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ROTORCRAFT SYSTEMS MODELLING FOR TWIN-ENGINE HEAVY HELICOPTER

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Abstract

The projected growth in air travel over the coming decades has been extensively documented in the open literature. Most of this growth comes from fixed wing aircraft travels, and therefore much research has been reported in this aircraft category. Much less documentation on the subject is available for the rotorcraft counterpart. Nevertheless, the environmental impact of rotorcraft should not be taken lightly. This research focuses on quantifying and reducing the negative environmental impact that rotorcraft operations have. This is achieved in particular by modelling the rotorcraft airframe systems and analyzing their environmental impact at mission level. This will be achieved by investigating the concept of a more-electric rotorcraft, in realizing the 'green rotorcraft' concept aspired to in the Clean Sky project. The Rotorcraft Mission Energy Management (RMEM) model is a tool developed which represents all of the secondary power generation and user systems on a rotorcraft. The RMEM simulates the onboard helicopter systems and determines, the shaft power and engine bleed air off-take requirements of each system for prescribed sets of flight conditions. For the purpose of demonstration, three generations of rotorcraft will be presented: the current, the near-term future and the medium-term future; with each generation having different levels of technology installed. A simulation of a mission case study will be presented which analyses the total shaft power off-take of each rotorcraft as a function of mission time.

1 Introduction

The quest for more-electric aircraft is a strong research trend in aerospace engineering at present. By replacing a conventional secondary power system with another electrically powered alternative facilitates a more efficient energy management on board the vehicle. For example, a conventional actuation system powered by hydraulics can be replaced with electrically powered electro hydrostatic or electromechanical actuators; and the need for continuous bleed air for ice protection can be removed by introducing an electrical de-icing strategy where heat can be applied as needed.

This work is a continuity of the previous work as part of the Clean Sky Technology Evaluator Project [1], in which a multidisciplinary framework has been developed capable of generating outputs for estimating rotorcraft systems power consumptions. The Rotorcraft Mission Energy Management Model (RMEM) models the power required on board a helicopter to ensure the functionality of the vehicle as well as the comfort of its occupants. In general, the RMEM consists of five sub-models. These sub-models are: Actuation System (AS), Electrical System (ES), Fuel System (FS), Environmental Control System (ECS), and Ice Protection System (IPS). The secondary power for these systems is extracted from the main engine in two forms: the shaft power off-take or bleed air.

A demonstrative case study for a Twin-Engine Medium (TEM) helicopter has been carried out to assess the potential and identify the limitations of the developed approach. The outcomes generated from this tool were subsequently served as the basis for another parametric study to assess the environmental impact of the rotorcraft by means of fuel burn and emissions computations.

2 General Description of the RMEM

RMEM is capable of modelling a wide range of on-board electrical and mechanical systems employed in rotorcraft. The end-result of the analyses includes the engine shaft-power and bleed-air off-takes which are required to sustain the operation of the on-board systems. These are essentially extracted from the installed power-plants affecting the specific fuel consumption (SFC), hence gaseous emissions. It is therefore understood that, such analyses of the shaft-power and bleed-air off-take, are critical in the context of mission analysis, where accurate information of total mission fuel burn due to primary and the secondary power systems is achieved. RMEM can be used to model conventional as well as novel systems at a preliminary design stage. Fig. 1shows a top-level view of RMEM.

