EVALUATION OF HELICOPTER FLIGHT MISSIONS WITH INTENDED SINGLE ENGINE OPERATION

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Current helicopter power train design of light and medium class helicopters is mainly driven by safety considerations. Thus, these helicopters have two or more engines installed. However, in up to 60% of the helicopter flight mission time, the available installed maximum continuous power of the engines is not needed [1]. Hence, the engines are running most of their operation time in part load. But turboshaft engines have their lowest specific fuel consumption (SFC) at high engine loads. Taking this into account, an operational strategy can be an intended controlled shutdown of one engine. At the same time, the load of the remaining running engine is increasing, whereby the overall SFC is shifted to better values and fuel can be saved. This saving can be used either to reduce the mission-specific fuel consumption or to extend the flight mission time. Quantification of the fuel savings is the focal point of this paper. However, the intended operational engine usage strategy is limited to certain areas of the helicopter flight envelope. Hence, these areas of the envelope are specified by flight performance analysis of the helicopter in advance. Afterwards, realistic flight missions were chosen for subsequent flight mission simulations with and without intended single engine operation (ISEO). For this purpose a non-linear flight dynamics model of a reference helicopter is used. The turboshaft engine is represented by a quasi non-linear state space model and is integrated in the flight dynamics model. Finally, the resulting fuel saving potential is evaluated and details for flight mission modifications are given due to an enhanced usage of ISEO.

NOMENCLATURE AND ABBREVIATIONS

m	Helicopter gross mass
v_c	Vertical climb velocity
P_{climb}	Power required for climb maneuver
AEO	All Engines Operating
ASL	Above Sea Level
BSN	Business Flight Mission
Eng	Engine
EW	Empty Weight
FCS	Flight Control System
FDM	Flight Dynamics Model
HEMS	Helicopter Emergency Medical Service
HSS	Helicopter Simulation System
ISEO	Intended Single Engine Operation
MCP	Maximum Continuous Power
MTOW	Maximum Take Off Weight
N1	Gas generator spool speed
OEW	Operational Empty Weight
OPS	Offshore Platform Support Mission
Pwr	Power
SEO	Single Engine Operation
SFC	Specific Fuel Consumption
SSM	State Space Model
SV	Surveillance Helicopter Mission
Ref	Reference
H/C	Helicopter

1. INTRODUCTION

The current power train design of light and medium class helicopters is primarily driven by safety considerations. Consequently, these helicopters are equipped with two or three turboshaft engines. Figure 1 shows a usual power required curve for a conventional twin-powered helicopter in steady state flight at sea level. It can be seen that in a wide flight speed range, the power available from one engine is considerably higher than the required power to maintain the steady state flight. Furthermore, in up to 60% of the mission time of many helicopter flight missions, the helicopter is within this flight speed range, which is marked yellow in Fig. 1. Neglecting the times the helicopter is using this power difference for climb maneuvers, the turboshaft engines are operating in part load since the total available power is not needed [1].

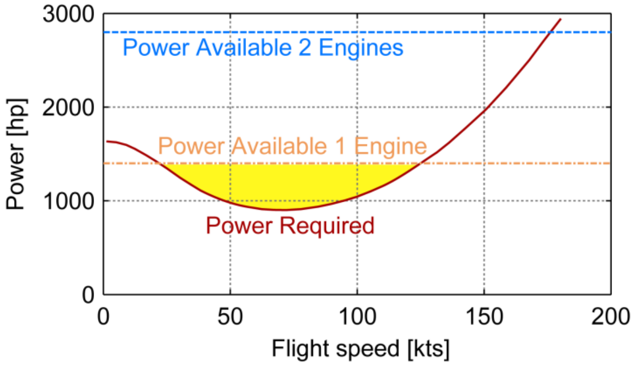

Fig. 1: Typical power required curve (adapted from [5])

Since the specific fuel consumption (SFC) of a turboshaft engine decreases with increasing engine load, the optimal case is achieved by operating the engines always at high loads. Since all engines are operating mainly in part load, an operational strategy for better fuel efficiency can be a controlled and intended shutdown of one engine during the flight, whereby the load of the other engine(s) increases. As a result, the overall SFC decreases and fuel can be saved over a certain mission time.

2. HELICOPTER AND ENGINE DEFINITION

The purpose of this research is to analyze the fuel saving potential of this intended single engine operation (ISEO) for currently used helicopter types. As it is often difficult to gather necessary technical information about helicopters and engines via public sources, two reference helicopters and two reference engines are defined. These reference models are similar to existing helicopters and engines which represent a basis.

2.1. Reference Helicopter Data

The first reference helicopter is assigned to light class helicopters and has a maximum MTOW of 2400 kg. Its performance is close to that of the BO 105. In this paper, the reference helicopter 1 is tagged as H/C_{Ref1}. The second helicopter is of medium class on the basis of its MTOW of 3700 kg. Here it is tagged as H/C_{Ref2} and its performance data is similar to that of the EC 145. Further information is given in Table 1.

	H/C_{Ref1}	H/C_{Ref2}
Mass [kg]		
MTOW [kg]	2400	3700
OEW [kg]	1200	1900
Max. Fuel [kg]	475	700
Max. Payload [kg]	1200	1800
Power Limits [kW]		
AEO TOP (5 min)	320	510
AEO MCP	270	475
OEI TOP (2.5 min)	350	570
OEI MCP	330	520
V_{NE} [kts]	148	153
Max. altitude [m]	5000	5000

Table 1: Mass data of the reference helicopters and their main transmission power limits

For both H/C_{Ref1} and H/C_{Ref2}, a maximum take-off weight (MTOW) is determined as well as the operational empty weight (OEW). There are several definitions of the OEW in technical literature, while the definition here is as follows: Baseline aircraft, engine and helicopter lubricants, unusable fuel and basic equipment. The maximum fuel amount is part of the maximum payload while the real usable payload is reduced by higher fuel amount requirements due to a higher required range.

