A COMPARISION STUDY OF ROTORCRAFT WITH HYBRID ELECTRIC PROPULSION SYSTEM

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ABSTRACT

Hybrid Electric Propulsion System (HEPS) is being developed as a novel propulsion system not only for the reduction of carbon emission but also for significant design freedom. However, the inevitable disadvantages of additional weight penalty and efficiency lost were induced by the electrification. Despite this, various aero-propulsive interactions enabled by the design freedom were proposed to overcome these impediments for enhanced performance of the aerial vehicle. Therefore, this study presents a comparative study of winged helicopter and fan-in-body, the two exemplary hybrid concepts of rotorcraft and fixed-wing, utilizing HEPS to investigate novel rotorcraft concepts capable of maximizing advantageous characteristics of the electrification. To this end, HEPS rotorcraft design framework was proposed, integrating the sizing of electrical devices and the aero-propulsive interaction. With the HEPS rotorcraft design framework, the design optimizations were carried out for two different mission profiles; resupply mission dominated by high-speed maneuver and reconnaissance mission dominated by the hovering and loitering missions. The success of this study presents that hybridization of the propulsion system incurs notable performance refinements for the mission requiring the maximum power with short operating time, mainly due to the inherent technological limitation of the battery.

NOMENCLATURE AND ABBREVIATIONS

A = Area (ft^2)
AR = Aspect ratio
b = Span (ft)
CRP = Contingency rated power
$C_1 \sim C_3$ = Engine coefficient
C_L = Lift coefficient (3-D)
C_l = Lift coefficient (2-D)
c = Chord (ft)
DOH = Degree of hybridization
FIB = Fan-in-body
$f_0 \sim f_3$ = coefficient for β surrogate model
GT = Gas-turbine engine
IRP = Intermediate rated power
$k_{i,j}$ = Scalar coefficient value for β
L = Lift force (lb)
L' = Lift force per span (lb)
LS = Lift sharing factor
$l_{c.g}$ = Non-dimension length from root chord and center of gravity
MCP = Maximum continuous power
N = Number
P = Power (HP)
R = Radius (ft)
SR = Slow down ratio of the main rotor
TR = Thrust ratio (T_{prop}/T_{total})
$TOGW$ = Take-off gross weight (lb)
V_∞ = Free stream velocity (ft/s)
V_{tip} = Velocity at the rotor tip (ft/s)
V_j = Total freestream and slipstream velocity
v_i = Induced velocity (ft/s)
u = Distance of disk upstream of wing leading edge (ft)
W = Component weight (lb)
WH = Winged helicopter
α = Angle of attack (rad)
β = Velocity multiplier
δ = Ratio of atmospheric pressure at altitude h to standard day sea level pressure
η = Efficiency coefficient
θ = Ratio of ambient pressure at altitude h to standard day sea level pressure
θ_{tw} = Twist angle (rad)
θ_i = Incidence angle (rad)
θ_0 = Collective pitch angle (rad)
λ = Taper ratio
ξ = Percentage of engine power supplied to accessory items
σ_d = Expansion ratio
ρ = Density (slug/ft^3)

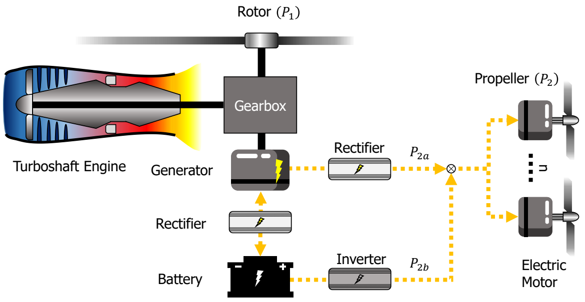
1. INTRODUCTION

Electrification of aircraft in various forms has shown not only the reduction of carbon footprints but also the potential for significant performance improvements by electrification of the current drivetrain system. This enables significant design freedom for various advantageous interactions that were not previously considered in the aircraft design. Therefore, the rotorcraft community has been challenged to design various forms of electrified rotorcraft. However, through examining various technological issues to achieve reliable electric VTOL vehicle, it has been deduced that current battery technology, in particular, is egregious for fully electrified application. Accordingly, the hybrid-electric propulsion system (HEPS) is being developed as part of an alternative resolution, and variants of rotorcraft concept with the HEPS has been proposed.

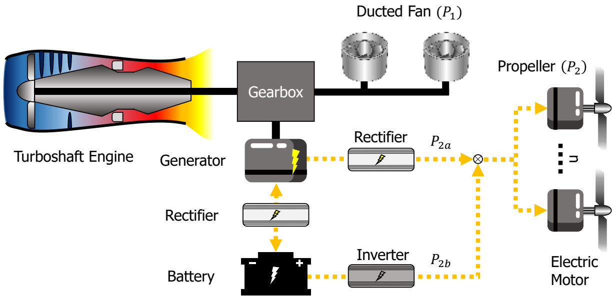
Johnson [1] suggested various electrified rotorcraft concepts for air taxi operations: a quadrotor using a fully electric propulsion system, a side-by-side helicopter using a hybrid propulsion system, and a tilt-wing using turbo-electric propulsion system. Fredericks [2] carried out the concept brainstorming, aerodynamic analysis, and mission analysis for VTOL aircraft with the HEPS: Trifecta, Split wing, Dos Samara, and Semi Tandem. However, these electrified rotorcraft concepts from previous studies have designed rotorcraft without considering various characteristics of the HEPS. The HEPS has three important characteristics since major component consisting of the gas turbine engine and electric counterparts. First, the optimal hybridization of the gas-turbine engine and electrical devices cuts the total energy. Second, using a gas turbine engine minimizes the capacity of the battery required to perform the mission. Third, the aero-propulsive benefit can be maximized with the design freedom that permits novel design configurations such as distributed electric propulsion (DEP). Therefore, this study presents novel rotorcraft concepts, which maximizes advantageous characteristics through electrification while examining the following considerations.

1) Hybridization between turboshaft engine and electrical devices for the energy reduction
2) Propulsion system capable of minimizing the battery capacity, one of the problematic drawbacks to the electrified powertrain
3) The aero-propulsive benefit obtained as distributed auxiliary thrusters with a high degree of freedom for design

The proposed concepts were winged-helicopter and fan-in-body, two exemplary hybrid concepts of rotorcraft and fixed-wing, utilizing a series-parallel hybrid-electric propulsion system as depicted in Fig. 1. To design the aforementioned concepts, the distinct characteristics of the HEPS considering the sizing of electrical devices and the aero-propulsive interaction obtained by distributed auxiliary thrusters were integrated into the rotorcraft design framework. The concept of hybridization was used when designing the propulsion system, and discharge and charging module of the battery was considered to minimize the battery capacity required at mission analysis. Also, the effect of distributing the propulsion system was accounted for the aero-propulsive benefits at the flight analysis module. In addition, among various application fields, design optimization was performed for the resupply and reconnaissance mission, which pose significant differences in mission range, hovering loitering time. Through the design optimization results, the advantages of HEPS rotorcraft that can be obtained were presented quantitatively.



