CHAPTER 15

Helicopter Formation Flight for Improved Mission Effectiveness

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Abstract

Formation flight is a technique used for tactical reasons in military aviation. Recent numerical and experimental research has demonstrated that formation flight conducted with helicopters also yields aerodynamic benefits and has the potential to reduce fuel consumption. A new physics-based mathematical model has been developed which can be used to quantify the effect of formation flight on fuel burn, range and endurance (flight time) for typical military missions conducted with multiple helicopters. Simulations with the new mathematical model show that a total fuel saving of about 10% can be achieved at the expense of 7% extra flight time for a long-range cruise flight with two UH-60A Black Hawk helicopters. The results underline that significant fuel savings can be achieved by the Royal Netherlands Air Force and its NATO allies if formation flight is applied to large scale transport missions with multiple helicopters.

Keywords: formation flight, helicopter performance, military operations, fuel efficiency

15.1 Introduction

Formation flight is a well-known technique in military aviation used for various tactical reasons such as the maximisation of firepower and mutual protection (Department of the Navy, 2017). Formation flight is defined by the European organisation for the safety of air navigation (Eurocontrol) as a flight consisting of more than one aircraft which, by prior arrangement between the pilots, operates as a single aircraft with regard to navigation and position reporting, as well as clearances issued by air traffic control (Eurocontrol, 2019: 22). In a standard military formation each aircraft/element of this formation shall remain within one nautical mile horizontally and 100 ft. vertically from the formation leader (Eurocontrol, 2019: 12). The US Navy Air Training Command defines the general objective of formation flying as follows. To employ and control multiple aircraft flying in close proximity to accomplish an assigned mission in a manner that will minimise the effectiveness of enemy opposition (Department of the Navy, 2017: vi).

More specifically, the main advantages of formation flight in military aviation are the following. By flying in close proximity, it becomes more difficult for enemy radar systems to detect and identify separate aircraft. Vice-versa, formation flight is beneficial for the search and detection of enemy targets. From the early days of aerial combat, the visual search and detection of targets has been of high importance and the techniques for visual search in air combat are therefore taught in military aviation schools (Schallhorn, 1990). The human eye can only focus at large distances in a narrow 2 degree fixation. It therefore takes a significant amount of time to visually search the sky for enemy aircraft. The likelihood of visual detection can be improved greatly by application of formation flight because members of the formation only have to systematically search a specific sector in the sky (Stillion, 2015). Even with the technological advances in sensors, visual search remains important. Furthermore, different aircraft in a formation may have different sensors. In addition to detection related benefits, multiple aircraft in formation can also have more firepower than a single aircraft. Another advantage of formation flight in military aviation is the reduced need for radio communication (Department of the Navy, 2017). Only the lead aircraft has to communicate with for example airborne early warning and control (AWACS) or the Joint Terminal Attack Controller (JTAC) and the other aircraft follow the actions of the lead. Other military examples where formation flight is employed are aerial refuelling and air assault missions. In air assault missions, ground combat forces are transported by helicopters with the aim to seize or hold terrain (Department of the Army and Marine Corps Combat Development Command, 2004).

Over the past 20 years, various experimental research studies conducted by the United States Air Force and NASA have demonstrated that formation flight can also be used effectively to reduce fuel consumption. This reduction in fuel consumption can be achieved by making use of the basic physical principle that all aircraft generate wake vortices as a result of a pressure difference on the wing. These wake vortices, which contain a significant amount of energy, remain present at large distances behind an aircraft. In a specific region of a wake vortex, the air has an upward motion (upwash). A second aircraft can achieve an aerodynamic benefit if it is positioned in this upwash region of a wake vortex. Effectively, the second aircraft can perform a descending flight relative to the air which has an upward motion. A descending flight requires less power than a flight at constant altitude. Relative to the earth, the second aircraft remains at the same altitude.

The most important fixed-wing flight test programs of the last 25 years, focused on the quantification of achievable fuel reduction by means of formation flight are summarised in Table 15.1. Note that some of the results in this table represent savings for a single flight condition whereas other results are for a complete mission.

Table 15.1. Overview of key experimental flight test programs in the United States since 1998.