The Torque Limits are applied to the main transmission, and due to a fixed main rotor speed, the torque is equivalent to power. Here slightly modified helicopter main transmissions are assumed in comparison to the original torque limits of the two existing basic helicopters. Since during ISEO the whole engine power is provided by only one shaft to the transmission, there is a one-sided load application. Thus, the transmission components may undergo higher stresses than in AEO, and the components have to be reinforced for long-time ISEO application. A drawback here may be a payload reduction since the additional weight of the strengthened helicopters parts has to be compensated for if there is not to be any influence on the performance of a given helicopter.

2.2. Reference Engine Data

Since performance data of reference helicopters are used, the engines are also defined as reference engines Eng_{Ref1} and Eng_{Ref2}. Different Allison 250 types are installed in numerous BO 105 versions. The version 250-C20B is the basis for the Eng_{Ref1} of the H/C_{Ref1}. For the flight mission simulations, the existing state-space model [4] is slightly modified to meet the given requirements of the $Eng_{Ref1.}$

The Eng_{Ref2} is based on the Turbomeca Arriel 1E2 as this type is used in the EC 145 which is the basis of the H/C_{Ref2}. The relevant power limit data of both chosen reference engines is listed in Table 2.

	Eng_{Ref1}	Eng_{Ref2}
Power Limits [kW]		
AEO TOP (5 min)	350	560
AEO MCP	310	525
OEI TOP (2.5 min)	370	590
OEI MCP	350	560

Table 2: Data of the used reference engines

3. HELICOPTER FLIGHT DYNAMICS MODEL AND ENGINE MODEL

In reference [4], the Helicopter Simulation System (HSS) used is presented. The HSS contains a helicopter flight dynamics model (FDM) and a mission management tool which are used for the mission analysis [3]. As the FDM represents originally the helicopter type Airbus Helicopters BO 105 CBS, it is slightly adapted to represent the H/C_{Ref1} via a new dataset. Due to steady state flight performance validation, several power required polars are flown with the simulated helicopter and are compared to the power required curves of chapter 4. To maintain almost the same flight tracks and flight segment times, the missions are flown by a flight control system (FSC) augmented with an autopilot, discussed in [4].

A quasi non-linear state space model (SSM) simulates the engines. The SSM model of the BO 105 powerplant Allison 250-C20B is discussed in [4] and [5] and is used for the H/C_{Ref1} after an adaption to meet the Eng_{Ref1} parameters.

4. FLIGHT ENVELOPE AND POWER REQUIRED ANALYSIS

Before simulating flight missions, the helicopter flight envelope areas in which ISEO is allowed have to be determined. Several parameters influence this certain area such as flight altitude, remaining useable engine power, remaining required maneuvering power, flight mass and helicopter flight velocity.

4.1. Parameters regarding installed power

First, parameters influencing the installed engine power are analyzed. The power of the turboshaft engines is reduced by increasing flight altitude. In fact, the reduced ambient temperature at greater altitudes has a positive effect on the delivered power and thermodynamic efficiency, but nevertheless the declining air density has a greater influence on the overall engine performance and leads to a power reduction at higher altitudes. Based on the Allison 250 SSM and several performance data sets for turboshaft engines, a simple correlation is set up to obtain maximum available power of the engines in percentage of the maximal available power at sea level ISA conditions. This can be seen in Fig. 2.

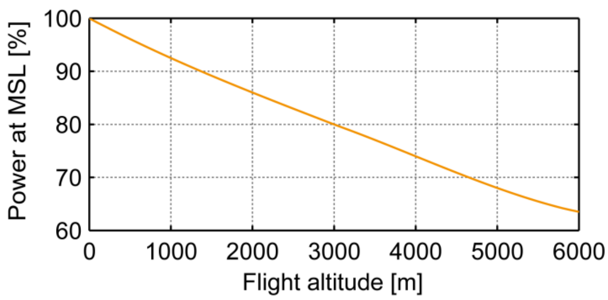

Fig. 2: Percentage MSL power of turboshaft engines at different flight altitudes and ISA conditions

Another parameter affecting engine performance is the pressure recovery factor of the inlet due to flight speed. In most cases helicopter engines are located in an engine bay surrounded by several objects such as pipes, hydraulic units, main transmission parts, oil coolers, etc. Thus, there are multiple flow losses minimizing the pressure recovery factor and leading to a loss of total pressure at the inlet. Since determining the loss factors is quite complex, and due to the use of reference helicopters, the pressure loss caused by the engine bay is neglected and not implemented. Moreover, the total pressure at the inlet of the engine is assumed for all flight speeds of the helicopter to be the static ambient pressure. Thus, the flight speed has no influence on the power available. In addition, the main rotor downwash has no influence on the simulated engine performance in the whole flight speed range.

4.2. Parameters regarding useable power

The engines in helicopters are also used for power generation, supplying the helicopter with electrical energy and hydraulic pressure as well as air conditioning capabilities. This leads to a reduction of the usable power for maintaining flight states. Assumptions for the power off-take for both helicopters are given in Table 3.

Furthermore, as the power turbine rotational speed is too high for direct rotor drive, engine gearboxes and helicopter transmissions are used. Thus, mechanical losses in the transmissions exist and the losses are reducing the power available for the rotors. The assumed transmission power loss coefficients are also given in Table 3.

	H/C_{Ref1}	H/C_{Ref2}
Power off-take [kW]	15	20
Transmission loss [%]	2	1.8

Table 3: Power off-take values and transmission loss coefficients for the reference helicopters

4.3. Parameters regarding power required

Not only is the power train influenced by certain parameters regarding reasonable ISEO, but also the flight mass and the flight altitude have a high influence on the required power. Since with increasing altitude the air density gets lower, more power is required to maintain flight at lower air speeds with the same flight mass.

To obtain a first impression of the power required for level flight of the two reference helicopters, two power polar plots are given for each helicopter. The polars are created by using the energy method and are afterwards compared to flight performance data of similar helicopters due to validation.

