation between numerical and experimental data with potential fuel saving of up to 20% for low aspect ratio wings. For higher aspect ratio wings, where the induced drag component in cruise is lower, the expected total drag reduction is lower. The physical phenomenon behind the drag reduction encountered in formation flight has been understood for a long time, but formation flight has never seriously been employed in civilian airline traffic.

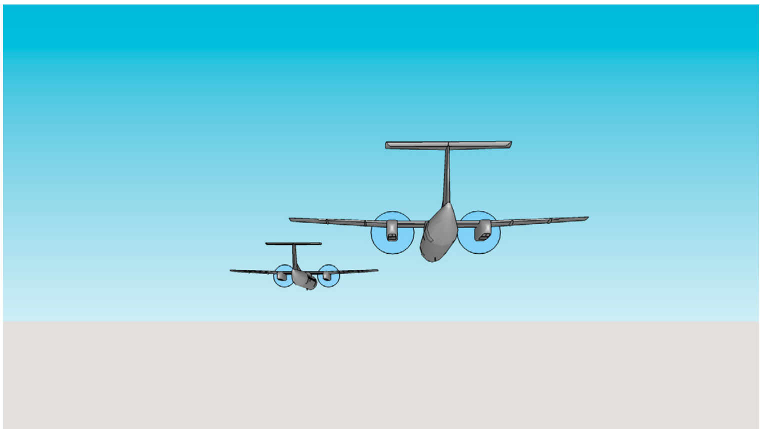

Fig. 1. Artist impression of the Dash-8 formation flight with the following 2.75 spans downstream, wingtip-wingtip.

Migrating birds are known to utilize formation flight for long distance flights. A range increase of 71 percent is reported, Lissaman & Shollenberger (1970), for a group of 25 birds in comparison with the range of a single bird. This equates to a similar reduction in fuel consumption and thus total drag coefficient. This relatively high drag reduction is attributed to the morphing (biological) capability of the birds, were they individually can optimize their span loading in flight. This is something not currently available for fix wing aircraft. The aircraft formation could in theory be kept in position by human input throughout the flight, which has indeed been the case for military aircraft flying in formation. However, the workload of the pilots will be high if no automation is included in the system. Extensive work has been performed by Giulietti et al. (2000) and Ryan (2017) to map out the control problem of station keeping, together with an analysis of the failure modes. On the military side, formation flight has been extensively used for the last 100 years, however the primary considerations were tactical, such as navigation or suppressive fire coverage and only exceptionally as a fuel saving measure. The increased fuel efficiency is due to the decrease in induced drag caused by the up-wash formed by the vortex system of a lifting wing. The formation flight then becomes a virtual extension of the span of the constituent aircraft thereby increasing the aspect ratio. The drag polar eq. 1:

$$C_{Di} = \frac{C_L^2}{\pi e AR} \tag{1}$$

can then be used to express the formation global drag coefficient as eq. 2:

$$C_{Di,2} = C_{Di,1}\frac{AR_1}{AR_2} \tag{2}$$

Fig. 2 show the theoretical maximum induced drag reduction when adding more aircraft to a formation. The NASA flight tests show a roughly 40% drop in induced drag for one aircraft of a pair of F18A aircraft in a two-ship formation. This measurement is close to the theoretical maximum of 50%. However the drag reduction of the lead aircraft was not measured and simulations show that the lead aircraft had significantly lower drag reduction.

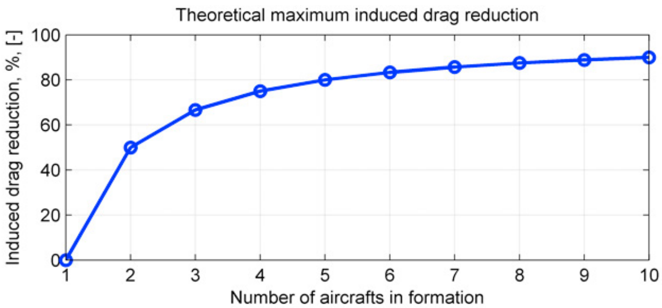

Fig. 2. Expected theoretical maximum induced drag reduction from formation flight, based on increased virtual aspect ratio.