(a) Powertrain Architecture of Winged Helicopter concept



(b) Powertrain Architecture of Fan-in-body concept

Figure 1: Hybrid Electric Propulsion System Architectures

2. CONCEPTUAL DESIGN FRAMEWORK

2.1. Overall Design Flow

A conceptual design framework for rotorcraft using HEPS was based on the in-house Rotorcraft Initial Sizing and Performance Estimation Code and Toolkit + (RISPECT+) [3], and its overall process is shown in Fig. 2. First, rotorcraft sizing is performed to obtain the gross weight, fuel weight, and total battery energy required to perform the mission with the input data such as design variables and constraints. Then, the fitness value is calculated from the fitness function,

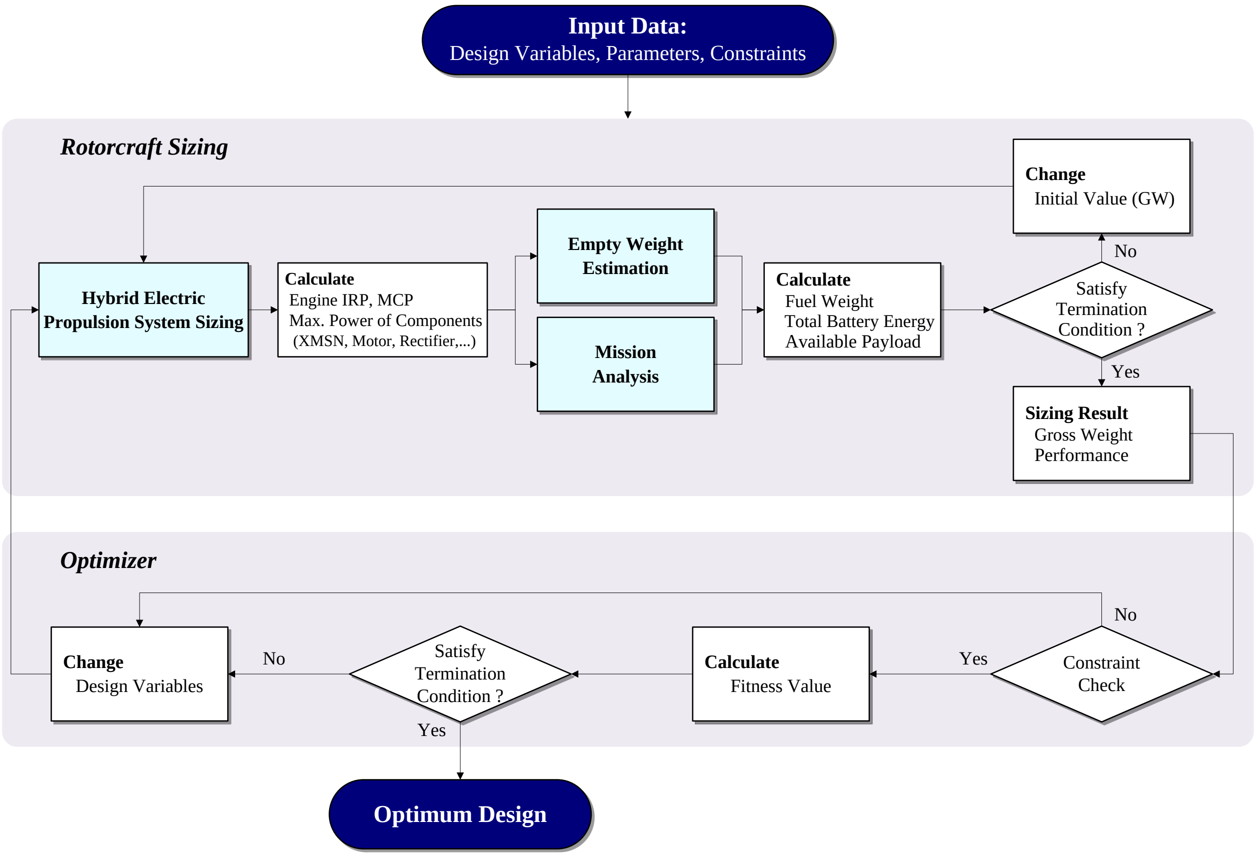


Figure 2: Overall Design Flow Chart

and the optimal configuration is derived while manipulating the design variables until the termination condition is satisfied. The overall design process for rotorcraft using HEPS is similar to the conventional rotorcraft's sizing process, with additional consideration for distinctive characteristics of HEPS in the design framework. Therefore, this study considers the characteristics of electrical components and aero-propulsive benefits by distributing auxiliary thrusters in the sizing and analysis modules. Detailed explanations are described in sections 2.2 to 2.4.

2.2. Hybrid Electric Propulsion System Sizing

As depicted in Fig. 3, the propulsion system is sized based on the maximum required power acting on each component and aircraft within the design space. The sizing methodology for each component is given in Table 1. For the hybridization of the propulsion system, Degree of Hybridization (DOH) concept is used. DOH is the defined a ratio between electrified power and total required power as shown in equation (1) and Fig. 4 [4]. Using the DOH, the maximum continuous power (MCP) of the engine is calculated with equation (2). Then, the maximum power of each component is calculated to using the equation (3) as well as the efficiency coefficient. Through this process, the electric devices and transmission are sized to

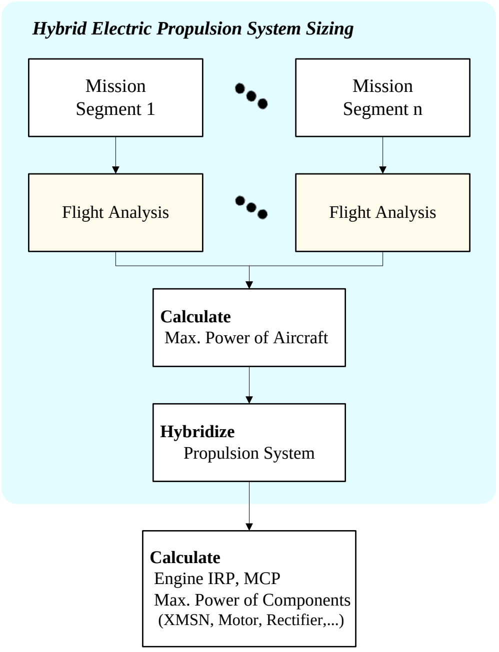


Figure 3: Propulsion System Sizing Flow Chart

operate at their maximum power throughtout the mission as much as possible.