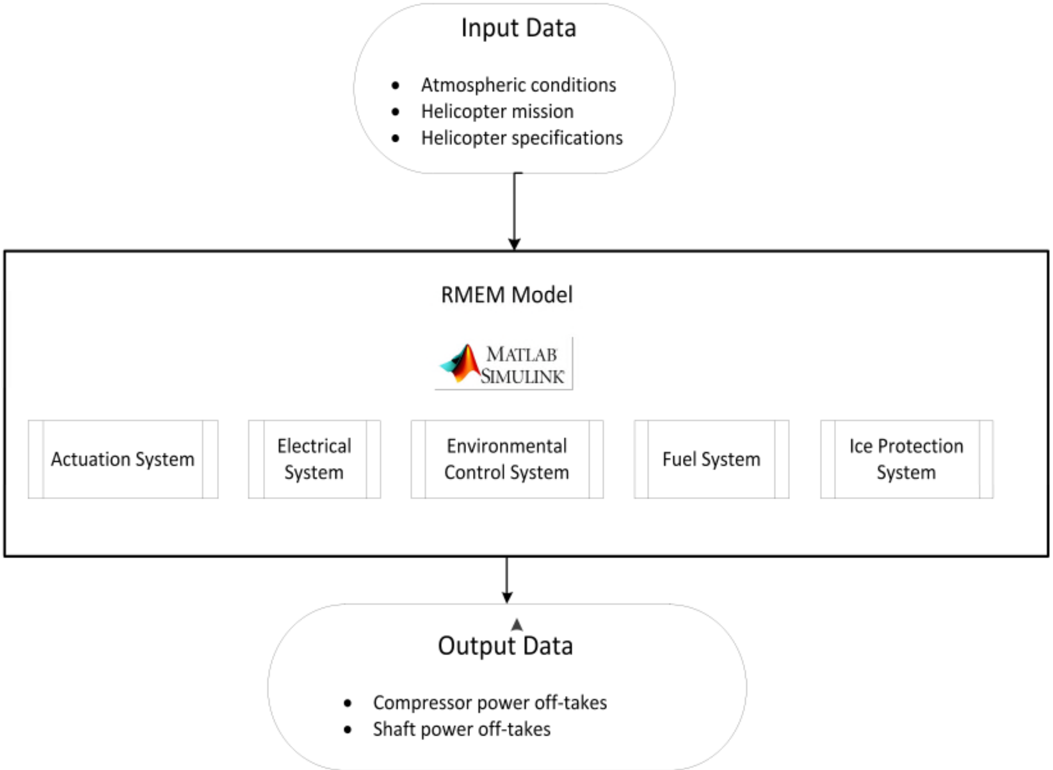

Fig. 1 RMEM model overview

3 Model Development

3.1 Actuation System

The AS model estimates the steady-state power required by the actuators to apply the trim control angles at the main and tail rotor swash plates for a given trim condition. It employs a steady-state actuator model capable of computing the system's power requirement to apply a designated force. RMEM incorporates three different actuation architectures to allow comparison of various subsystem technologies for conceptual rotorcraft. These include; (a) central hydraulic actuation with engine driven pumps, (b) electro-mechanical actuation with a gearbox and a ball screw, and (c) localised electro-hydrostatic actuation.

3.1.1 Electro-servo Hydraulic Actuation (ESHA)

The ESHA contains three main elements. The pump provides a pressure jump and flow rate in the hydraulic circuit. The servo valves reacts to a given voltage and allows a given flow rate through. The actuator is presented with a given opposing force and requires a flow rate to achieve the actuation force. To avoid system complexity, other system components, such as relief valves, sensors, reservoir tank and heat exchanger, are not modelled in this analysis. The pump and actuator combination is modelled with Equations (1) and (2). The flow rate is provided by the servo valve as given in Equation (3). The servo motor current I_v, is estimated with the input actuator movement rate and defined motor characteristics. At the same time the valve voltage is corrected with a feed-forward lookup table for an applied actuator force.

Actuator steady state movement rate,

$$\frac{dx}{dt} = \frac{1}{A_c} * Q_L - C_{12} * \Delta P \qquad (1)$$

Actuator pressure drop,

$$\Delta P = \frac{1}{A_c} * \left(B_v * \frac{dx}{dt} + F_{ac}\right) \qquad (2)$$

Servo valve flow rate,

$$Q_L = Q_R * I_v * \sqrt{\frac{\Delta P_v}{\Delta P_r}} \qquad (3)$$

3.1.2 Electro-Mechanical Actuation (EMA)

The EMA contains an electric motor, a gear box and a ball screw actuator. Equations (4) to (9) [2] describe their modelling equations involved and the required design parameters. The electric motor turns a load at a given angular velocity as a function of input voltage. The load torque determines the current requirements. The load torque and rotation rate of the motor is then translated to the ball screw via the gear ratio of the gearbox. The ball screw reacts to an input force on the piston and moves with a constant velocity. The pitch of the screw determines the change from rotational to linear movement and also affects the torque on the screw for a given input force.