The Munks stagger theorem states that for a system of lifting surfaces, the total induced drag is not dependent of the stream wise position of the individual wings. However, the distribution of induced drag between the wings or aircrafts as the case is in formation flight, does depend on the stream wise position. Knowledge about the formation drag reduction gives a possibility to analyse the cost benefits of flying in formation between two city pairs. A simple flight path optimization trade study was performed to visualize the real world impact of flying in formation when departure and arrival airports differ.

1.2. Integrated Logistics

Air cargo freight transportation is critical to today's global business, albeit it being an expensive affair than surface transportation. According to DHL, that has a presence in over 220 countries and territories across the globe, with over 15,000 consolidation flights every week, DHL (2017). Air cargo freight services allow connecting efficiently very distant markets and feed global manufacturing chains in a speedy and flexible. Further, the CEO of JF Hillebrand, an international logistics service provider and leader in airfreight beverage forwarding, reports that they have a presence in 91 countries with a turnover of 1.2 billion in: Bernard (2017). The air cargo industry is critical to support worldwide trade which has become an important engine for economic development, Storto (2017). The use of air cargo freight has made it easier for shippers to reduce on total logistics cost. This reduction of cost can be achieved through transportation of air cargo using formation flying, reduction in warehousing, inventory and reordering costs. The current business trend in developing an agile supply chain, just-in-time deliveries, hence global outsourcing has fueled growth of air cargo freight market: Mitra & Leon (2014). Air cargo freight transportation is vital for trade, a report by International Air Transport Association forecasts that the value of international trade shipped by air this year (2017) will be USD 5.5 trillion, which represents less than 1 % of world trade by volume, but over 35 % by value. This trade is equivalent to USD18.6 billion worth of goods every day.

Although the demand for timesensitive air cargo is becoming a major issue, particularly with increasing congestion in the airways and air network, Azadian (2012), volume is no longer a competitive capability of landside operations, Low et al. (2010). For the air cargo freight logistics industry, the reduction of costs and delivery lead time of the logistics supply chain system is tantamount to any business minded organization. Like any other industry air cargo freight industry comes with its challenges that are caused by structural changes that hit the demand for air cargo freight services and the global air cargo freight industry, Dablanc (2009), that ranged from, increased turbulence and uncertainty in world events such as the technology bust, rising cost of manufacturing and rise in protectionisms after the economic downturn, whereby companies moved back their supply chains producing goods closer to home, thus less need to ship finished products and parts.