$$(1)\ DOH = \frac{P_{elect}}{P_{elect} + P_{mech}} = \frac{P_{elect}}{P_{max}}$$

$$(2)\ P_{MCP} = \frac{[(1 - DOH)P_{max} + \Delta P]}{1 - \xi} \times C_3$$

$$(3)\ \begin{bmatrix} \eta_{xmsn} & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_m & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_r & -1 & 0 & 0 \\ 0 & 0 & 0 & \eta_r & 0 & 0 \\ 0 & 0 & 0 & 0 & \eta_r & 0 \\ 0 & 0 & 0 & 0 & 0 & \eta_c \end{bmatrix} \begin{bmatrix} P_{xmsn} \\ P_m \\ P_g \\ P_{r,1} \\ P_{r,2} \\ P_c \end{bmatrix} = \begin{bmatrix} (P_1)_{max} \\ (P_2)_{max} \\ 0 \\ (P_{2a})_{max} \\ P_{charge,limit} \\ (P_{2b})_{max} \end{bmatrix}$$

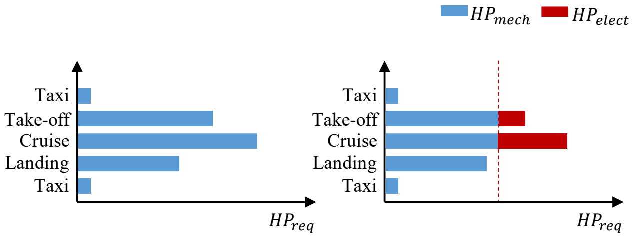


Figure 4: Degree of Hybridization (DOH) [4]

Table 1 Method used in the Component Sizing

Component	Used method
Turboshaft engine	Rubber engine sizing method [5]
Motor	Efficiency coefficient (η_m)
Generator	Efficiency coefficient (η_g)
Rectifier	Efficiency coefficient (η_r)
Converter	Efficiency coefficient (η_c)
Thermal management system	Efficiency coefficient $(\eta_m, \eta_g, \eta_r, \eta_c)$

2.3. Mission Analysis

The HEPS Rotorcraft performs the given mission profile using hydro-carbon based fuel and batteries. Accordingly, the mission analysis module shown in Fig. 5 calculates the fuel weight and total battery energy through the flight analysis for each mission segment. In addition, since the weight of the battery is the major drawback that must be resolved to obtain feasible design, charging and discharging module of the battery was added to minimize total battery required with the engine coefficient [5], as shown in equation (4) and (5). If the power required to carry out the mission is greater than the engine MCP, the status of the battery is determined to be discharged, and in the opposite case, the charging of the battery is obtained. Therefore, the fuel consumption and the total energy of the battery required for the mission are computed through the mission analysis module.

$$(4)\ \Delta P = P_{req} - P_{@MCP}$$

$$\begin{cases} \dot{W}_{fuel} = C_1 \delta \sqrt{\theta} P_{IRP} + C_2 P_{@MCP}/\eta & at\ \Delta P > 0 \\ \dot{W}_{fuel} = C_1 \delta \sqrt{\theta} P_{IRP} + C_2 \left(P_{req} + P_{charge}\right)/\eta & at\ \Delta P < 0 \end{cases}$$

$$(5)\ E_{bat} = \sum_{i=1}^{i=n} (\Delta E_{bat})_i$$

$$\begin{cases} \Delta E_{bat} = \Delta P/\eta \times t & at\ \Delta P > 0 \\ \Delta E_{bat} = -P_{charge}/\eta \times t & at\ \Delta P < 0 \end{cases}$$

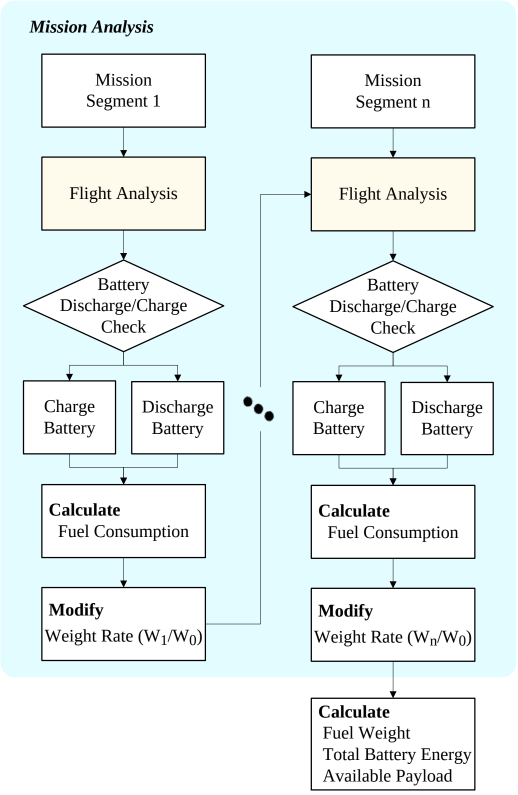


Figure 5: Mission Analysis Flow Chart

2.4. Flight Analysis

The HEPS rotorcraft with distributed auxiliary propulsion system has an aero-propulsive benefit. The flight analysis process based on previous study [3] is carried out with these characteristics, as shown in Fig. 6. Beginning with the forward flight analysis, the lift generated by the wing is computed without the aero-propulsive effects. Using the result of the wing aerodynamic analysis, the lift-sharing ratio during forward flight is derived using the equation (6), and aerodynamic analysis of the main propulsive unit is carried out. Subsequently, additional drag forces generated by the wake of the main propulsion systemis computed. In addition, the aerodynamic analysis of the fuselage is performed, and aerodynamic analysis of the auxiliary propulsion

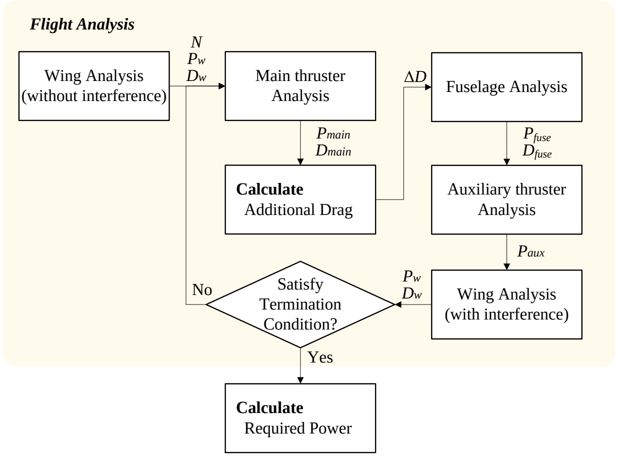


Figure 6: Flight Analysis Flow Chart

system which generates the required thrust for forward flight is calculated.