Power Required for H/C_{Ref1}

The flight mass of the helicopter has a non-negligible influence. As Fig. 3 shows, this has to be considered especially at lower speed ranges. Hence, shortly after take-off the helicopter has nearly its high take off mass and therefore the meaningful ISEO flight speed ranges will probably be at higher flight speeds. Nevertheless, the influence of the gross mass for higher flight speeds is reduced. Thus, ISEO capabilities at higher flight speeds will not be constrained as much as at lower speeds regarding gross mass.

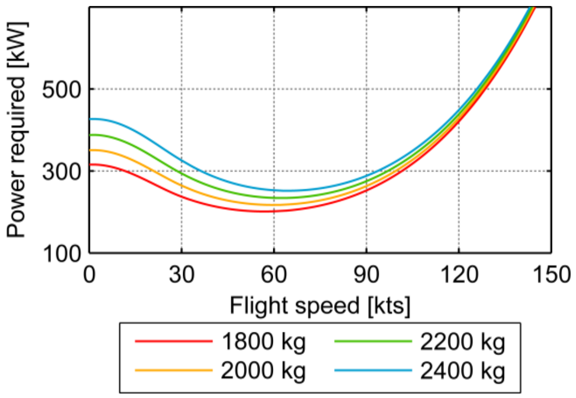

Fig. 3: Power required for level flight with different flight masses (MSL, ISA conditions, H/C_{Ref1})

In addition, with increasing altitude, there is a decrease in atmospheric pressure. Thus, air density is decreasing and more power is required in order to maintain a level flight with given gross mass. This is shown in Fig. 4 for the H/C_{Ref1} with a gross mass of 2000 kg.

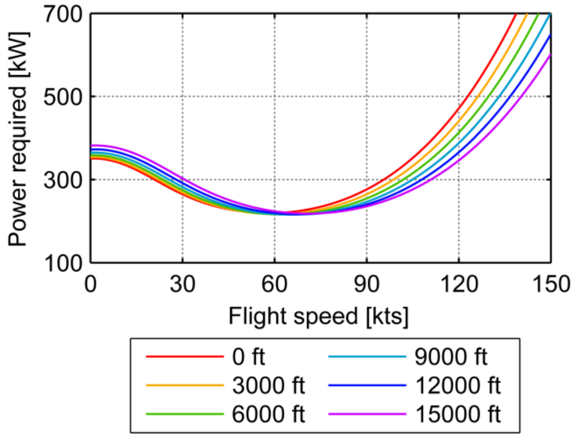

Fig. 4: Power required for level flight at different altitudes (flight mass = 2000 kg, ISA conditions, H/C_{Ref1})

A closer look at Fig. 4 reveals a good consistency with basic helicopter literature. There it is often said that due to lower density at higher altitudes the parasitic drag gets lower and thus the required power for steady state flight conditions is also reduced. However, analysis of flight performance charts of different helicopter types show the same effect. But in this case values of the true airspeed have to be considered. The indicated airspeed gets lower for greater altitudes due to density and compressibility effects at higher flight speeds. For this reason the indicated airspeed at the cockpit gauges may decrease whereas the true airspeed is increasing.

Power Required for H/C_{Ref2}

Besides the H/C_{Ref1}, the following power polars of the H/C_{Ref2} illustrate the power required for different flight altitudes and gross masses. As already mentioned earlier, the influence of the altitude leads to a similar behavior of the power polars. This is shown in Fig. 5.

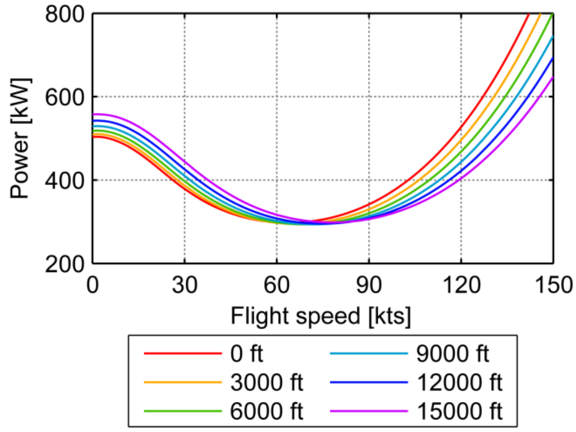

Fig. 5: Power required for level flight at different altitudes (flight mass = 2700 kg, ISA conditions, H/C_{Ref2})

Thus, flying at higher altitudes makes the meaningful ISEO speed range greater but the engines provide less power at higher altitudes, and accordingly the speed range may become even smaller.

The final power polar (see Fig. 6) visualizes the effect of different gross masses on the power required for the H/C_{Ref2}. As already said in the H/C_{Ref1} section, the gross mass influence is reduced at higher flight speeds.

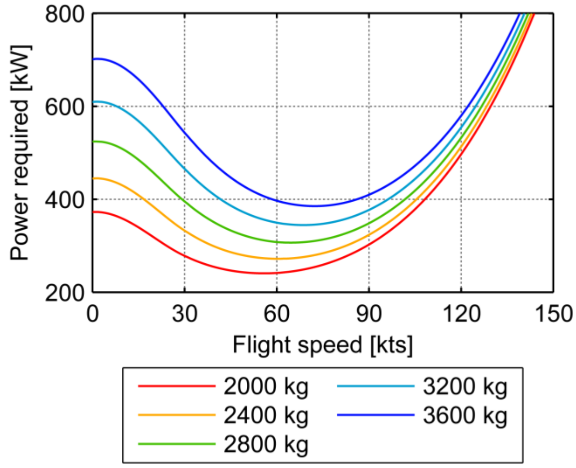

Fig. 6: Power required for level flight with different flight masses (MSL, ISA conditions, H/C_{Ref2})

Thus, the required power at different flight altitudes, ambient conditions and gross masses is given for steady state level flight and is used for further ISEO analysis.