The size of the electronic goods is ever becoming smaller, the storage facilities of ocean ships have advanced to allow fresh goods traveling by sea, and the airlines providing passenger services have increased their operation capacity by purchasing larger aircraft such as the Boeing 777 which has a surplus capacity in the bellies of the passenger aircraft, Storto (2017). The cost of fuel have increased substantially thus raising air cargo freight transportation costs when compared to ocean shipping thus seriously impacting the air freight cargo industry logistics, because in numerous cases fuel represent half of the total expenses for air freight cargo transportation. These challenges can negatively impact on air freight cargo operations, and even increase competitive pressure inside the industry. To deal with such challenges, the air cargo operators are searching for innovative solutions, i.e. using smaller airports to avoid the congestion and delay that occur in major airports, replacing the aging aircraft fleets with new fuel-efficient models that also reduce the amount of emissions and impact on climate change, and optimizing air routes, Terry (2012), and use of formation flying. Further, less than one-third of the air freight cargo is carried by means of fully dedicated freighter planes on specialist freight services that include express carriers, while the remainder two-thirds is carried in the belly-holds of passenger planes, Storto (2017). It is likely that the amount of goods shipped using the belly space of passenger planes will increase more than the amount of goods transported by dedicated planes unless a permanent solution to this challenge is found through use of flying in a formation with dedicated services to air freight cargo transportation. Indeed, the growth of international air passenger traffic on the one side and the adoption of modern long-range efficient planes such as the Boeing B777, Airbus A330, Boeing B787, and Airbus A350 on the other are creating an increasing amount of low cost underbelly freight capacity and a network of destinations and routes that is continuously expanding, Storto (2017). Consequently, many global air cargo operators are moving out of the dedicated air freight market, while others are reducing the size of their fleet, and some others are creating strategic alliances to widen their route network. The air cargo industry is thus undergoing an important restructuring, and flexibility in air freight service has thus become an important issue to allow specialized carriers like formation flying to adapt rapidly and efficiently to changing conditions of the turbulent environment. IATA reports that optimism is in the air, since after many years of almost no growth, demand, measured in freight tonne kilometers (FTKs) grew by 3.8% in 2016 almost doubling the industrys average growth rate of 2.0% over the last five years. Freight capacity, measured in available freight tonne kilometers (AFTKs), has increased by 5.3% in 2016, IATA (2017). In Boeings 2016-17 forecast report, world air cargo traffic has strove to maintain sustained growth since the end of the global economic downturn in 2008 and 2009, air cargo began growing again with growth of 4.8% in 2014, Boeing reports. Global forwarders attest to this, for instance Kuehne + Nagel is ranked as the second largest global airfreight forwarder which manages over 1.3 million tons per annum with a network of Over 5,000 airfreight specialists at 300 branches globally, Kuehne-Nagel (2017). This has called for optimization of air freight cargo transportation by flying two or more planes together so as to cut down on fuel cost and hence a great reduction in the cost of air cargo logistics.

Air cargo freight transportation is a critical area of business to most airlines, albeit rising fuel prices, Barber (2010), growth rates of nearly 6 % are predicted annually up to 2029. Air freight cargo transportation can be transported via any route chosen by the carrier. Integrated logistics is important to a nations economy because it deals with air freight cargo delivery globally, flow of materials from suppliers to customers throughout the value stream which helps increase the speed of flow and facilities, Chang & Lai (2017), facilities can be in form of aircrafts. Barker & Zabinsky (2010) suggested that governments should legislate to improve and develop sustainable integrated logistics.

However, although many papers have focused on the idea of sustainability within the supply chain context (refer Seuring and Mller, 2008; Srivastava, 2007 for review), there is very little work done to understand the role and importance of integrated logistics in an organization's quest towards sustainability, Dey et al. (2011), of air freight cargo transportation. Though adding sustainability throughout the organization takes creativity, many firms have learned how to use it to differentiate themselves from their competitors, reduce costs, and improve services to their customers, Seuring & Gold (2012). Air freight cargo transportation has progressively developed into an authoritative issue facing integrated logistics processes today. A logistics operation represents the integrated management of all the activities required to move products through the supply chain and subsequently, the logistic cost, Bin & Chaoyuan (2005). For most profit making organizations, logistics costs is substantial and ranks second only to the cost of goods sold. According to the International Monetary Fund (IMF), logistics costs average about 12 % of the world's gross domestic product each year, Ballou (2004). Wood et al. (2012) stated that logistics system refers to an assortment of carriers, forwarders, bankers and traders that facilitate transactions, trades and movements of good. Specifically, the components of a typical logistics system are: customer service, demand forecasting, distribution communications, inventory control, material handling, order processing, parts and service support, plant and warehouse site selection, purchasing, packaging, return handling and transportation, and warehousing and storage. Firms work with its trading partners (suppliers, shippers, distributors and customers) to improve their logistics activities and hence, greatly improve business performance, Sandberg & Abrahamsson (2011), and reduce the logistics cost, Baykasoglu & Kaplanoglu (2007). For firms to have a competitive advantage the logistics function need to play a prominent role Mollenkopf et al. (2010) on cost cutting.

From the practitioner and the research community perspective, optimizing air freight cargo transportation logistics through formation of flying method is a field worth exploring. Indeed, many contributions on the theme of logistics on air freight cargo and flight formation separately can be found in the extant literature, but the combination of the two themes have not been addressed yet, thus leaving to be a robust and novel study. Therefore the focus of this study is on air cargo freight transportation through formation of flight and how it can optimize and sustain cargo logistics. The discussion mainly develops from the perspective of the public, rather than focusing specifically on the company needs of air cargo freight transportation.