The method used for the calculation of the aero-propulsive interaction in this study is based on the surrogate model developed by Patterson [6]. This surrogate model was generated based on CFD simulations of an actuator disk and an NACA 0012 airfoil, and the model includes several assumptions as follows:

1) The velocity increase at the actuator disk is computed assuming uniform axial inflow
2) The flow is attached
3) Lift due to swirl effect is neglected (actuator disk assumed)
4) The wing is fully immersed in the slipstream

The aero-propulsive interaction considered for wing analysis using the induced velocity due to the auxiliary thruster analysis is shown in equation (7). The two-dimensional geometry depicted in Fig. 7 shows the orientation of the propeller disk. These array of thrusters on the wing are aligned in spanwise direction of the wing to generate slipstream. Such configuration increases the actual relative airspeed by the airfoil to generate additional ΔC_l. In this case, the slipstream velocity is assumed to be uniform, and the influence on the slipstream height is considered as the surrogate model described in equation (8). The velocity correction multiplier β in equation (8) was derived to account for the propeller velocity due to the contraction of the wake. With R/c being the wake radius over the wing chord ratio and equation (8) incorporating the position of the propeller from the leading edge of the wing in equation (9), this interference effect is extended to the three-dimensional wing using the equation (10). With the increments of the lift generated by the wing and aero-propulsive interactions, the effect of distributing the propulsion system is considered for the calculation of the required power during forward flight. During hover, unnecessary modules are neglected.

In this study, flight analysis was performed with the analysis method described in Table 2, considering the fidelity and computation time of the analysis method used in the conceptual design phase.

$$(6)\ LS = 1 - \frac{L_w}{GW}$$

$$(7)\ C_l \approx \left(1 + \frac{\beta v_i}{V_\infty}\right) C_{l_\alpha} \left[\theta_i + \alpha_\infty - \left\{\alpha_{L=0}\left(1 + \frac{\beta v_i}{V_\infty}\right)\right\}\right]$$

$$(8)\ \ \beta = f_0 + f_1\left(\frac{R}{c}\right) + f_2\left(\frac{R}{c}\right)^2 + f_3\left(\frac{R}{c}\right)^3 + f_4\left(\frac{R}{c}\right)^4$$

$$(9)\ \ f_i = k_{i,0} + k_{i,1}\left(\frac{u}{c}\right) + k_{i,2}\left(\frac{u}{c}\right)^2 + k_{i,3}\left(\frac{u}{c}\right)\left(\frac{V_j}{V_\infty}\right) + k_{i,4}\left(\frac{V_j}{V_\infty}\right) + k_{i,5}\left(\frac{V_j}{V_\infty}\right)^2$$

$$(10)\ \ \frac{\Delta C_L}{C_{L_\infty}} = \sum_{i=1}^{N}\left(\frac{\Delta L'}{L'_\infty}\right)_i\left(\frac{b_{blown}}{b}\right)_i$$

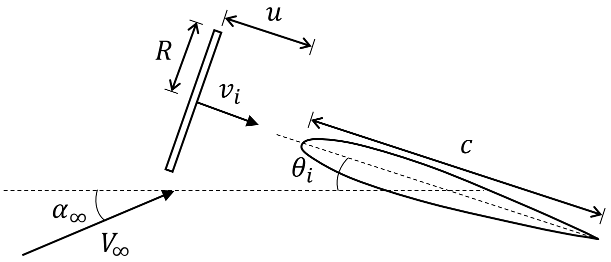


Figure 7: Orientation of Freestream Velocity and Propeller Disk with Respect to a Local Airfoil Section [6]

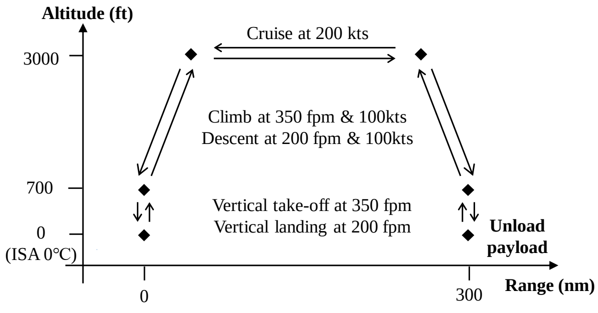
Table 2 Component Analysis Method

Component	Analysis method [6-10]
Main thruster	Blade element momentum theory Blade element theory
Wing	Oswald's factor Empirical factor (β)
Aux. thruster	Momentum theory
Fuselage	Empirical formula

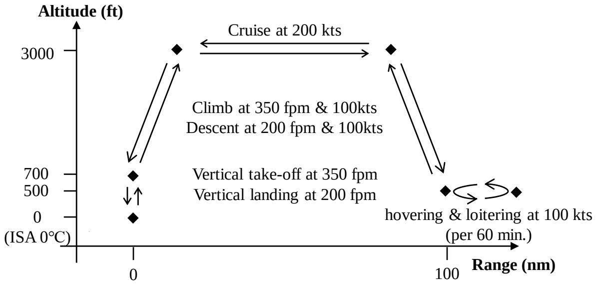
3. DESIGN OPTIMIZATION

3.1. Mission Profile

In order to accentuate the difference in the flight mechanism of the winged helicopter and the fan-in-body concepts, two distinctive reconnaissance, and resupply missions are compared in this study. Assuming 500lb payload, reconnaissance mission consists of loitering and hovering as depicted in Fig.



(a) Resupply Mission



(b) Reconnaissance Mission

Figure 8: Mission Profile

8, while the resupply mission consists of a flight range of 200km to a military camp located 300nm distance, and unloading of the 500lb payload for the returning flight.

3.2. Design Assumptions

Detailed requirements for design were replaced by several assumptions at the conceptual design phase. The applied assumptions are as follows:

1) Winged helicopter

1-1) While hovering, the torque generated by the main rotor is offset by the auxiliary propellers located on right side of the wing.
1-2) In the case of HEPS rotorcraft, tip clearance between propellers is assumed to be $0.1D_{prop}$.
1-3) It utilizes an articulated hub system, and shaft axis is located at the C.G point of the aircraft.
1-4) Based on the actual rotorcraft configuration, fuselage's width and height are assumed to be $0.3R_{mr}$, and fuselage fineness ratio is 5.1[11].
1-5) It utilizes two identical engines for redundancy.
1-6) It reduces the speed of the rotor when performing a high-speed flight. This study assumes that the reference speed for the decelerated rotor is 100 knots.

2) Fan-in-body

2-1) It utilizes the fan to perform hover and transient flight, and during forward flight, the wing produces lift to perform like a fixed-wing aircraft.
2-2) The clearance between the ducted fans is R_{fan} for accounting for the space of gearbox, fuel tank, and etc.
2-3) To have sufficient space for the ducted fan and the payload, the fuselage's width and length are assumed to be $1.2\ d_{fan}$ and $4d_{fan}$accordingly. Additionally, the duct height is assumed to be $0.5R_{fan}$ for the ideal effect of duct [12].
2-4) It utilizes two identical engines for redundancy.
2-5) The material of the duct is carbon-fiber composite [12].
2-6) The required power for the attitude control vane is assumed to be 3% of the total required power [13].