4.4. Safety margin definition

In addition to the power required definitions, a power safety margin has to be defined. Although ISEO is primarily planned for steady state level flight, unplanned events such as sudden wind gusts or necessary heading changes can occur. During these events, a restart of the shut-off engine should not be required. Further helicopter flight dynamics analysis during single engine operation has not been done yet, for which reason a simple approach for the safety margin definition is used. During ISEO, the helicopter should be capable of climbing at a rate of 250 ft/min. As a result of assuming several simplifications [5] [6], the required climb power can be defined as

(1) $$P_{climb} = v_c \cdot m$$

where v_c is the vertical climb rate and m the flight gross mass of the helicopter. Thus, with a fixed climb rate the power margin depends only on the flight mass of the helicopter. Whether this power margin is sufficient has to be proven by extensive flight dynamic analysis.

4.5. Reasonable ISEO flight speed ranges

Although the main transmission can be extensively reinforced to sustain OEI torque limits for a longer time than defined by OEI operations, this paper is focused on ISEO with slightly adapted AEO MCP torque limits compared to the basic helicopters for long-lasting ISEO during the flight. Nevertheless, this restriction minimizes the meaningful speed range for ISEO but is a more realistic approach preventing extensive reengineering issues.

ISEO flight speed range for H/C$_{Ref1}$

For the H/C$_{Ref1}$ the additional margin is assumed to be 5% higher than the original helicopter configuration. Thus, the possible ISEO flight speed range can be extended. The final result is shown in Fig. 7.

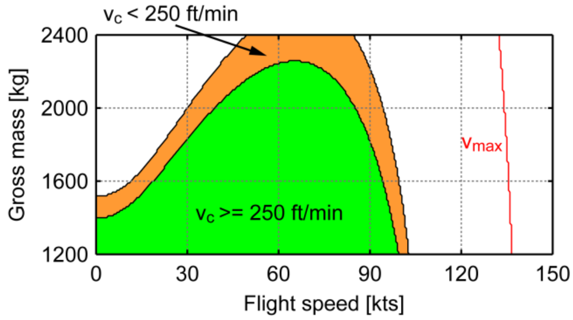

Fig. 7: Reasonable areas for ISEO (H/C$_{Ref1}$, altitude = 1000 m ASL)

The red line marks the limit where required power equals available power. The latter can be restricted by transmission and engine torque limits. At lower altitudes, the transmission limit comes into effect. Within the orange area, steady state level flight can be maintained during ISEO but a remaining climb rate of 250 ft/min cannot be guaranteed. This climb rate is present in the green area, within which also higher climb rates, and thus also greater maneuverability, are possible.

At first glance the area of reasonable ISEO seems quite major. But since the EW of the helicopter is 1200 kg and with the addition of fuel and payload as well to the EW, usual flight masses are between 1800 kg and 2200 kg. With a gross mass of 1800 kg and at an altitude of 1000 m, the speed range for reasonable ISEO is reduced to between 30 kts and 90 kts flight speed. Due to these limits, a hover flight state during ISEO, for instance, is not possible. Thus, ISEO can only be applied at certain flight speeds. The flight altitude of 1000 m ASL is chosen since for safety reasons ISEO should not be applied close to the ground.

The graph in Fig. 8 visualizes the possible ISEO speed ranges for the same configured helicopter but at flight altitude of 3000 m ASL. If reasonable ISEO is to be applied, the helicopter's gross mass has to be below 2000 kg. In any case, the flight speed range is still small. Thus, reasonable ISEO may be applied at moderate flight altitudes to obtain major flight speed ranges.

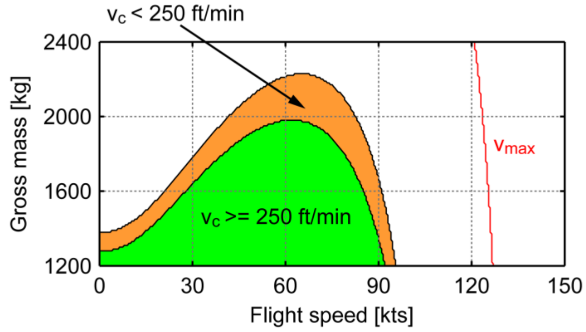

Fig. 8: Reasonable areas for ISEO (H/C$_{Ref1}$, altitude = 3000 m ASL)

ISEO flight speed range for H/C$_{Ref2}$

For the H/C$_{Ref2}$, the additional torque margin is 33% of the maximum allowed AEO MCP transmission torque of the original helicopter configuration. The following graph in Fig. 9 shows the area again wherein ISEO is reasonable at a flight altitude of 1000 m ASL. One can see that with a gross mass above 3400 kg, the flight speed area for a reasonable ISEO gets small, but for lower gross masses such as 2350 kg, the hover flight state is possible during ISEO. Thus, ISEO is here an option for gross masses close to the MTOW of 3700 kg and for flight speeds between 50 kts and 100 kts. Therefore helicopter flight missions with a high TOW are quite well suited for extensive use of ISEO during the mission. It may be possible that at the mission end, ISEO may also be an option for very low flight speeds because gross mass is reduced due to fuel burn.

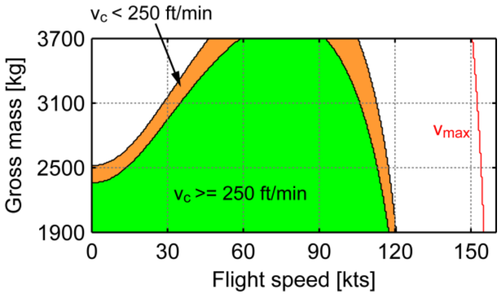

Fig. 9: Reasonable areas for ISEO (H/C_{Ref2}, altitude = 1000 m ASL)

Since helicopters operate at different altitudes, the next diagram in Fig. 10 shows the ISEO areas at 3000 m altitude ASL.

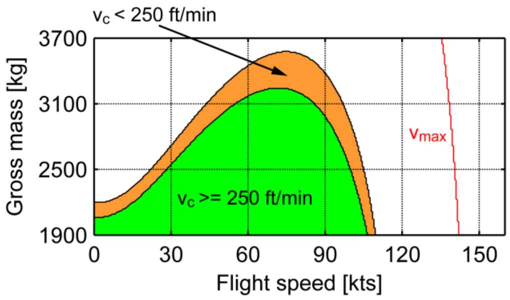

Fig. 10: Reasonable areas for ISEO (H/C_{Ref2}, altitude = 3000 m ASL)

Due to altitude effects, the available engine power is reduced as are the areas of reasonable ISEO. Thus, the possible savings of ISEO are further reduced as the helicopter has to operate in this smaller flight speed range and at lower gross masses.