A study by Chang & Lai (2017) found that logistics infrastructure is an important factor. While Ke et al. (2015) in their study found that an industry with a higher contribution margin ratio uses more air freight. This study advances the arguments made by Fisher (1997) and Ke et al. (2015) that air cargo freight transportation requires an efficient integrated logistics and more responsive supply chain through reduction of costs by formation flying.

2. Method

As the physical principle behind the induced drag is covered within potential flow, the phenomenon can readily be investigated using potential flow numerical methods. Two application cases of formation flight were analysed in this paper. The first being a formation of two general aviation aircraft, the second being a formation of two commercial turboprop aircraft. The aircraft were numerically modelled in the vortex lattice method Tornado. A grid convergence study was done to assure low result sensitivity to meshing. Various relative positions in the y-z plane of the formations were computed, both aircraft in a trimmed state. Trimming was done in 4 axes: Heave, pitch roll and yaw. The surge component was left as a result i.e. excess/deficit thrust. Throughout the longitudinal separation was kept as 2.75 spans, both in order to allow comparison with the NASA flight test data, and to ensure that the influence on the lead aircraft was kept low. The output was compared with a baseline of a single aircraft aerodynamics. A result matrix was set up with different lateral and normal (cardinal) positions in order to evaluate the optimum relative wingtip position. From the induced drag reduction maps, a cut off level of 30-40% was selected to give a sweet spot large enough for a human pilot to have manoeuvring room to keep the formation station. The total drag was built up from the induced drag and the friction, zero lift drag coefficients. The zero lift drag was treated differently in the two cases, were in the general aviation case manufacturers data was used, while in the commercial case, a drag component build-up was employed. A linear relation between drag and fuel consumption was assumed, giving direct access to total flight fuel expenditures.

A flight path optimization was performed, with the goal of minimizing trip cost, evaluating cash operating costs (COC). A moderate-high fuel price was assumed setting the fuel cost at half of the per-passenger-mile COC. A comparison between the cost of solo flight and partial formation flight was made. In the formation flight case an allowance was made for the solo legs needed to meet up in formation. Fig. 3 shows an example case with two separate departure and arrival cities. The solo flight A and B are shown, together with the optimum (Least fuel burn) partial formation route.

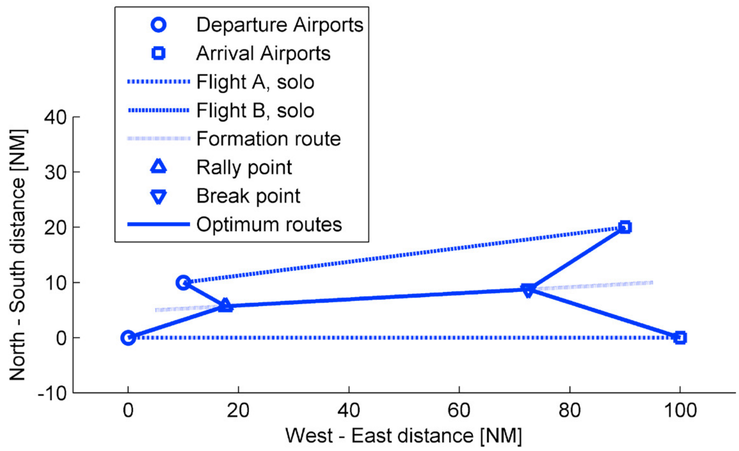

Fig. 3. Typical setup of fractional formation flight. Two aircraft take off from different airports; merge their flight paths at the rally point, split up at the break point for a final solo leg towards their respective destination airports.