Steady state motor rotation rate,

$$\omega_a = \frac{V_a}{K_v} - \left(\frac{R_a}{K_t K_v}\right) T \qquad (4)$$

Steady state motor torque balance,

$$T = T_L + C_{coul} sign(V_a) + B_v \omega_a \qquad (5)$$

Gearbox relationships for torque and rotation rates,

$$\omega_{gearbox} = \frac{\omega_a}{\tau} \qquad (6)$$

$$T_L = \frac{T_{gearbox}}{\tau} \qquad (7)$$

Ball screw linear to rotation rate,

$$\dot{x} = p\omega_{gearbox} \qquad (8)$$

Ball screw torque balance,

$$T_{gearbox} = p(F_L + B_v \dot{x} + C_{coul} \tanh \dot{x}) \qquad (9)$$

3.1.3 Electro-Hydrostatic Actuation (EHA)

The EHA which combines previously described elements of hydraulic and electric systems contains an electric motor, a fixed displacement pump and the hydraulic actuator. The electric motor provides the torque and rotational rate to the pump, to provide a flow rate and pressure difference to the actuator. The actuator reacts to the input force and moves at a constant velocity. The modelling equations utilized are the same as previously described for ESHA and EMA and hence include Equations (1), (2), (4), and (5).

3.2 Electrical System

The electrical system incorporated in the RMEM is modelled based on a bottom-up approach by means of an Electrical Load Analysis (ELA) of the helicopter. An extensive database is generated to incorporate electrical components of a case study helicopter. The ELA determines the power requirement of the individual systems on-board by evaluating the average and maximum electrical power demands for all flight segments (pre-start, take-off, hover, climb, cruise, and landing).

A database is generated to incorporate the electrical and electronic equipment of the selected rotorcraft, by means of an Electrical Load Analysis as outlined in [3]. The fundamental principle of an Electrical Load Analysis requires the listing of each item of electrically powered equipment and the associated nominal power rating for its operation. The power requirement for a piece of equipment may have several values depending on its utilization during each flight phase. Hence, in such analysis, an exhaustive list of all equipment requiring electrical power usage on board is tabulated, along with the respective power rating during five different flight segments: Pre-Start, Take-off, Climb, Hover, Cruise, and Landing.

The operating time which is defined as the "average operating time of the electrical equipment" of each of the electrical loads is included in this analysis, which can be classified as *continuous* or *intermittent*. If the 'on' time of the equipment is the same or relatively close to the operating time of the rotorcraft mission, then it is considered as operating continuously for all flight phases. In other instances, the electrical load is regarded as an intermittent load. For each flight phase, the total power consumption of all the electrical devices is summed up to give an electrical load profile for a given mission.

3.3 Ice Protection System

The IPS model in RMEM allows for hot air and electric thermal protection strategies. Thermal loads can be included for probe, windscreen, engine-intake, and blade protection. The IPS can operate in a conventional mode selection of either on or off, or in a more advanced system where the actual energy required to provide the icing protection is calculated.

3.3.1 Conventional anti-icing system

The modelling of a conventional on/off system is relatively simple, and follows a bottom-up component load analysis, such as that described in section 2.3 Electrical System.