Finally, if it is possible to adapt existing and recurring mission profiles to a new mission profile suitable for ISEO, the potential savings due to ISEO can be maximized. However, due to several restrictions, not every helicopter flight mission can be so adapted. Thus, in a next step the potential fuel saving due to ISEO has to be quantified to give a statement about mission types for which ISEO is a feasible option.

5. MISSION DEFINITION AND FLIGHT MISSION RESULTS

In order to analyze the fuel saving potential due to ISEO, several missions are flown using H/C_{Ref1} since this helicopter marks the lower range of possible fuel savings. Since helicopters have many applications, four representative mission types are selected:

- Offshore Platform Support (OPS)
- Helicopter Emergency Medical Services (HEMS)
- Surveillance (SV)
- Passenger Transportation (BSN)

Before the mission types are further analyzed, the OPS mission will be used to show the approach for determining the ISEO capable flight mission areas.

5.1. Example approach for ISEO application

Having a first impression about power required during an OPS flight, a standard mission is simulated with realistic flight parameters. The flight track length is 115 miles, and flight altitude and flight speed are given in Fig. 11.

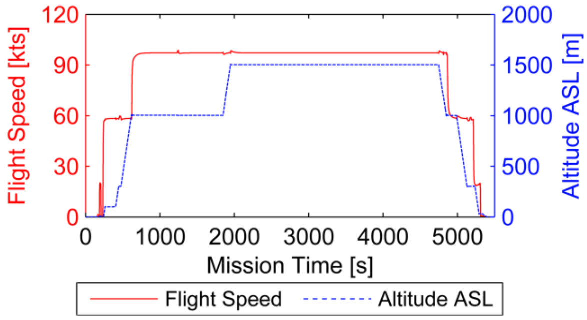

Fig. 11: Flight speed and altitude of the OPS mission

The start gross mass is 2100 kg. After some hovering and maneuvering at the heliport close to the coast, the helicopter accelerates to 58 kts and then climbs to a flight level of 1000 m. When the flight track leaves the coast area, H/C_{Ref1} further accelerates to 98 kts and climbs up to 1500 m ASL which is the cruise altitude. Shortly before approaching the offshore platform, a deceleration and a decline is performed. The resulting power required is shown as follows in Fig. 12.

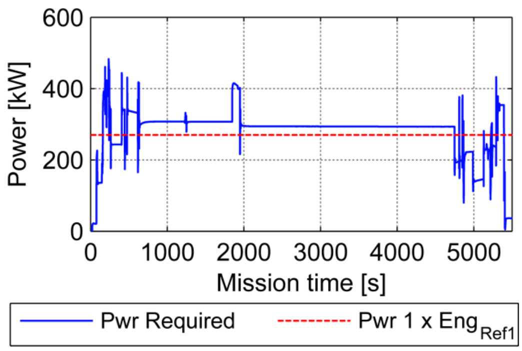

Fig. 12: Power required during the OPS mission and power available of one engine

It is obvious that most of the flight mission phases cannot be performed by ISEO. Thus, parameters like gross mass or flight speed have to be modified to meet essential ISEO criteria. Therefore, the cruise speed is reduced to 85 kts and cruise altitude is reduced by 500 m to 1000 m ASL. The new power required is as Fig. 13 shows. One can see the power required during the cruise flight is below the power available of Eng_{Ref1}, and hence these flight sections can be performed with ISEO. However, the mission time is extended by approximately 12 minutes because the cruise speed is reduced.

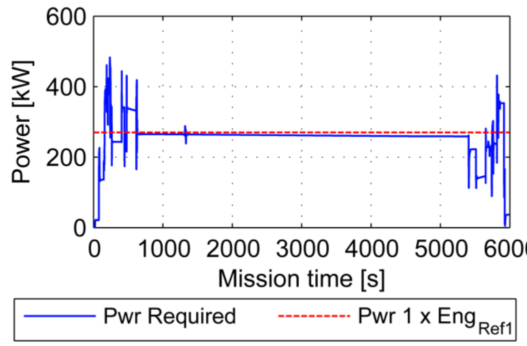

Fig. 13: Power required after flight mission parameter modification

After analyzing the possible mission sections for ISEO, a decision is made for applying ISEO only during cruise flight. Nevertheless, ISEO can also be applied during decline as power required is less than during cruise. Finally, ISEO is performed during mission time between 620 s und 5340 s. Thus, for more than one hour the helicopter is performing its flight with only one engine operative, as Fig. 14 shows.

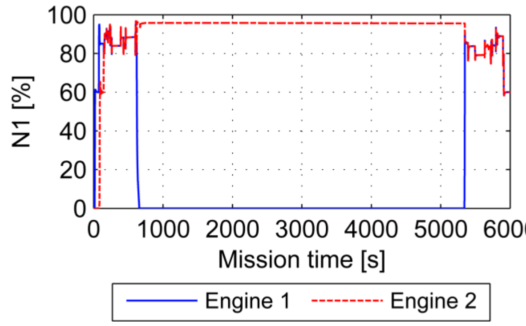

Fig. 14: Gas generator spool speed of both engines

The red dashed curve indicates the higher speed of the gas generator of engine 2 as all load has to be carried by engine 2. According to this, shortly before ISEO, both engines run at 85 % gas generator speed. After applying ISEO, the gas generator speed of the remaining running engine increases to 96%. At these higher loads, the engine has a better SFC, resulting in a lower overall fuel flow, as Fig. 15 shows.