3. Results

3.1. General Aviation

The first case analysed was a general aviation case. The formation was a two aircraft group consisting of a Cessna 182 as lead aircraft, and a Cessna 152 as the trailing aircraft. Fig. 4(a) show the panelling and generic formation setup. 41 by 41 simulation points were used in the z-y plane, or a total of 1681 simulation points. The y offset of the number two aircraft varied from 0 to 2.8 span widths and the z offset varied from -1 to 1 span widths. The grid convergence is shown in fig. 4(b)

The variation in y- and z-offset gave a plane of drag reduction shown in fig.5(a) The highest induced drag reduction can be found about 10% of the span inboard of the wingtip were about 60% in a very small area. Areas with no results is where the numerical condition of the numerical solution is too high, indicating a degenerate solution. The required control surface deflections for trim are shown in fig. 5(b). The flight state was Mach 0.17 (107 kts) at FL 60. Cruise lift coefficient was 0.30 to trim the aircraft in heave.

In order to evaluate the total drag, the friction drag component was estimated as the zero lift drag, and was retrieved from Cessna aircraft data Leisher et al. (1957). The values for the C182 were also used for the C152 variant. The results are shown in table 1, where the total drag reduction on the number 2 aircraft in the formation is shown to be about 4.4%.

3.2. Commercial transport

For the commercial air transport case, a two aircraft formation consisting of two Bombardier Dash-8 series 200 was modelled. Fig. 6(a) show the panelling and a generic formation setup. The mesh panelling density was determined by

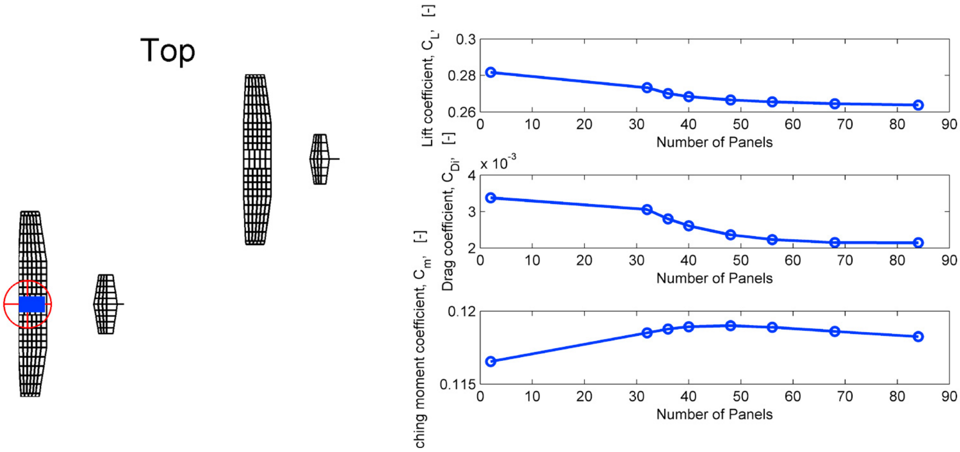

Fig. 4. (a) Mesh setup for the Cessna formation, top view. C182 as lead aircraft, C152 as number 2. The longitudinal separation is 2.75 span. (b) Grid convergence study for the Cessna geometries.