3) Electric devices

3-1) Specific power and efficiency coefficient are referenced from the NRA goal [14].
- motor / generator: 8.0 hp/lb, 96.0 %
- inverter / rectifier: 11.6 hp/lb, 99.0 %
- Thermal management system: 0.413 hp/lb

3-2) Specific energy of Battery is 0.153 hp-hr/lb based on 2025s battery technology [15].

3.3. Problem Definition

Take-off gross weight is an important parameter when comparing aircraft performance. Therefore, single objective function to minimize the take-off gross weight of the aircraft is carried out, while imposing following three performance constraints and four configuration constraints. Performance constraints consist of the maximum lift coefficient of airfoils, propeller limit RPM, and battery energy required. In order to consider the stall characteristics of the rotor and the wing, a constraint is applied for the maximum lift coefficient. Accounting for the noise of the propeller, the maximum RPM is set as a previous studies recommended limit as a constraint [16]. In addition, to consider the safe operation of the vehicle in emergency situations of OEI condition, fixed provision of battery capacity together with the engine CRP power enable 2.5 minutes hover capability. The shape constraint consists of the size of the components and the location of the center of gravity. This includes radius constraints for the tip-ground clearances of the thrust augmented propellers. Moreover, accounting for the structural integrity of the components, the aspect ratio is set as the shape constraint. Lastly, the wing span is limited in order to account the space occupied by the rotorcraft.

The optimal design problem is performed using the design variables and parameters summarized in Table 3 and Appendix.

Objective (1):

Min. Take-Off Gross Weight (lb), TOGW

Constraints (7):

$$C_l \leq C_{l_{limit}} \qquad RPM_{prop} \leq RPM_{limit}$$

$$E_{min} \leq E_{bat} \qquad R \leq R_{limit}$$

$$AR \leq AR_{limit} \qquad b_w \leq b_{w_{limit}}$$

$$l_{min} \leq l_{CG} \leq l_{max}$$

Table 3: Design Variables for Rotorcraft

Component	Winged helicopter (17)	Fan-in-body (15)
Main thruster (rotor / fan)	$R, c, V_{tip}, \theta_{tw}$	$R, c, \theta_0, \theta_{tw}$
Wing	b, AR, λ, θ_i	b, AR, λ, θ_i
Aux. thruster	$^*N, R, c, RPM$	$^*N, R, c, RPM$
Horizontal tail	b, AR	b, AR
Etc.	$^*DOH, SR, TR$	$^*DOH$

*design variables used only for HEPS concept

3.4. Design Optimization

Since most of the analytic equations used in this study consist of algebraic equations, the computation time is approximately 5 to 10 seconds per case. The Evolutionary Algorithm, which is a non-gradient-based method, is adopted as an optimization method by taking advantage of the short computation time. Using this method, optimized rotorcraft which performs the resupply and reconnaissance missions, were obtained. Detailed explanations are described in section 3.4.1 ~ 3.4.2.

3.4.1. Optimization Results (Resupply)

The results of the optimal design for the resupply mission are shown in Table 4. The TOGW of winged helicopter and fan-in-body with the gas-turbine engine were estimated to be 3,397 lb and 3,020 lb accordingly. When the HEPS was integrated for the propulsion system, the additional electrical equipment required to operate the HEPS increased the empty weight, thereby resulting in a design result that increased the gross weight. As a result, the gross weight of the HEPS winged helicopter increased to 5,028 lb compared with the concept using the gas-turbine engine only. However, if HEPS is used as a propulsion system, gross weight reduction can be obtained by increasing the forward flight efficiency due to the aero-propulsive interaction. Significant aero-propulsive effects were obtained from the time when there were more than four auxiliary thruster systems. Also, unlike the HEPS fan-in-body, the HEPS winged helicopter had the smallest gross weight when it had six propellers. As the number of propeller increases, the thrust required by one propeller to offset the anti-torque was decreased by $0.5N_{prop}$ times, but the area per propeller was reduced by $\frac{1}{(N_{prop})^2}$ times, resulting in an increase of the induced power. Thus, as the number of propellers increases, the aero-propulsive efficiency in the forward flight increases, while the efficiency in the hovering deteriorates, resulting in an appropriate number of six. Since the disadvantage from the additional components required to drive the HEPS is greater than the aero-propulsive benefit for the case of the winged-helicopter, the gross weight of the HEPS was estimated heavier than the other concept. In the case of the fan-in-body, a contrasting result from the winged helicopter was obtained. The fan-in-body concept gains lift using both wing and ducted fans when performing low-speed flight such as the transient flight. During low-speed maneuver, an additional momentum drag is generated by the duct wakes as derived from the equation (10). In a transient flight when the maximum power was identified, the momentum drag was 1.9 times larger than the fuselage drag at 200kts. For this reason, the aero-propulsive benefit obtained from HEPS can minimize the momentum drag that occurs in low-speed flight, which acts as a snowball effect to reduce the gross weight of the rotorcraft. Thus, it led to a conclusion that the HEPS is a highly efficient propulsion system for the FIB concept, has additional drag on the transient flight.

$$(10)\ D_{fan} = -\frac{\rho A v_i}{\sigma_d \sqrt{\cos\alpha}}\left(V_\infty - v_i\sqrt{\cos\alpha}\tan\alpha\right)$$

A comparison study was carried out between two types of rotorcraft propulsion system design results: the concept of the gas-turbine engine only and the concept of HEPS with the smallest gross weight. 3-D modeling of the design result is shown in Fig. 9. In the case of the fan-in-body, when the propulsion system was switched to the HEPS from the gas-turbine engine, TOGW and total energy were reduced by up to 34% as shown in Table 4. It means that the advantages of aero-propulsive interaction and hybridization were dominant than the disadvantages of a penalty of additional weight for electrical devices. In addition, the fan-in-body concept utilized a ducted fan to perform axial flight such as take-off or landing, requiring 2 times the power required for cruise mission as shown in Fig. 10. However, since these missions were performed within 10 minutes approximately, the required energy of the battery to perform each mission was trivial; 10hp-hr ~ 30hp-hr. Therefore, the fan-in-body concept was able to reduce the amount of fuel required by 50% when performing axial flight.