Year	Program	Aircraft type(s)	Fuel savings	Reference
1998	NASA Autonomous formation flight	F/A-18	18%	Vachon et al. 2002
2001	USAF TALON GAGGLE	T-38	~11%	Wagner et al. 2002
2003	NASA SURF	F/A-18, DC-8	~29%	NASA 2003
2004	USAF F-16 DOLLAR	F-16	~13%	Morgan 2005
2010	NASA/USAF/Boeing C-17 CAPFIRE	C-17	~7%	Pahle et al. 2012
2012	DARPA AFRL $AVE	C-17	> 10 %	Bieniawski et al. 2014
2016	NASA Cooperative trajectories	C-20 – GIII	8%	Hanson (2015)

A more complete and extensive overview is provided by Nangia and Brown (2020) for the interested reader. Altogether it can be concluded that fuel reductions in the order of 7–10% can be achieved for military transport aircraft and fighter aircraft in a typical mission, when the trailing aircraft of the formation consistently flies in the upwash of the wing vortex of the lead aircraft of the formation. In recent years many research studies have been conducted to investigate the potential of formation flight for commercial aviation. For sake of brevity, these studies are omitted from the current chapter.

All research in the field of formation flight has been focused so far on fixed-wing aircraft. It was hypothesised by Voskuijl (2018) that fuel reductions may also be achieved when helicopters fly in formation. Helicopters leave a wake similar to a fixed-wing aircraft. Close behind a helicopter the wake is very complex and unstructured with tip vortices emanating from individual rotor blades. The wake is however fully developed in a system comparable to that of fixed-wing aircraft at about a length of 10 to 20 rotor diameters behind a helicopter. Due to the asymmetric nature of helicopters, the wake is however also asymmetric. The upwash region is stronger on the advancing blade side (Caprace et al., 2017). Experimental research and numerical simulations conducted at the Netherlands Defence Academy in collaboration with Delft University of Technology have recently confirmed the hypothesis (Duivenvoorden et al., 2022). In fact, even larger fuel reductions can be achieved at a single flight condition compared to fixed-wing aircraft due to the asymmetric nature of the wake of a helicopter rotor. So far, the research has focused on a proof of concept. The numerical simulation models used so far are quite complex and computationally expensive. These models are suitable to assess the formation flight performance in a single flight condition defined by the weight of the helicopters, the airspeed and flight altitude. The models are however not suitable for flight mission analysis in which optimal trajectories are computed for a variety of operational conditions.

The aim of the current research is twofold. The first objective is to develop a generic physics based model that can be used to quantify the effect of formation flight on flight mission performance parameters such as fuel burn, optimal flight speed and flight time. This model should be accurate and computationally efficient. The second objective is to use the new model to quantitatively analyse the effect of formation flight for typical military missions conducted by the Royal Netherlands Air Force and its NATO allies.

The article is structured as follows. In Section 2, an overview is given of previous research in rotorcraft formation flight with the aim to improve efficiency. This section also includes a description of the type of helicopter selected for this research and the rationale for choosing this specific helicopter. Next, a new equation is proposed in Section 3 which can be used to model formation flight for flight performance and mission analysis. Section 3 also includes the verification and validation of the mathematical models. The new equation is used in Section 4 to analyse the potential effect of formation flight on fuel burn, range and flight time for military missions. Finally, conclusions and recommendations are made.

15.2 Background

A detailed numerical simulation model of two UH-60A Black Hawk helicopters in formation flight was developed by Duivenvoorden et al. (2022). This specific helicopter was chosen as a use-case primarily because a vast amount of flight-test data of this helicopter has been published in the public domain as a result of the UH-60A Airloads Program (Kufeld et al., 1994). Furthermore, the UH-60A is representative of a typical military utility helicopter with a conventional main rotor and tail rotor. The numerical simulation model of the follower aircraft in the formation is based on a rigid multi-body dynamics model (Pastorelli, 2008). The inflow of the main rotor is modelled with a Peters-He model (Peters and He, 1995). These models are known to be accurate for performance, stability and control applications (Manimala et al., 2007). The numerical simulation model of the follower helicopter is validated against the FLIGHTLAB Generic Rotorcraft model, a validated commercial off-the-shelf rotorcraft simulation model. The presence of the lead helicopter in the formation is modelled with a flat wake model (Wilson, 1991). The follower helicopter is positioned by an automatic flight control system within the simulated wake of the lead helicopter. A complete description of the numerical simulation model is provided by Duivenvoorden et al. (2022).