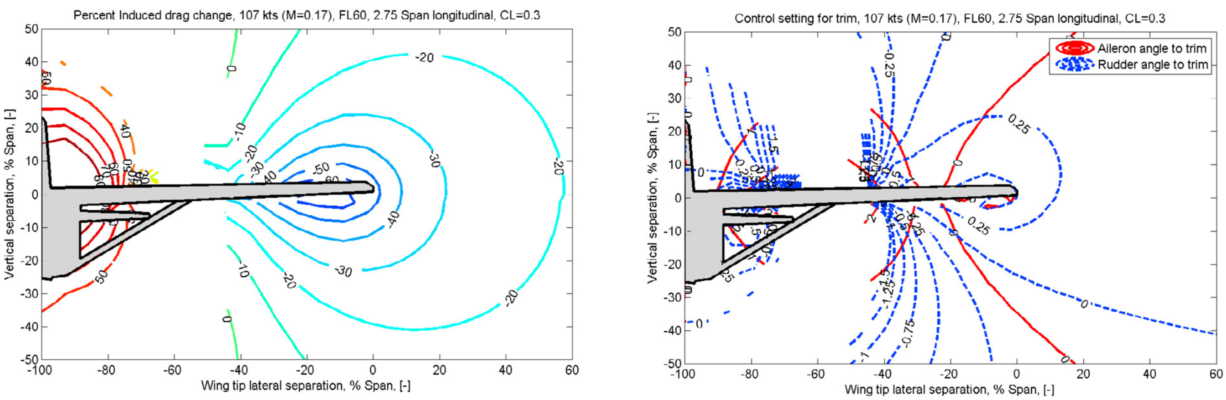

Fig. 5. (a) Iso curves of induced drag reduction in percent of the following aircraft, showing the Cessna 182 outline. Origin position marks wingtip to wingtip. (b) Iso curves of control surface deflection to trim.

Table 1. Total drag reduction for the following aircraft. Two Bombardier Dash-8 in staggered formation, cruise conditions.

Parameter	Baseline	Formation	Reduction
C_{Di}	46	32	30 %
C_{D0}	274	274	0 %
C_D	320	336	4.4%
L/D	9.4	9.8	-

the grid convergence study shown in fig. 6(b). The flight state was Mach 0.47 (289kts) at FL200. Cruise lift coefficient was 0.34, which trims the aircraft in heave with 15500 kg mass.

The drag reduction results of the Dash-8 formation is presented in fig. 7(a), showing the reduction in induced drag as a function of relative wingtip position. The minimum value reported is close to 80% reduction close to the wingtip in a very small area, while 30-40% reduction is available in a much in a much larger area. Worst case scenario is when the aircraft are positioned directly in line, where the induced drag is increased by 80%. Fig. 7(b) shows the induced

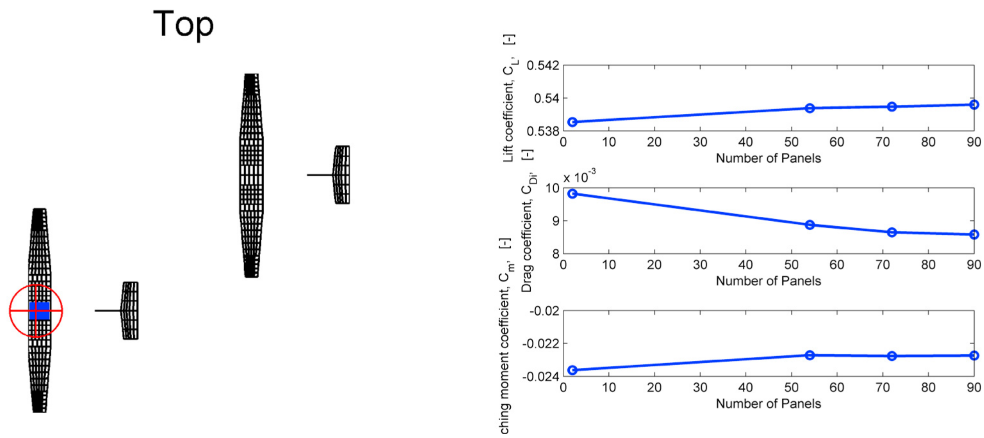

Fig. 6. (a) Numerical mesh for the commercial Dash-8 formation case, top view. The following aircraft in position [2.75 0 -1], [Span]. (b)Grid convergence history for the Bombardier Dash-8, number of panels in the geometry. Convergence criterion: iteration delta less than 0.01.

drag reduction of the lead aircraft. The reduction is as expected much lower, in the order of 1 to 2%. Fig. 8 show the control surface deflection needed for trim.