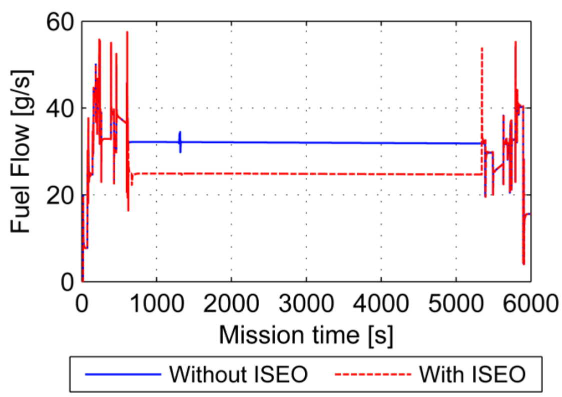

Fig. 15: Overall fuel flow of the mission

Without ISEO, the overall fuel flow of both engines is 32 g/s. As one is shut down, this value is reduced to 25 g/s. Cumulatively over time, 34 kg of fuel can be saved (see Fig. 16), which is 19% of the fuel used during the mission without ISEO.

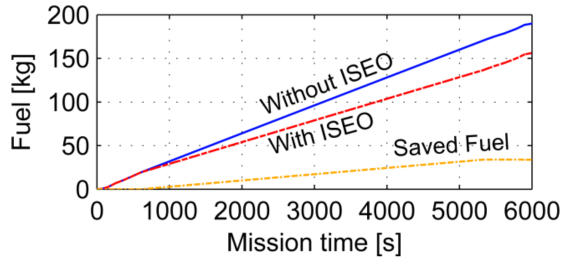

Fig. 16: Used fuel of the mission with and without ISEO and the saved fuel amount caused by ISEO

This approach of determining the fuel saving potential by ISEO is also used for the other missions.

5.2. HEMS Mission

The HEMS mission will mark the lower end of potential ISEO fuel saving potential as the intention of medical helicopter services is to get to the needy person as quickly as possible. As the figures of chapter 4 show the inability of ISEO during high speed flight, ISEO may only be applicable during medium speed flights such as return flights from a hospital to the helicopter base. Such a mission is simulated in this section. The helicopter is located in a city of a sparsely populated and mountainous country. Thus, the approach to the accident site is rather long as is the transport of the needy person to the hospital. After handover at the hospital, the helicopter returns to its base using ISEO at its cruise altitude of 600 m. The overall flight track length is 206 miles. The flight speed and altitude plotted against mission time is as follows:

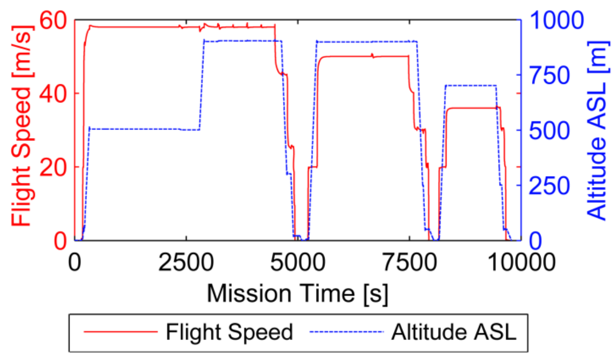

Fig. 17: Flight speed and altitude of the HEMS mission

The first mission element to time step 5000 s is the fast approach to the accident site. After 2800 seconds, the helicopter has to climb to 900 m due to overfly of mountains. After the landing at the accident site, one person weighing 80 kg is loaded into the helicopter. Then the helicopter flies to the hospital, where the person is unloaded. During the short flight back to the main base, ISEO is applied. The requirement for ISEO – power required must be lower than power provided by one engine – is achieved in the last mission element as Fig. 18 below shows.

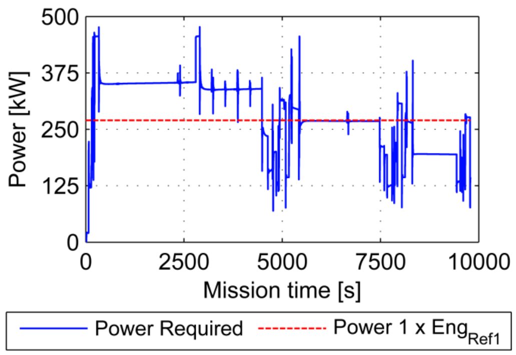

Fig. 18: Power required during the HEMS mission

If the speed of the second mission element had been reduced, ISEO operation would have been possible here also. Regarding the fuel used during the mission, Fig. 19 shows the low saving potential.

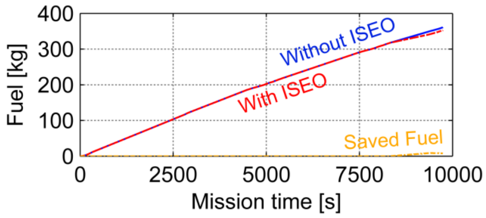

Fig. 19: Used fuel of the mission with and without ISEO and the saved fuel amount caused by ISEO

Overall the engines burned 361 kg of fuel during the mission without ISEO. The application of ISEO at the third mission element saved only 9 kg of fuel, which means a saving potential of 2%. If ISEO had been used in the second mission element as well, the saving would have been greater. Nevertheless, a long HEMS mission may not be suited for reasonable ISEO. Analyzing a short HEMS mission, one would get the same results. The shorter the flight distance using ISEO, the less the saving potential is.

5.3. Surveillance Mission

The section for the surveillance missions is divided into two subsections. The first one analyzes a search mission of a police helicopter. The second one is a mission doing aerial imaging over a certain area.

Police Mission

This helicopter flight mission is of usual type. A person is missing close to a riverside, and a helicopter is requested to do a wide-area search using a thermal imaging camera. The helicopter is located at a heliport approximately 25 miles away from the search area. It flies directly and fast to this area and does the search by following the course of the river upstream. After 9 miles, the helicopter turns 180 degrees and now flies against the former flight direction. This procedure is done twice to ensure that the missing person is not overlooked. Then the helicopter climbs to a new cruise altitude and returns to its heliport (see Fig. 20). The gross mass of this flight is 1950 kg at the beginning.