The key result obtained with the numerical simulation model is presented in Figure 15.1. It shows the reduction of the required main rotor power of the follower helicopter as a function of the lateral and vertical position with respect to the lead helicopter. The lateral position (*y*) and vertical position (*z*) are nondimensionalised with respect to the rotor radius (*R*). The weight of both helicopters is identical and the airspeed is 57 m/s for the simulations presented in Figure 15.1. A maximum reduction in main rotor power of 22% is achieved at the optimum location. This reduction occurs when there is a small lateral overlap of the helicopter rotors. It should be noted that the flat wake model does not include the effect of self-induced displacement. In reality, the optimal vertical position of the follower helicopter will be somewhat below the lead helicopter unlike the predicted vertical position in Figure 15.1. The follower helicopter should be located about 15 rotor diameters (*D*) behind the lead helicopter such that the wake is fully developed (Caprace, 2007). An impression of the resulting formation is displayed in Figure 15.2. It is essentially a combination of an echelon formation and a trailing formation.

Figure 15.1. Main rotor power reduction as a fraction of solo flight for UH-60 Black Hawk helicopters in formation flight (Image source: Duivenvoorden et al., 2022).

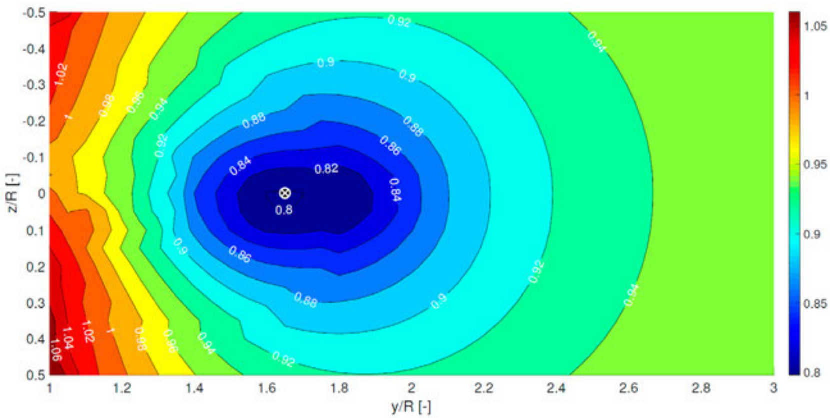
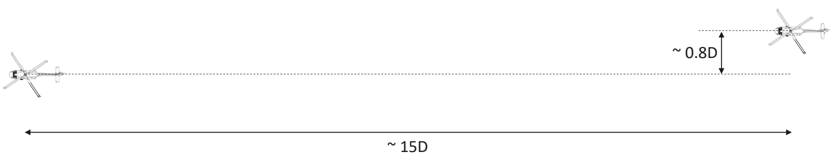


Figure 15.2. Typical geometry of the formation to achieve the maximum aerodynamic benefit.



The effect of airspeed on the maximum achievable main rotor power reduction was investigated in Duivenvoorden (2019). In terms of a percentage, the main rotor power reduction decreases with airspeed. It should however be noted that in absolute terms, the required power in solo flight increases with airspeed.

Table 15.2. Optimal main rotor power reduction as a function of forward airspeed for two UH-60A Black Hawk helicopters in formation flight.

Airspeed [m/s]	Main rotor power required of follower helicopter [% of solo flight]
41	66
46	71
51	76
57	78
62	83

Parallel to the numerical simulations, two wind tunnel campaigns were conducted at the Netherlands Defence Academy (Morée, 2019 and van der Veen, 2020). These experiments confirmed that a main rotor power reduction can be achieved and showed reductions in the same order of magnitude as the numerical simulations.