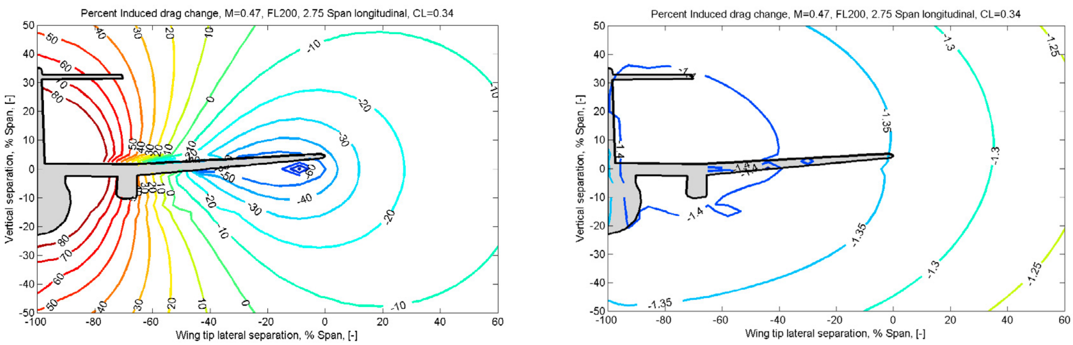

Fig. 7. (a) Iso curves of induced drag reduction in percent of the following aircraft, showing the Bombardier Dash-8 outline. Origin position marks wingtip to wingtip. (b) Iso curves of induced drag reduction of the lead aircraft, showing the Bombardier Dash-8 outline.

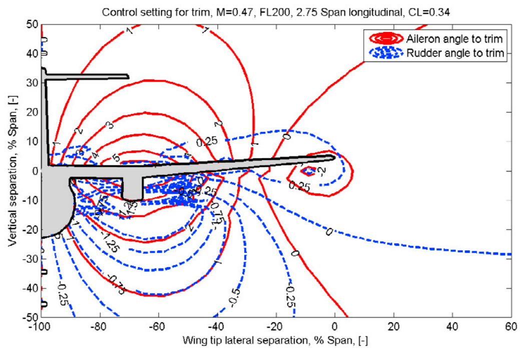

Fig. 8. Iso curves of control surface deflection to trim.

The friction drag was evaluated with a flat plate analogy for the lifting surfaces and the fuselage and nacelles were evaluated with the Eckerts equation, drag component build-up method. This yielded a zero lift drag of 139 drag counts. Added together the total drag for the baseline is 174 dcts and 166 dcts for the number 2 aircraft in the formation. Values are available in table 2:

Table 2. Total drag reduction for the following aircraft. Two Bombardier Dash-8 in staggered formation, cruise conditions.

Parameter	Baseline	Formation	Reduction
C_{Di}	35	21	40 %
C_{D0}	139	139	0 %
C_D	174	166	8%
L/D	19.5	20.7	-

3.3. Operational Logistics

In order to do an evaluation of the effects of formation flight in a transport scenario with separate departure and arrival cities, a trade study was performed. The Dash-8 formation case was used as input for a simulated formation flight between the two city pairs Linkping (LPI) - Amsterdam (AMS) and Stockholm (ARN) London (LHR). The flight ranges are 513 vs 756 NM. The optimized formation route is shown in fig. 9. The optimum flight trajectory had its rally point just south-west of Linkoping and the breakpoint north east of AMS.

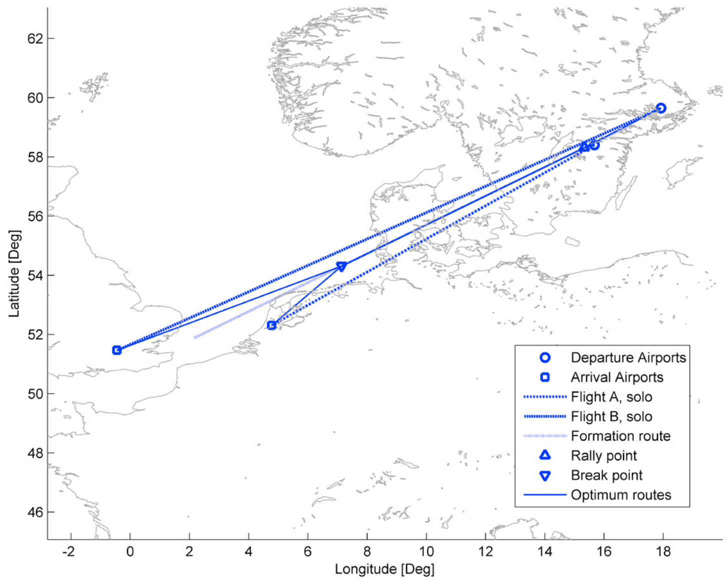

Fig. 9. Flight routes between LPI - AMS and ARN LHR, Together with the optimized formation route.