However, the result of the WH conceptual design was completely different from that of the FIB. Since the engine MCP of HEPS winged helicopter concept was calculated to be 469hp based on the cruise mission, the battery acted as the unnecessary components throughout the mission profile except for cruise

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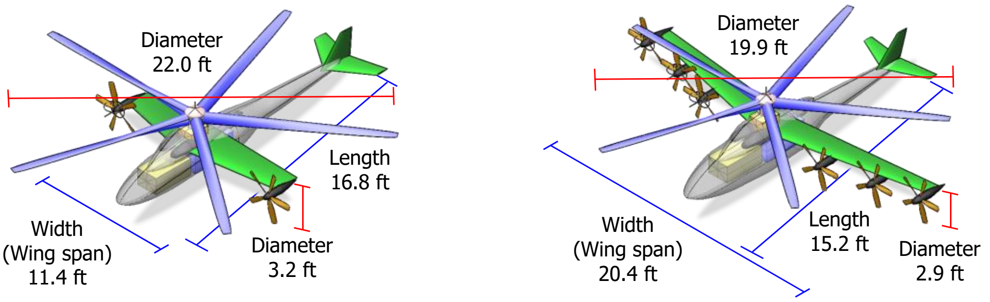
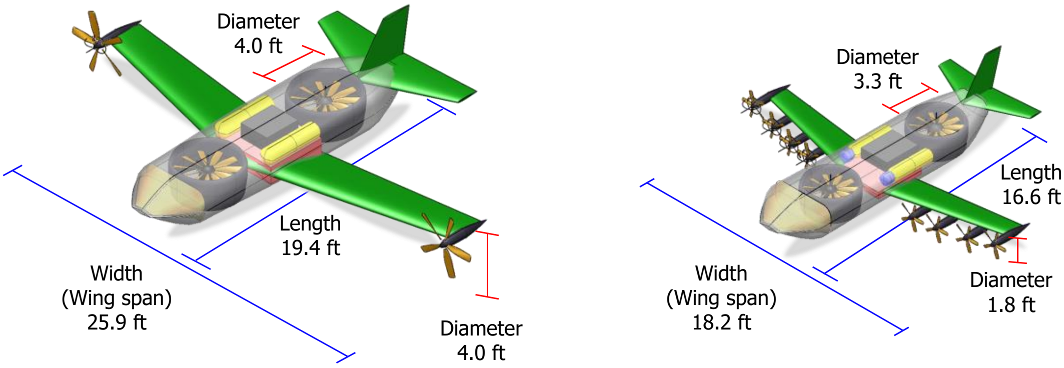
segment. In addition, the battery capacity required to hover over 2.5 minutes under OEI conditions was also very small; 8.2 hp-hr. Thus, trivial DOH was derived, which means that a battery-free hybrid-electric propulsion concept, turbo-electric, is suitable for the winged helicopter. It was also deduced that the disadvantage of the additional weight of the electrical devices was greater than the advantage of

Table 4: Design Optimization Results (Resupply Mission)

Type	Winged helicopter					Fan-in-body				
	GT	HEPS				GT	HEPS			
N_{prop}	2	2	4	6	8	2	2	4	6	8
$TOGW$ [lb]	3,397	5,028	4,427	4,164	4,328	3,020	3,757	2,881	2,742	2,706
W_{empty} [lb]	1,793	2,955	2,611	2,486	2,573	1,873	2,620	1,951	1,844	1,817
W_{fuel} [lb]	1,104	1,573	1,315	1,175	1,253	644	636	426	399	388
E_{total} [hp-hr]	2,157	2,872	2,398	2,163	2,307	1,055	1,155	789	717	698
E_{bat} [hp-hr]	-	5.97	6.65	8.20	7.94	-	25.94	21.39	20.59	20.16
DOH	-	0.020	0.020	0.026	0.026	-	0.486	0.522	0.512	0.516
P_{MCP} [hp]	457	645	535	469	506	372	263	169	163	165



(a) Winged helicopter with turboshaft engine only (b) Winged helicopter with HEPS $(N_{prop} = 6)$



(c) Fan-in-body with turboshaft engine only (d) Fan-in-body with HEPS $(N_{prop} = 8)$

Figure 9: 3D Modeling of Design Optimization Results (Resupply Mission)

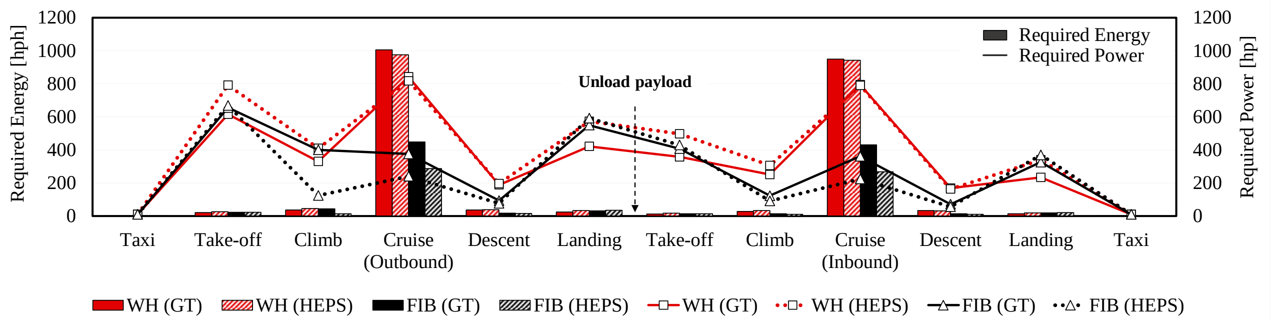


Figure 10: Required Power and Energy at Mission Segments (Resupply Mission)

propulsive interaction through hybridization of the propulsion system.

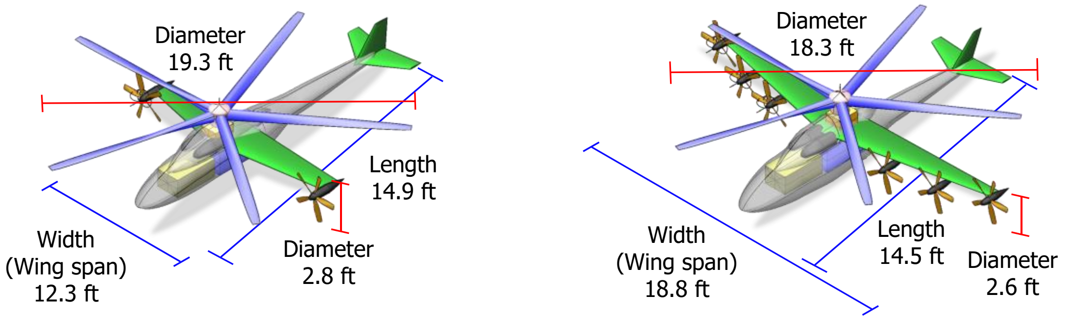
3.4.2. Optimization Results (Reconnaissance)