3.3.2 'Smart' anti-icing system

A more advanced system may use power as a function of the actual energy required to provide the ice protection given the severity of the icing encounter. The 'smart' anti-icing modelling approach initiates with the calculation of the current icing conditions from the employed mission profile. Next these conditions are combined with the geometry to produce a water catch efficiency and hence ice accretion rate. This is followed by a heat balance analysis, which includes convective, sensible, evaporative, kinematic and aerodynamic heat flows. The unbalanced element is therefore, equal to the anti-icing heat requirement. The value however does not describe how this flow is transferred, which in this model may be achieved via electric heating elements or hot air mass flows. The employed equations and theoretical background are based on the work of Meier et al. (2010) [4] and Bowden et al. (1964) [5]. The empirical description of the water catch efficiency is based on test data from a number of aerofoils in [5].

Ice accretion

An empirical curve is used to calculate an impingement parameter K, which then estimates the total catch efficiency. This implicitly assumes that the protected surface has an aerofoil-shaped geometry.

The impingement parameter K is estimated with Equation 10 as presented in [5]. It depends on values such as the free stream velocity, air density, and reference length.

$$K = 1.87 * 10^{-7} * \left(\frac{1.15 * V_{\infty} * 1.94}{\mu * g}\right)^{0.6} * \dots$$

$$\cdots \frac{MVD^{1.6}}{12 * \rho^{0.4} * c_{geo} * 3.28} \quad (10)$$

$$Q_{water} = V_{\infty} * LWC * E_m \quad (11)$$

Heat Balance

The heat flow required per unit area of protected surface can be expressed by an energy balance which maintains a constant temperature (Meier et al. 2010).

$$Q_{anti} + Q_{kin} + Q_{aero} = Q_{sen} + Q_{evap} + Q_{con} \quad (12)$$

$$Q_{anti} + Q_{kin} + Q_{aero} = Q_{sen} + Q_{evap} + Q_{con} \quad (13)$$

Anti-icing Provision

The wet anti-icing model produces a requirement for the heat Q_{anti} to be added per area A_{surf} to maintain a wet surface at a given temperature. If such a system is to be electric, this information is relatable to the electric power requirements of the heating elements. Such elements will not transfer all heat to the surface but will also have losses to the surroundings. These can be accounted for with an efficiently factor η_{sur}

$$P_{elem,gen} = \frac{Q_{anti} * A_{surf}}{\eta_{sur}} \quad (14)$$

3.4 Fuel System

The Fuel System sub-model provides a mathematical analysis of the power required by the pump to deliver fuel from the tanks to the engines. The model computes the total pressure losses along the delivery line between the tanks and the engines. These losses are generally attributed to the fuel lines and also other components such as valves, water filter, and water extractor.

The pressure loss is the mechanical energy converted to thermal energy due to frictional resistance to flow. Two main sources can generate these losses: Turbulence due to elements or changes in the flow path (tubes), and the friction due to a surface such as the pipe wall. Generally, the pressure loss due to fuel line is estimated by means of standard equations of fluid dynamics in a pipe flow.

Similarly, the pressure losses due to the components of the fuel delivery system are calculated. These losses are namely for components including filters and valves.

The constructional layout of the actual fuel delivery system on the helicopter is required for this modelling approach.

Equation (16) is applied in each of the elements in the fuel system, and summed in order to acquire the head loss average of the entire system.

$$\Delta P_{overall} = k_1 \left(\frac{\dot{m}^2{}_1}{2gA^2{}_1\rho_1} \right) + k_2 \left(\frac{\dot{m}^2{}_2}{2gA^2{}_2\rho_2} \right) + \cdots \ldots + k_n \left(\frac{\dot{m}^2{}_n}{2gA^2{}_n\rho_n} \right) \quad (15)$$

3.5 Environmental Control System

The RMEM ECS modelling capability allows for simulation of a variety of types of system, including:

- Combustion Heater
- Electric Element Heater
- Vapour Cycle Temperature Control System

Regardless of the type of ECS implementation, the first step is to establish the cabin heat balance, and as such the following sub-modules are included:

- Mass flow calculation as per the ventilation requirements;
- Calculation of the cabin heat loads;
- Mass flow calculation for thermal regulation.