15.3 Modelling Formation Flight for Helicopter Mission Analysis

The theory of helicopter performance modelling for mission analysis can be found in various text books (e.g. Johnson, 2013 or Prouty, 2001). In its simplest form, it is typically based on the blade element method and actuator disc theory (van Holten and Melkert, 2002). The total power required by the main rotor in forward flight consists of several terms.

$$P_{MR} = P_i + P_p + P_d + P_{par} + P_c$$

Where P_{i} is the induced power. It is calculated with the following equations.

$$P_i = kW\overline{v}_i\sqrt{\frac{W}{2\rho\pi R^2}}$$

$$\overline{v}_i = \frac{1}{\sqrt{(V\sin\alpha + v_i)^2 + (V\cos\alpha)^2}}$$

The factor k in the equation accounts for non-uniform inflow and rotational velocities in the wake. The relation for the nondimensional induced velocity ($\overline{v}_i$)

is derived based on the theory developed by Glauert (1926). The angle of attack is calculated based on force equilibrium in forward flight, assuming the helicopter is a point mass and neglecting H-forces (van Holten and Melkert, 2002). H-forces are forces acting in the tip-path-plane of the rotor disc which are the result of a periodic change in the lift induced drag and the zero lift drag of the rotor blade over a revolution. In the equation, the nondimensional velocities ($\overline{V}$ and $\overline{v_i}$) are defined as the airspeed and the induced velocity, respectively, divided by the induced velocity at hover. The profile drag power in forward flight ($P_p + P_d$) can be estimated as an analytical function of advance ratio (μ) using blade element theory (van Holten and Melkert, 2002).

$$P_p + P_d = \frac{\sigma \overline{C_{D_p}}}{8} \rho (\Omega R)^3 \pi R^2 (1 + n\mu^2)$$

The parasite power (P_{par}) is the power required to overcome the drag of the fuselage and empennage of the helicopter. It is expressed as an equivalent flat plate area multiplied by the dynamic pressure and the airspeed.

$$P_{par} = \sum (C_D S) \tfrac{1}{2} \rho V^3$$

The equivalent flat plate drag area (m²) for the UH-60A helicopter is a function of the angle of attack of the fuselage (Yeo, Bousman & Johnson, 2004). The angle of attack in this equation is defined in radians.

$$\sum (C_D S) = 3.265 + 13.45\,\alpha^2$$

The climb power (P_c) is equal to the weight of the helicopter (W) multiplied by the climb rate (C), which is in fact the time rate of change of the potential energy.

$$P_c = WC$$

The tail rotor also requires power. The horizontal component of the tail rotor thrust multiplied by the distance of the tail rotor to the main rotor (l_{tr}) must equal the main rotor torque to achieve a moment equilibrium if the contribution of the vertical tail is neglected. With the tail rotor thrust known for a given flight condition, the power required for the tail rotor (P_{TR}) is calculated analogous to the main rotor power. Finally, the total engine power is computed by summing the main rotor power and tail rotor power and by accounting for gearbox and transmission losses.

$$P_{total} = (P_{MR} + P_{TR})\, k_{gb}$$

The numerical values of the performance model are summarised in Table 15.3.

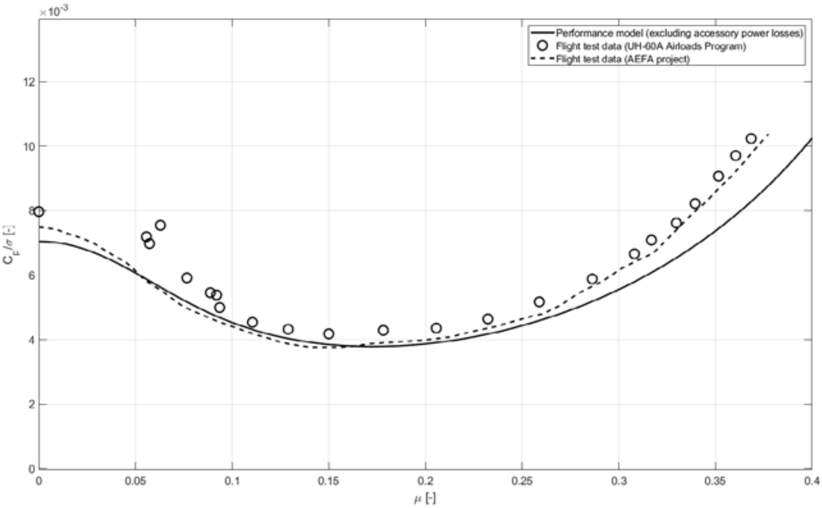
Table 15.3. Helicopter and performance model parameters.