Design optimization was conducted for reconnaissance missions, where hovering and loitering were the main tasks accounting for 63 % of the total mission. As shown in Table 5, the tendency for gross weight changes as the number of auxiliary thrusters increased or the propulsion system is switched from gas-turbine engine to HEPS. However, all configurations with HEPS had higher gross-weight than the concept with gas-turbine engine only. It means that in all cases, the handicap of additional electrical devices was consequential than the benefits of aero-propulsive interaction and hybridization of the propulsion system. To investigate these results in detail, a comparative study was conducted on the concept of gas-turbine engine and the concept of HEPS with the smallest gross weight, and 3-D modeling of the design result is shown in Fig. 11. The maximum required power of the winged helicopter concept was calculated from the cruise mission with 200 knots, and that of the fan-in-body was estimated from the transient flight at 40 knots. Because sizing of the hybridized propulsion system is based on the maximum required power, the battery of the HEPS winged helicopter concept acted as unnecessary components throughout the mission profile except for the cruise segment. For this reason, the tendency of design results for the winged helicopter concept was predicted almost identical to the resupply mission. For the HEPS fan-in-body concept, although the battery was used for the mission utilizing a ducted fan during hovering and transient flight, the DOH was estimated to be 0.1~0.12, for the following reasons.

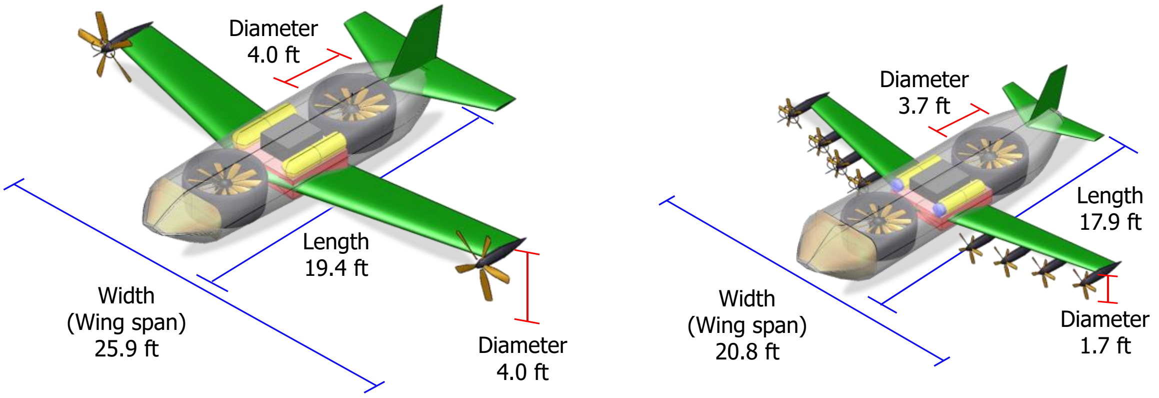
The specific energy of the battery used in this study is 0.153 hp-hr/lb based on 2025s technology, which is approximately 1/65 times as large as that of the hydrocarbon-based fuel [17-19]. Due to the limitations of current battery technology, the battery design used for HEPS was performed to fit the constraint that minimum battery capacity to meet OEI condition. In addition, since the battery is used in situations where the power required to perform the mission exceeds the maximum continuous power of the engine, the DOH determined was calculated to use 13 hp-hr of the battery energy in hovering which demand power of 610 hp, as shown in Fig. 12. If the specific energy of the battery is improved by the development of electrical technology, the hybridization of the propulsion system could provide significant performance improvements.

Table 5: Design Optimization Results (Reconnaissance Mission)

Type	Winged helicopter					Fan-in-body				
	GT	HEPS				GT	HEPS			
N_{prop}	2	2	4	6	8	2	2	4	6	8
$TOGW$ [lb]	2,488	3,524	3,301	3,264	3,455	2,942	4,680	3,300	3,191	3,150
W_{empty} [lb]	1,397	2,144	2,083	2,048	2,180	1,839	3,247	2,176	2,069	2,030
W_{fuel} [lb]	590	878	716	714	773	600	933	624	622	618
E_{total} [hp-hr]	889	1,275	1,065	1,117	1,190	904	1,445	957	950	932
E_{bat} [hp-hr]	-	1.78	0.04	6.22	3.65	-	15.84	13.30	13.23	932
DOH	-	0.010	0.012	0.054	0.038	-	0.180	0.102	0.100	0.102
P_{MCP} [hp]	357	526	417	384	428	357	491	338	338	343



(a) Winged helicopter with turboshaft engine only (b) Winged helicopter with HEPS $(N_{prop} = 6)$



(c) Fan-in-body with turboshaft engine only (d) Fan-in-body with HEPS $(N_{prop} = 8)$

Figure 11: 3D Modeling of Design Optimization Results (Reconnaissance Mission)

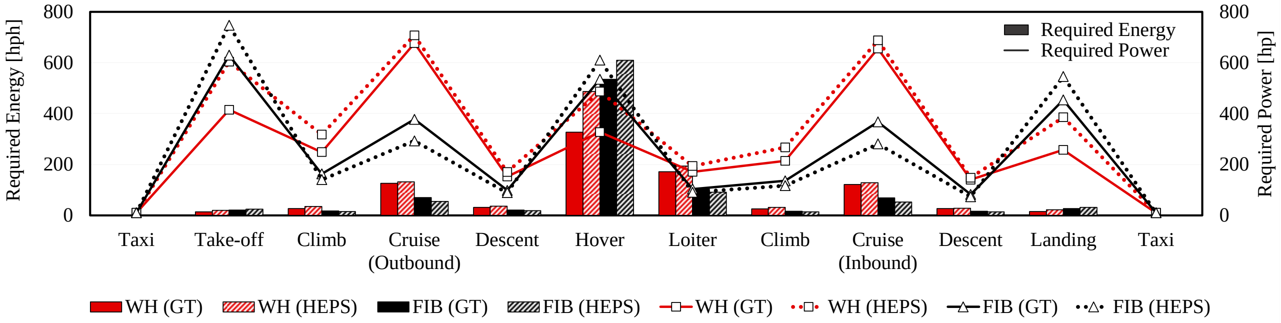


Figure 12 Required Power and Energy at Mission Segments (Reconnaissance Mission)

4. CONCLUSION

This study carried out the comparative study of two exemplary hybrid concept, winged helicopter, and fan-in-body, in order to suggest novel rotorcraft concepts capable of maximizing advantageous characteristics of electrification. To this end, the noticeable characteristics of the HEPS accounting for the sizing of electrical devices and the aero-propulsive benefits by the design freedom were combined into the rotorcraft design framework. Utilizing the HEPS rotorcraft design framework, the design optimizations were carried out for two different mission profiles; resupply mission dominated by high-speed maneuver, and reconnaissance mission oriented by the hovering and loitering. As a result of the design optimizations, the conclusions were as follows:

1) HEPS's additional weight penalty in electrical devices causes an increase in empty weight. Therefore, to use HEPS more efficiently than the

gas-turbine engine propulsion system, it is necessary to maximize merits of the HEPS such as aero-propulsive benefit through hybridization of the propulsion system. Without the merits of HEPS, the gross weight increased by more than 30% when the propulsion system was switched from gas-turbine to HEPS. However, when the aero-propulsive benefit was integrated by increasing the number of auxiliary thrusters, the gross weight decreased by up to 30%. Even with a proper hybridization of the propulsion system, a gross weight reduction of 10% and a total energy reduction of 30% were achieved compared to the turboshaft engine concept.