The kinetic heating, solar radiation, systems heat loads, passenger and crew heat loads and avionics heat loads are considered in the thermal regulation calculation. The necessary thermal regulation was achieved applying the standard steady state energy balance equation.

4 Case Study

4.1 Vehicle Configuration

The RMEM-TEH is set up into three different configurations for technology evaluation purpose. These configurations are namely the *Baseline*, *Reference*, and Co*nceptual*, which are defined as the following:

- Baseline: Typically an established conventional technology;
- Reference: Comparatively progressed technology;
- Conceptual: Advanced technology.

A summary of the rotorcraft systems for all of the vehicle configurations is tabulated in **Error! Reference source not found.**.

4.2 Vehicle Selection

A twin-engine heavy helicopter has been selected as an example of a case study of the RMEM. Vehicle specifications for the twin-engine heavy class rotorcraft selected is as defined follow.

The twin-engine heavy rotorcraft is powered by two engines capable of producing 1500 shaft horsepower. It has a typical number of five bladed single main rotor system with a five blade anti-torque tail rotor. Two separate hydraulic systems are used in conjunction with the mechanical linkage of the flight controls, which presents the 'baseline' configuration for this vehicle configuration. The aircraft is fitted with fixed, non-retractable landing gear. The main landing gear fitted with two main wheels per side and also a tail landing gear fitted with a single wheel. The primary and auxiliary hydraulic systems provide hydraulic boost to the primary servo cylinders and the auxiliary servo cylinder which is linked to the Automatic Flight Control System (AFCS). The passenger cabin provides seating for up to 19 passengers and provision for cargo handling. The aircraft also has external hard points for fitting a cargo hook enabling external loads of up to 4500 kg (10 000 lbs).

4.3 Simulation Set-up

The hypothetical scenario of the mission accounts for a helicopter which operates from Den Helder airport in the Netherlands. The helicopter transits towards two specific oil and gas platforms, transferring personnel and payload, prior to returning to Den Helder airport. The trajectory of the mission is illustrated in Fig. 2 and the mission altitude profile in Fig. 3.

Fig. 2 Oil and gas mission trajectory

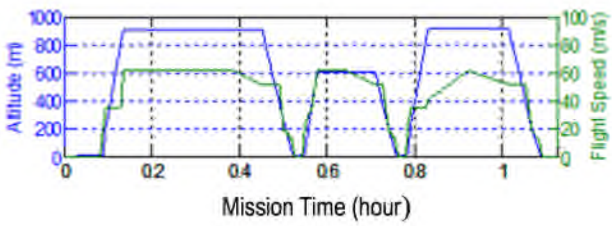

Fig. 3 Mission Profile

5 Simulations and Results

5.1 System Assessments

5.5.1 Actuation System

Fig. 4 shows the power profile required by the Actuation System for the main and tail rotors for all configurations. The overall actuation power demand for the Baseline configuration exhibits a very high power usage due to the continuous use of the hydraulic pumps within the conventional cable-and-control rods boosted with hydraulics for flight controls. The overall actuation power demands for the Reference and Conceptual configurations exhibit a lower value due to the use of power-by-demand actuation technology, by means of the adoption of the standalone electro-hydrostatic actuators (Reference) and electro-mechanical actuation system (Conceptual). The trend exhibited in this figure is in consistent with those reported in [6] and [7] which were similarly applied into fixed-wing aircraft.

5.5.1 Electrical System

The electric loads illustrated in Fig. 5 shows an increasing electrical power demand profile from Baseline to Reference, and Conceptual as the rotorcraft adopts a 'more-electric' configuration. The higher electrical loads for the Reference and Conceptual configurations are due to incorporation of advanced technologies based on modern avionics equipment.