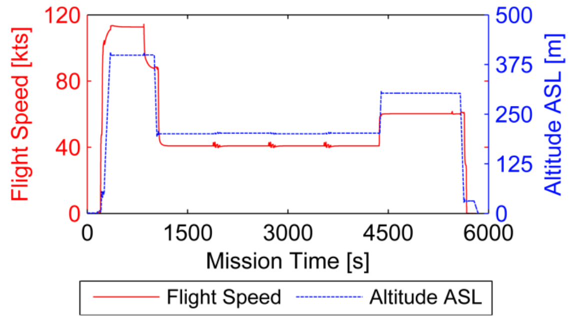

Fig. 20: Flight speed and altitude of the SV 1 mission

Consequently, flight speeds are moderate after approaching the search area and during the return flight back to the base. Thus, the power requirement during these flight states is not so high as to require the power of two engines, as the following graph of power required in Fig. 21 shows.

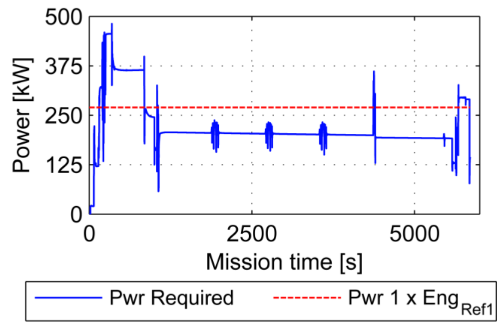

Fig. 21: Power required during the SV 1 mission

It can be clearly seen that for more than 2/3 of the mission time, the helicopter can be in ISEO mode to save fuel. Thus, the whole search pattern is flown with ISEO as well as the return flight to the base. In comparison to the HEMS mission, the graph of Fig. 22 shows a much better fuel saving. In this case, 20% of fuel can be saved using ISEO in the suitable mission areas.

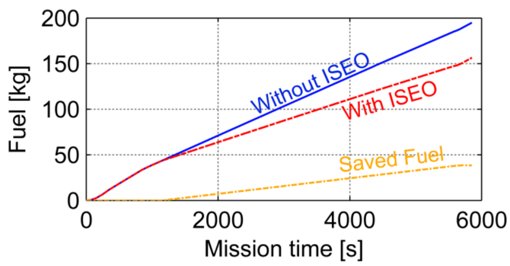

Fig. 22: Used fuel of the mission SV 1 with and without ISEO and the saved fuel amount caused by ISEO

The shutdown time of one engine during ISEO is 75 minutes. Consequently over one hour of engine life time can be saved with ISEO.

Aerial Imaging Mission

The aerial imaging mission may be a perfect fit for ISEO operations. During the mission, the helicopter follows a known flight path for full coverage of an area at a constant height and speed for quite a long time. Besides aerial imaging, a similar procedure is performed for ground analysis within the area of aero geophysics. Here, probes are towed behind a helicopter for ground scanning. Unfortunately, this is done at low heights such as 100 m above ground level, which can be too low to ensure sufficient safety in an event of total power loss. The simulated mission here is described as follows. The scanning area is 56 miles away from the helicopter base. For this approach flight, the helicopter climbs up to 500 m ASL and has a speed of 70 kts. Shortly before entering the scanning area, the helicopter declines to 200 m ASL and reduces its speed to 35 kts. Then ISEO operation starts for the entire scanning flight and the return flight. The scanning of the ground is done using a flight pattern of equally-spaced parallel linear flight tracks. The flight back to the base is also performed with ISEO, but with higher flight speeds such as 70 kts and at an altitude of 300 m ASL (see Fig. 23).

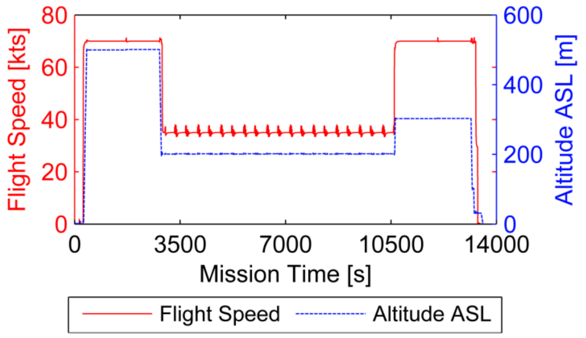

Fig. 23: Flight speed and altitude of the SV 2 mission

The resulting power required vs. mission time shows that for more than 90% of the mission time, ISEO is possible. However, the approach to the scanning area is performed by AEO, and only when the scanning is started does the helicopter switch into ISEO mode. Despite the power-required peak at mission time 10500 s, the helicopter is kept in ISEO as the peak is caused by the FCS. A actual pilot should be able to fly the transition between level flight and climbing more smoothly. Shortly before landing, the helicopter switches back to AEO mode.

The reduction of power required due to loss of fuel mass can be clearly seen in Fig. 24. In this mission, the fuel tanks are completely full at the mission start.

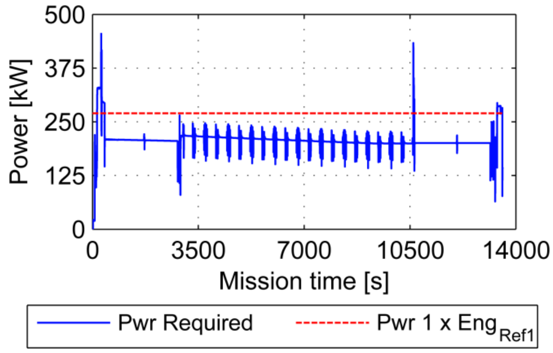

Fig. 24: Power required during the SV 2 mission

Although the helicopter is in ISEO mode for 75% of the mission time, there is only a fuel saving of 19% which is 84 kg fuel. This can also be seen in Fig. 25.