2) Due to the limitation of battery technology, the battery is forced to have a minimum capacity. Accordingly, hybridization of the engine and the electric devices should be performed based on the mission requiring the maximum power with short operating time in order to make the most efficient use of the battery. If the battery can assist the engine by generating a lot of power within a short period of time, energy reduction effect, as well as reduction of fuel could be obtained. An example of such case is seen from the design result of the HEPS fan-in-body concept to perform a resupply mission. Conversely, if hybridization is performed based on a mission that requires a long operating time, it will require a low DOH value and in return, advantages of the HEPS will not be utilized. In particular, the winged helicopter was designed similarly to the turbo-electric concept, with near-trivial DOH since the hybridization was carried out on forward flight with long operating hours.

In the HEPS rotorcraft design, an analysis technique with high fidelity is needed for the electric propulsion system to make the design even more realistic. In the future, if the electrical circuit analysis is carried out utilizing the HEPS rotorcraft concept design of this study, it will provide more realistic design results.

ACKNOWLEDGEMENT

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APPENDIX

Design Parameters and Variables

Table A1: Design Parameters

Design parameters		Value
Rotor / Fan	Airfoil	WH : NACA 0012 FIB : NACA 23012
	N_b	WH : 5 FIB : 11
Wing	Airfoil	NACA 23012
Propeller	Airfoil	NACA 0012
	N_b	5
H-tail wing	Airfoil	NACA 2412
	λ	0.4
V-tail wing	Airfoil	NACA 0012
	V_{vt}	0.07
	AR	1.5
	λ	0.4
Etc.	Engine	GE-T700 (Rubber engine)

Optimization Results

Table A2: Optimization Results of Winged Helicopter (Resupply Mission)

D.V	GT	HEPS			
N_{prop}	2	2	4	6	8
R_r	11.0	11.4	10.2	10.0	10.1
c_r	0.69	0.72	0.64	0.64	0.66
$V_{tip,r}$	656	650	686	662	638
θ_{tw}	-6.0	-8.9	-8.4	-10.5	-9.1
SR	0.86	0.92	0.85	0.86	0.91
b_w	11.4	18.8	19.5	20.4	21.7
θ_{incid}	6.3	5.2	3.5	3.7	3.7
AR_w	4.9	11.4	10.8	12.4	15.0
λ_w	0.52	0.49	0.58	0.39	0.46
R_{prop}	1.6	1.7	1.5	1.4	1.13
c_{prop}	0.58	0.58	0.34	0.45	0.58
RPM_{prop}	3530	3502	3626	2982	3516
TD	0.99	0.95	0.97	0.99	0.97
b_t	4.7	4.3	5.0	5.0	3.8
AR_t	3.12	4.6	4.2	5.0	4.4
DOH	-	0.02	0.02	0.03	0.03

Table A3: Optimization Results of Fan-In-Body (Resupply Mission)

D.V	GT	HEPS			
N_{prop}	2	2	4	6	8
R_{fan}	2.02	2.0	1.8	1.7	1.7
c_{fan}	0.30	0.3	0.34	0.25	0.24
$\theta_{0,fan}$	47.7	45.3	47.7	54.1	53.1
$\theta_{tw,fan}$	-16.6	-15.8	-23.0	-22.7	-20.5
b_w	25.9	25.8	22.9	19.6	18.2
θ_{incid}	11.9	13.6	13.5	13.4	12.8
AR_w	7.3	6.8	10.7	9.0	8.5
λ_w	0.52	0.53	0.52	0.59	0.44
R_{prop}	2.02	2.0	1.3	1.1	0.89
c_{prop}	0.28	0.36	0.23	0.21	0.20
RPM_{prop}	3256	3078	3872	4004	4118
b_t	10.6	11.7	5.96	5.8	6.0
AR_t	4.1	5	5	4.9	5.0
DOH	-	0.49	0.52	0.51	0.52

Table A4: Optimization Results of Winged Helicopter (Reconnaissance Mission)

D.V	GT	HEPS			
N_{prop}	2	2	4	6	8
R_r	9.68	10.2	9.96	9.2	10.0
c_r	0.61	0.64	0.64	0.58	0.64
$V_{tip,r}$	650	614	614	638	668
θ_{tw}	-7.2	-8.8	-6.5	-7.0	-8.4
SR	0.89	0.99	0.93	0.87	0.88
b_w	12.3	14.1	19.7	18.8	20.4
θ_{incid}	4.9	6	3.8	3.9	3.4
AR_w	6.34	8.6	13.3	11.2	11.9
λ_w	0.38	0.58	0.46	0.22	0.56
R_{prop}	1.42	1.52	1.48	1.34	1.08
c_{prop}	0.64	0.81	0.29	0.43	0.43
RPM_{prop}	3690	3068	3502	3180	3810
TD	0.99	0.8	0.98	0.99	0.96
b_t	4.4	4.0	4.0	5.0	5.6
AR_t	3.24	4.6	4.1	4.2	4.9
DOH	-	0.01	0.01	0.05	0.04

Table A5: Optimization Results of Fan-In-Body (Reconnaissance Mission)

D.V	GT	HEPS			
N_{prop}	2	2	4	6	8
R_{fan}	2.02	2.56	2.07	1.93	1.87
c_{fan}	0.30	0.37	0.30	0.28	0.27
$\theta_{0,fan}$	50.1	48.9	46.9	54.4	54.3
$\theta_{tw,fan}$	-14.6	-16.0	-23.0	-20.3	-20.1
b_w	25.9	28.0	25.8	19.6	20.8
θ_{incid}	11.9	11.9	11.9	11.7	11.0
AR_w	7.3	5.9	11.4	7.7	9.1
λ_w	0.46	0.58	0.54	0.65	0.39
R_{prop}	2.02	2.55	1.32	1.02	0.87
c_{prop}	0.26	0.34	0.28	0.33	0.33
RPM_{prop}	3298	3274	3800	4004	4128
b_t	10.8	15.4	5.96	6.9	6.6
AR_t	4.4	4.9	4.6	5.0	5.0
DOH	-	0.18	0.1	0.1	0.1