5.5.1 Ice Protection and Fuel Systems

The constant value of IPS power requirement shown in Fig. 6 is due to the continuously operating electric elements in the probes. The power required for anti-icing of engine-intake and windscreens is zero as the mission occurs under International Standard Atmosphere (ISA) conditions where there is no icing account for all configurations. Anti-icing is set to 'off' by the pilot.

The figure also shows the power required to operate the fuel pumps, which is independent of fuel flow from the engines. The fuel pumps are set to deliver maximum fuel flow rate for all configurations. The fuel is recirculated in the tanks when maximum fuel flow rate is not required to be fed to the engines.

5.5.1 Environmental Control System

The fuel flow in Fig. 7 indicates the flow rate of the Janitrol gas used in the combustion heater for the Baseline and Reference configurations. In the figure above, the inclusion of an electric heater for the Conceptual configuration raises up the electrical power requirement especially during high-power flight phases.

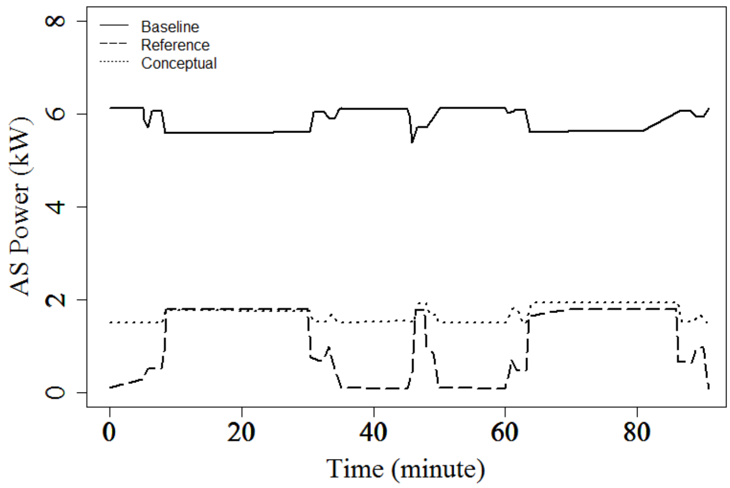

Fig. 4 Actuation System power demand

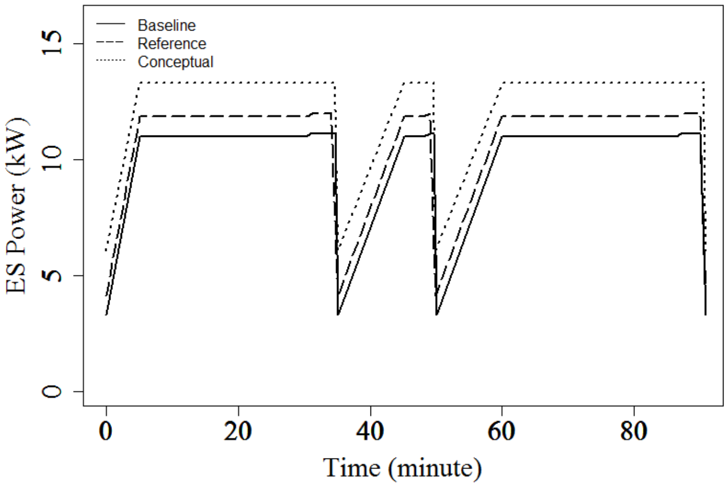