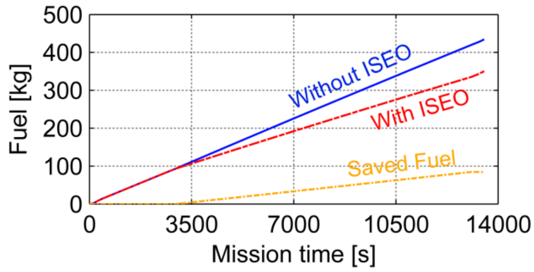

Fig. 25: Used fuel of the mission SV 2 with and without ISEO and the saved fuel amount caused by ISEO

5.4. Passenger transportation

Besides off-shore platform support, medical services and surveillance missions, there is an additional mission type in the form of passenger transportation. This may comprise regular air connections between destinations as well as nonscheduled flights for companies and individuals. Here a helicopter flight mission for a company is simulated and is referred to subsequently as business mission (BSN). At the start destination, three passengers are aboard. During the first mission segment, the helicopter flies to a city and picks up another person. During this short flight, ISEO is used to save fuel. After the stopover, the helicopter again uses ISEO to reach its final destination.

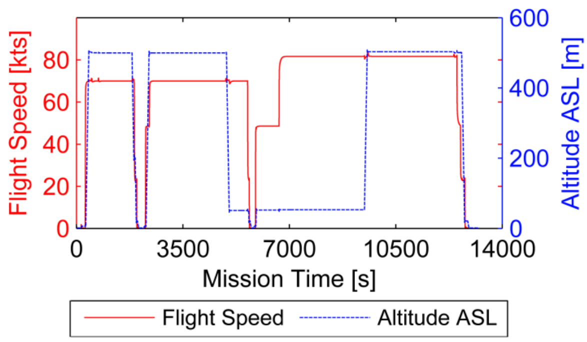

Fig. 26: Flight speed and altitude of the BSN mission

After releasing the four passengers at the destination the helicopter returns to its home base again using ISEO. The resulting ISEO segments with flight speed and height can be seen in Fig. 26. Since there is no refueling during the mission and due to the fuel weight loss, the helicopter's velocity for the return flight is slightly higher than during the first two mission segments. Due to some restrictions, the first part of the return flight is at a low height. Afterwards the helicopter climbs up to 500 m ASL.

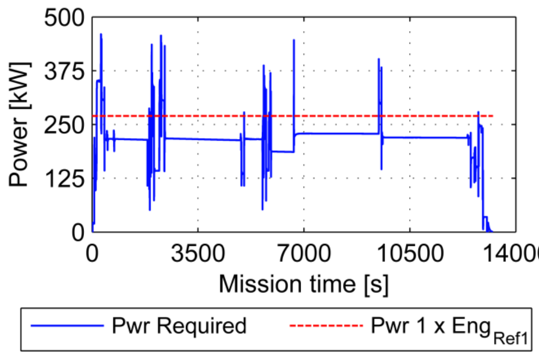

Fig. 27: Power required during the BSN mission

As Fig. 27 shows, there are four major mission segments in which ISEO is reasonable. During the first two segments and during the last one, ISEO is commanded. Overall, this leads to a fuel saving of 50 kg (see Fig. 28), and in comparison to the used fuel with only AEO during the mission, the saving potential is 12%.

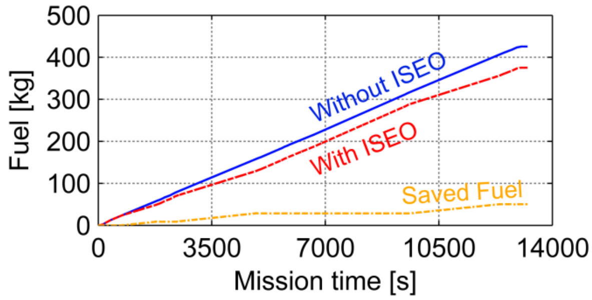

Fig. 28: Used fuel of the BSN mission with and without ISEO and the saved fuel amount caused by ISEO

Nevertheless, using ISEO several times during a mission increases the start/stop cycle count. Since some components are life-cycle limited the additional cycles, due to ISEO usage, have to take into account in a future business case.

5.5. Mission Comparison

Table 4 below summarizes all the relevant parameters regarding ISEO, in particular the saved fuel amount. There seems to be an imaginary boundary of the saving potential in the area of 20% of the used fuel. But this saving cannot be achieved for every mission. The maximum savings are highly dependent on the time ISEO is used as well as flight speed, gross mass and altitude. Depending on the appropriate flight mission profile, one has to decide whether a helicopter capable of ISEO is suitable for the mission.

	Mission time [min]	ISEO time [min]	ISEO time [%]	Track Length [mile]	Used Fuel [kg]	Saved fuel [kg]	Saved fuel [%]
OPS	104	79	76	112	190	34	19
HEMS	164	17	11	206	361	9	2
SV 1	98	75	77	52	195	39	20
SV 2	226	169	75	165	434	84	19
BSN	221	110	50	199	426	50	12

Table 4: Result of the helicopter flight mission analyses

6. CONCLUSION AND OUTLOOK

First, the operational strategy of ISEO is presented and the useful areas for ISEO in the flight envelope for two different helicopters are determined. Since H/C_{Ref1} is slightly underpowered for useful wide range application of ISEO, the fuel saving potential will not be as high as for the one of the sufficiently powered H/C_{Ref2}. Nevertheless, simple mission analysis with H/C_{Ref1} shows a maximum fuel saving potential of approximately 20% depending on the flight mission. Thus, ISEO can help to reduce the overall fuel consumption of helicopter flight missions.

However, before using such an operational strategy, several issues have to be discussed such as engine failures during ISEO [2] or increasing maintenance costs because of increasing engine start and stop cycles. Then reinforced main helicopter transmissions assumed in this paper allow the use of a wider range of the available engine power. This may lead to higher weights of the drive train, resulting in a lower payload if the performance of the helicopter is not to be influenced. Furthermore, the safety power margins have to be investigated in greater detail by means of extensive flight dynamics analysis. Another eligible system would be active controls for the pilots indicating the boundaries of the flight envelope during ISEO, whereby in getting to the boundaries, the pilots have to use more muscular strength to move the controls further. Additionally the pilots can be supported by visual aids in the cockpit displays.

7. COPYRIGHT STATEMENT

8. REFERENCES

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