Description	**Variable**	**Value**	**Reference**
Mean profile drag coefficient	$\overline{C_{D_p}}$	0.009 [-]	Johnson 2010
Distance tail rotor	l_{tr}	10.67 [m]	Department of the Army 1996
Factor to relate advance ratio to profile drag power	n	4.65 [-]	Johnson 2013: 177
Main rotor radius	R	8.18 [m]	Shinoda, Yeo & Norman 2002
Tail rotor radius	R_{tr}	1.68 [m]	Johnson 2010
Main rotor solidity	σ	0.0862 [-]	Shinoda, Yeo & Norman 2002
Tail rotor solidity	σ_{tr}	0.1875 [-]	
Main rotor rotational velocity	Ω	258 [rpm]	Shinoda, Yeo & Norman 2002
Tail rotor rotational velocity	Ω_{tr}	1159 [rpm]	Johnson 2010
Power specific fuel consumption	SFC	0.288 [kg/kWh]	Johnson 2010
Gearbox and transmission losses	k_{gb}	1.04 [-]	Johnson 2015

With these values, a baseline performance model of the UH-60A Black Hawk was constructed. For a gross mass of 8732 kg, the nondimensional power coefficient (C_p) computed with the performance model is compared to the power coefficient measured in flight for two separate flight test campaigns. Results of the comparison are presented in Figure 15.3.

In general, the performance model is in good agreement with the flight test data sets. Accessory power losses are not included in the performance model whereas the engine power measured in the flight tests includes accessory power. Hence, it is expected that the performance model predicts a somewhat lower power coefficient. Especially at higher advance ratios, the model shows somewhat larger discrepancies with the flight test data. It should be noted that both flight test campaigns also show differences. The aim of the current research is however not to develop a highly accurate flight performance model. A representative model is required which can be used to evaluate the relative effect of formation flight. Based on the comparison in Figure 15.3, the performance model is deemed representative and suitable for the current research.

Figure 15.3. Comparison of the baseline performance model of the UH-60A helicopter with flight test data (Bousman and Kufeld, 2005).



The power reduction of the follower aircraft in the formation is directly related to the strength of the wake vortices of the lead helicopter. The strength of these wake vortices in turn are directly related to the induced velocity of the lead helicopter. It is therefore proposed to model the power reduction in formation flight with the following equation.

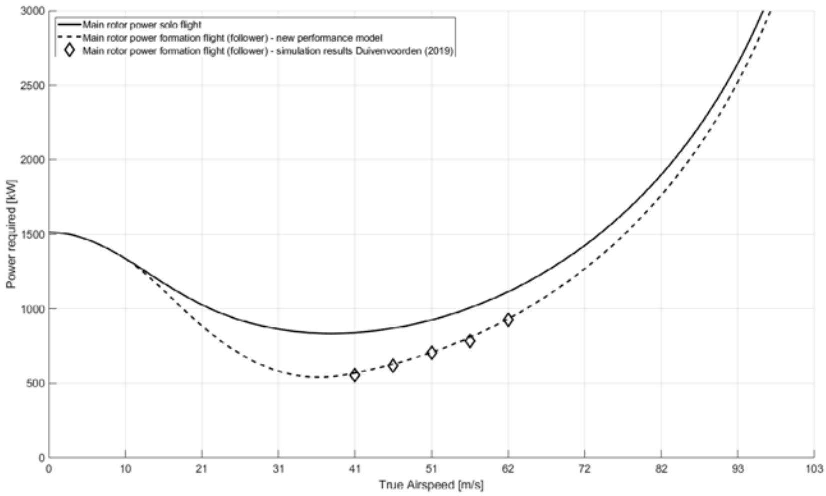
$$P_{follower,formation} = kW\left(v_{i_{follower,solo}} - k_f B\, v_{i_{lead}}\right)$$