Fig. 5 Electrical System power demand

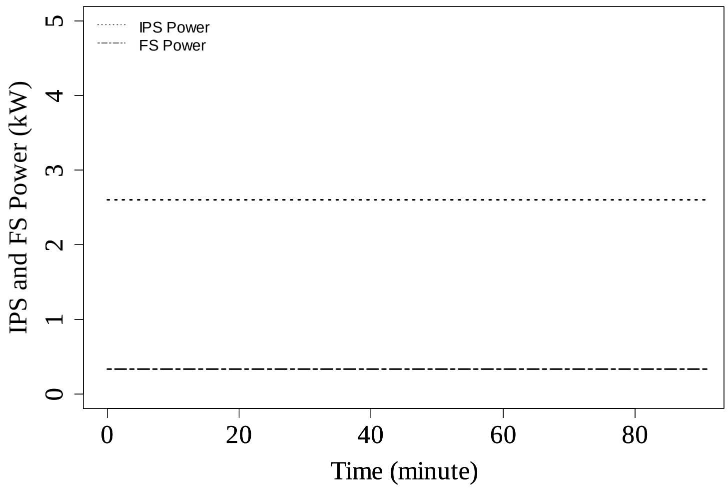

Fig. 6 Fuel and Ice Protection Systems power demands

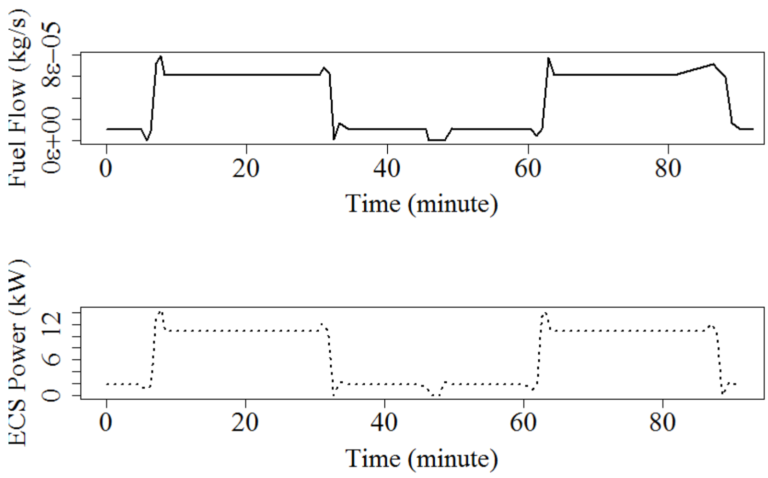

Fig. 7 Environmental Control System fuel flow (Baseline & Reference), and power demand (Conceptual)

5.2 Total Shaft Power Off-take

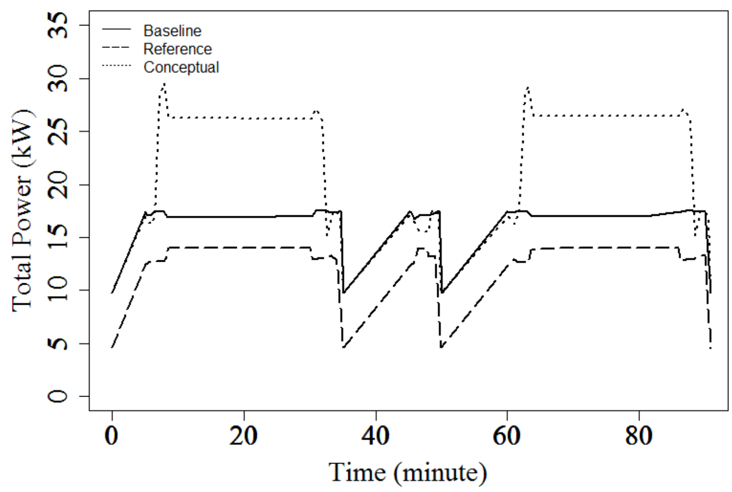

Fig. 8 Total shaft power off-takes

As an overall result, Fig. 8 shows the total shaft power off-take for all configurations for this case study. For the Baseline configuration, the power peaks at approximately 20 kW, which is half of the electrical power generating capacity on a Sikorsky S-61 (40 kW). On the other hand, the Reference configuration has a slightly reduced peak power at approximately 16 kW. The reduced peak power is due to the adoption of power-by-demand Actuation System for the Reference configuration. The total shaft power off-take for the Conceptual configuration reaches its peak at a significant value of 35 kW. The high peak value is due to the high electrical power demand from the Environmental Control System, which adopts the use of electric heater element in place of the combustion heater.