In order to assess formation flight effects on the cash operating costs (COC), the drag reduction was assumed to directly equate to a similar fuel saving, with no other effects on the COC. A medium to high fuel price was assumed setting the fuel cost to 50% of the COC. The original drag reduction of 8% on one aircraft is distributed equally on the two aircraft, lowering the fuel save to 4%. With the fuel cost being 50% of the COC, a maximum 2% reduction in COC for the flight segment in cruise is expected. The COC is in turn increased by the increase in trip distance incurred from having to travel to the rally points and from the separation points. The results are presented in table 3. For this study the two aircrafts were assumed to share the induced drag reduction. The formation fraction is the fraction of the total flight distance that was done in formation. Notably for this city pairing is that the ARN-LHR flight only can stay in formation for about 45% of the trip. In total, the change in cost fraction, i.e. the reduction in COC based on formation flight is about 2 permille, making it just about break even for this application case.

Table 3. Formation flight with different departure and arrival airports.

Flight	Solo distance, [km]	Fromation distance, [km]	Distance increase, [%]	Formation fraction Ff, [-]	Delta Cost fraction, Cf [-]
A LPI-AMS	964	967	0.3	0.7	-0.0101
B ARN-LHR	1462	1481	1.5	0.45	0.0038
Total	-	-	0.9	-	-0.002

4. Discussion

The vortex lattice method omits effects of thickness, viscosity and wake rollup. The thickness effects on the formation flight results should be smaller than the error margin of the VLM itself. Wake rollup and viscosity however will impact the results. At the 2.75 span stations downstream, a real wake will have started to roll up into two distinct vortices rather than a vortex sheet. The mutual interference will then move the vortex cores, and with that the formation sweet spot, slightly inboard and downward from the lead aircraft centerline. Viscous losses will have started to dissipate the vortex cores, lowering the available upwash and thus the drag reduction. The zero lift drag computations. with drag component buildup are low order and thus significant errors are expected. The L/D of the general aviation case is in the reasonable range, while the commercial case L/D is a bit high. No consideration of the Breguet range equation was made in the fuel save computations.

In the flight route computations for the operational logistics, the distances are computed as great circles using the Heaversine function. This works with a spherical earth model and will give errors in distance in the order of 1. The impact on the results is deemed to be low as the reported results are deltas from a baseline value, which will cancel out the original error to a large extent. A comparison of COCs between formation flight and slower solo flights are left to a later study.

5. Conclusions

The computed total drag reductions can be converted to fuel reduction and, with knowledge of other flight related costs, to the COC of a specific flight. For flight entirely made in formation the Dash-8 case would give a total COC reduction of 2% which is significant. When applied to routes with separate arrival and departure cities, the fuel reduction from the formation flight can quickly be nullified by the formation setup costs. Increase in flight time, extra distance to reach the formation rally and separation points incur additional costs. The future for air cargo freight transportation with formation flying should not be underestimated. Geographical boundaries have become invisible due to movement of materials and products from one station to another. This has been necessitated by continuous search of increased profit margins by way of cost cutting, either through cheaper manufacturing methods, cheaper raw materials or even cheaper labour. These combinations cannot be found in one region but rather scattered across the globe. This quest has caused search for an optimal place for production and then transporting the finished products to various countries where there is demand. Therefore movement of materials or products from one place to another at a reduced cost is mandatory. Hence optimizing and sustaining flight formation through integrated logistics is critical to global operations in search for cost cutting techniques for their businesses.

From a cost-motivated perspective, this study shows that formation flight for commercial aviation seems to be economically viable.

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