The factor k_f accounts for several physical phenomena which are not directly captured by the equation. The velocity field of the wake is not uniformly distributed and it may be that only part of the rotor disc is located in the wake. Furthermore, the magnitude of the velocity of the upwash in the wake can be different from the induced velocity of the lead helicopter. Altogether the factor k_f can be interpreted as an efficiency and it is expected to be less than 1. This new equation is implemented in the performance model, and at airspeeds below the speed for minimum power it is gradually phased in with a one minus cosine function (B) according to the following equation.

$$B = \frac{1}{2} - \frac{1}{2}\cos\left(\left(\frac{V - V_1}{V_2 - V_1}\right)\pi\right)$$

The factor B gradually varies from 0 to 1 in between the speeds V_1 and V_2. In this study, the formation flight effect is phased in the speed range of 10–40 m/s.

Figure 15.4. Performance diagram for the baseline model and the extended model for formation flight (standard atmospheric conditions at sea, mass of both helicopters 8732 kg).

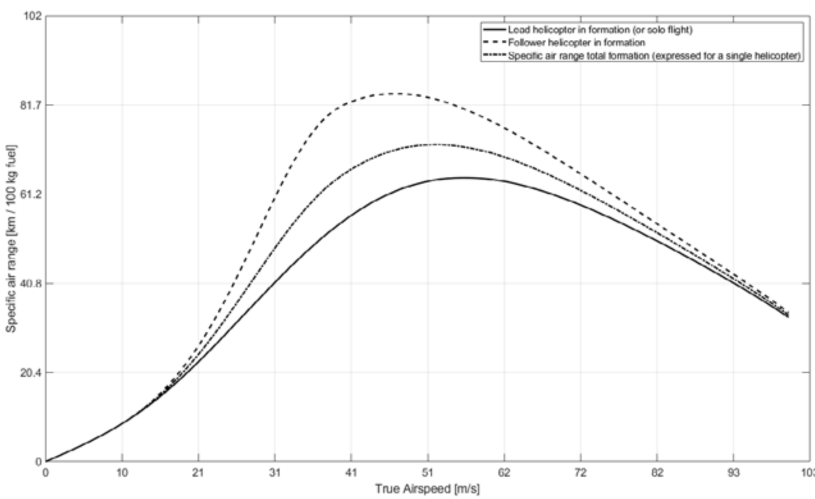


The results of the extended performance model are displayed in Figure 15.4. The baseline performance model shows the required power of the lead helicopter as a function of airspeed. The performance benefits as predicted by Duivenvoorden (2019) in Table 15.2 are applied to this power curve and displayed in the figure as well. Next, the factor k_f was tuned such that the formation flight performance model matches well with the predicted performance benefits. For this case, a factor k_f of 0.7 was selected. It can be observed that the extended model captures the performance benefits very accurately for airspeeds ranging from 41 to 62 m/s. If formation flights at airspeeds outside this range are of interest, then additional simulations with the detailed simulation model of Duivenvoorden et al. (2022) should be conducted in order to tune the factor k_f correctly. However, one should note that the most relevant range of airspeeds lies in between the airspeeds for maximum endurance (~39 m/s) and maximum specific air range in solo flight (57 m/s). In the next section, the formation flight performance model is used to analyse the effect of formation flight on mission performance in terms of range, endurance and optimal airspeeds.

15.4 Results and Discussion

The specific air range, defined as the distance a helicopter can fly per unit of fuel is a key parameter for mission analysis. The airspeed at which the specific range is maximal, is considered to be the optimal airspeed to achieve maximum range (for a given flight range it results in minimum fuel consumption). This optimal airspeed gradually changes during flight when the weight of the helicopter reduces and atmospheric conditions change. In case of a formation flight with the aim to reduce fuel consumption, the specific air range of the follower aircraft is different from a solo flight. The fuel consumption is reduced and the optimum airspeed for maximum efficiency is also changed. The specific air range for both solo flight and formation flight is displayed in Figure 15.5.