6 Conclusions

The RMEM models five secondary power systems which comprise of: Actuation System, Electrical System, Environmental Control System, Ice Protection System, and Fuel System. The RMEM capability has been demonstrated through several case studies of a twin-engine medium rotorcraft class, one of which has been presented here. During simulation, three different rotorcraft configurations are investigated; namely Baseline, Reference, and Conceptual, as the rotorcraft tends to adopt a 'more electric' technology.

Through the simulation, the total shaft power off-take of the rotorcraft has been analyzed. This has been achieved through the modelling of the electrical power demands by all of the RMEM systems for the vehicle. Shaft power demands for hydraulic power have also been calculated. Other forms of systems power are capable of being analyzed by the RMEM, and this has included a fuel burning combustion heater in this rotorcraft case study. For other studies, the RMEM is capable of establishing engine bleed air off-takes as required.

Nomenclature

A_c	Piston area (m^2)
B_v	Viscous friction (Nsm^{-1})
C_{12}	Leakage flow coefficient ($m^3s^{-1}Pa$)
E_m	Water catch efficiency (-)
$F_{ac,L}$	Force: actuator, load (N)
I_v	Servo valve current (A)
K	Impingement parameter
K_t	Torque constant of motor (NmA^{-1})
K_v	Velocity constant of motor ($Vsrad^{-1}$)

LWC	Liquid water content (-)
MVD	Median volume diameter (-)
SFC	Specific fuel consumption (-)
p	Ball-screw pitch (mrad^{-1})
$Q_{L,R}$	Flow rate: actuator, rated (m3s^{-1})
R_a	Armature resistance (Ohm)
T_L	Load torque (Nm)
τ	Gear ratio (-)
V_a	Armature voltage (V)
$\omega_{a,gearbox}$	Rotational rate: motor, gearbox (rads^{-1})
ΔP	Actuator pressure difference (Pa)
$P_{v,r}$	Pressure: valve, rated (Pa)
T	Torque (Nm)
C_{coul}	Coulomb friction coefficient (N)
V_∞	Free stream velocity (ms^{-1})
μ	Dynamic viscosity (Nsm^{-2})
c_{geo}	Reference length (m)
Q	Thermal heat flow per area (W/m^2)
$P_{elem,gen}$	Power required of electric heating element(W)

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Table 1 Overview of the Rotorcraft Mission Energy Management Model

RMEM-TEH Systems	Baseline	Reference	Conceptual
Actuation System	• Engine-mounted primary pumps pressurize the main and auxiliary hydraulic loops to 1500 psi. • Electrically operated servo valves control actuator movements. • Almost continuous power operation of pumps is required to keep pressurization.	• Utilizes standalone electro-hydrostatic actuators. • Power-on-demand operation.	• Electro-mechanical system, utilizing electric motors, a gearbox and a ball screw to convert rotational to linear motion. • Power-on-demand operation.
Ice Protection System	• Simple ON/OFF operation at pilot's discretion.	• Simple ON/OFF operation at pilot's discretion.	• An electric SMART wet running anti-icing system is chosen, which responds to current icing conditions. Hence power consumption is variable with mission parameters rather than a constant ON state. This will require additional sensing equipment and a feedback control considerations of the architecture.
Electrical System	• Electric generation is achieved with 2 AC 115V 3 phase generators running at 8010 rpm in the main gearbox. In addition a DC motor generator provides further power at 8131rpm. Electric components are listed in the Breaker panel together with amperage limits. • Generator efficiency is at a fixed value of 85%.	• Technologies are now based on modern avionics, lightning and display equipment. • Generator efficiency is at a fixed value of 85%.	• Similar to Reference. • Generator efficiency is at a fixed value of 85%.
Environmental Control System	• Janitrol Gas heater and blower. Heater blowers may be operated without gas heater for ventilation.	• Similar to Baseline.	• Electric heater element with blower.
Fuel System	• Electrically powered booster and transfer pumps.	• Similar to Baseline.	• Similar to Baseline and Reference.