Figure 15.5. Specific air range in formation flight (aircraft mass 8732 kg, standard sea level atmospheric conditions).



The optimal airspeed in solo flight for the conditions specified in Figure 15.5 is about 110 knots whereas for the follower helicopter in the formation, the optimal airspeed is about 92 knots. The specific air range of the follower helicopter when flying at this optimal airspeed is almost 30% higher. In formation flight, both helicopters must however fly the same airspeed. The optimal airspeed for the formation as a whole is approximately 103 knots and the corresponding specific air range of the complete formation compared to two solo flights is 12% higher. With the ability to assess the effect of formation flight on fuel use and flight time for a specific flight condition (point performance) it becomes possible to analyse a complete flight during which the helicopter weight gradually changes by means of numerical integration (path performance). The results of a complete cruise flight analysis, for different starting masses of the helicopters and flight ranges, are summarised in Table 15.4.

Table 15.4. Fuel required [%] and flight time [%] of a formation flight compared to two solo flights (constant altitude flight at 304.8 m in standard atmospheric conditions).

		Range [km]		
		200	*400*	*600*
Mass at start of cruise [kg]	*6350*	-8.0% / +5.8%	-7.7% / +5.8%	-7.6% / +5.6%
	7258	-9.1% / +6.3%	-8.9% / +6.3%	-8.6% / +6.3%
	8165	-10.0% / +6.9%	-9.7% / +6.8%	-9.6% / +6.7%
	9072	-10.7% / +7.8%	-10.6% / +7.4%	-10.4% / +7.2%

Hence, the total fuel saving is in the order of 8–10% for a cruise flight at the cost of a 6–7% increase in flight time. For the long range cruise flight over a distance of 600 km at the maximum starting mass of the helicopters (9072 kg), the total fuel saving is 182 kg at the expense of 13 minutes extra flight time. It can be observed that the relative fuel savings increase with the weight of the helicopters. This can be explained by the fact that the required power for a helicopter increases with weight. The velocities induced in the rotor wake by the lead helicopter therefore increase as well and this effect is key for the aerodynamic benefit of the trailing helicopter. The results show that the effect of flight range on the relative savings is small. This is expected as the maximum total mass of the fuel stored in the internal fuel tanks (1110 kg) is relatively low compared to the maximum take-off mass of the helicopter (9185 kg). Hence the weight variation throughout a cruise flight is relatively small.

15.5 Conclusions and Recommendations

Experimental research and numerical simulations conducted at the Netherlands Defence Academy in collaboration with Delft University of Technology have recently confirmed the hypothesis that significant fuel savings can be achieved if two helicopters fly in formation.

A generic physics based model was developed that can be used to quantify the effect of formation flight on flight mission performance parameters such as fuel burn, optimal flight speed and flight time. This new model was applied to simulate the UH-60A Black Hawk helicopter in formation flight. It was demonstrated that the aerodynamic benefit as a result of formation flight can be accurately captured by the model. The baseline model, without aerodynamic benefits due to formation flight, was compared to flight test data of the UH-60 Airloads Program. The comparison showed that flight test data and simulation results are in good agreement and it was concluded that the performance model is representative for the current research

The new model was subsequently used to quantitatively analyse the effect of formation flight for typical military missions conducted with multiple helicopters. The effects of flight distance (range) and the weight of the helicopter at the start of the flight on fuel use and flight time was analysed. For cruise flights conducted at 304.8 m altitude in standard atmospheric conditions, fuel savings of 8–10% are achieved at the cost of a 6–7% increase in flight time. For a long range cruise flight over a distance of 600 km at the maximum starting mass of the helicopters (9072 kg), the total fuel saving is 182 kg at the expense of 13 minutes extra flight time.

Two recommendations are made for future research. First, it is recommended to investigate the potential aerodynamic benefit of formation flight on manned-unmanned teaming operations. The generic physics based model suggests that very large fuel savings can be achieved if a small unmanned system flies consistently in the upwash of the rotor wake of a large helicopter. A second recommendation is to perform a flight test with full-scale manned helicopters to prove the concept of formation flight in real-life conditions.

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