ASME Paper Title: **Simulation Framework Development for Helicopter Mission Analysis**

Authors: Ioannis Goulos, Martina Mohseni, Vassilios Pachidis, Roberto D'Ippolito, Jos Stevens

ASME Conf Title: **ASME Turbo Expo 2010: Power for Land, Sea, and Air**

Volume/Issue: **Volume 3: Controls, Diagnostics and Instrumentation; Cycle Innovations; Marine** Date of Publication (VOR* Online): 22 Dec 2010

ASME Digital Collection URL: https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2010/43987/843/347455

DOI: 10.1115/GT2010-23389

*VOR (version of record)

Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air
GT2010
June 14-18, 2010, Glasgow, UK
DOI: 10.1115/GT2010-23389

GT2010-23389

Simulation Framework Development for Helicopter Mission Analysis

Ioannis Goulos
Department of Power & Propulsion
Cranfield University, UK

Martina Mohseni
Department of Power & Propulsion
Cranfield University, UK

Vassilios Pachidis
Department of Power & Propulsion
Cranfield University, UK

Roberto D'Ippolito
LMS International
Leuven, Belgium

Jos Stevens
National Aerospace Laboratory
NLR
Amsterdam, Netherlands

ABSTRACT

Helicopter mission performance analysis has always been an important topic for the helicopter industry. This topic is now raising even more interest as aspects related to emissions and noise gain more importance for environmental and social impact assessments. The present work illustrates the initial steps of a methodology developed in order to acquire the optimal trajectory of any specified helicopter under specific operational or environmental constraints. For this purpose, it is essential to develop an integrated tool capable of determining the resources required (e.g. fuel burnt) for a given helicopter trajectory, as well as assessing its environmental impact. This simulation framework tool is the result of a collaborative effort between Cranfield University (UK), National Aerospace Laboratory NLR (NL) and LMS International (BE).

In order to simulate the characteristics of a specific trajectory, as well as to evaluate the emissions that are produced during the helicopter's operation within the trajectory, three computational models developed at Cranfield University have been integrated into the simulation tool. These models consist of a helicopter performance model, an engine performance model and an emission indices prediction model. The models have been arranged in order to communicate linearly with each other. The linking has been performed with the deployment of the OPTIMUS process and simulation integration framework developed by LMS International. The optimization processes carried out for the purpose of this work have been based on OPTIMUS' built-in optimizing algorithms. A comparative evaluation between the optimized and an arbitrarily defined baseline trajectory's results has been waged for the purpose of quantifying the operational profit (in terms of fuel required) gained by the helicopter's operation within the path of an optimized trajectory for a given constraint.

The application of the aforementioned methodology to a case study for the purpose of assessing the environmental impact of a helicopter mission, as well as the associated required operational resources is performed and presented.

INTRODUCTION

The developments in technology of the 20th and 21st century regarding the industrial as well as civil transport activities have had as a direct result the continuous rise in energy demand. The progressively increasing rates of energy consumption have inevitably led to the imminent occurrence of fossil fuel depletion as well as to a severe environmental impact due to the emissions produced associated with fossil fuel combustion.

The helicopter industry has certainly played a major role in these developments and is most certainly affected by their aforementioned impact. The Advisory Council for Aeronautics Research in Europe (ACARE) in an attempt to minimize the environmental impact of the civil aviation has set a number of environmental goals which are to be achieved by 2020. These goals include reduction in carbon dioxide (CO2) and nitrogen oxides (NOX) by 50% and 80% respectively. According to Clarke [1], the realization of the aforementioned goals can only be achieved through the following: a) significant reduction in the number of operations, b) the incorporation of innovative and more efficient airframes – types of aircraft/rotorcraft in general or c) the deployment of alternative operational procedures – the seeking of optimal flight paths. However, the modern trends in air traffic show that in the forth-coming future the number of operations is more likely to be increased rather than decreased. Brooker [2] points out that the timeframe from the conception of an innovative design until the achievement of airworthiness certification can be quite substantial. Hence major innovations in airframe design will not be deployed into service until approximately the first half of the 21st century. It is therefore well understood that, given the timeframe of the standards set by ACARE, the sole route that can lead to the realization of the aforementioned goals is the modification of the already existing operational procedures and the seeking of alternative flight paths, the operation within which, would be associated with the minimal environmental impact possible. A large collaborative project with several organizations participating worldwide, focusing on the objective of finding the best alternatives or routes with the purpose of minimizing the environmental impact, is the European Clean Sky JTI (Joint Technology Initiative) [3]. Within the Clean Sky, several technologies will be developed and demonstrated, hence making another step towards achieving the aforementioned environmental goals set by the ACARE.

As the shortage of fossil fuels is becoming progressively more imminent, the price of crude oil will continue to rise, hence it is only reasonable that the price of aviation fuel will follow the same trend. This trend is responsible for constituting the total operational fuel consumption as a key factor in minimizing the overall operational cost. It is therefore realized that a deployed helicopter operational procedure must, not only comply with imposed ATC constraints, but also to be accompanied by the minimal fuel consumption feasible. This can be achieved by seeking alternative routes-trajectories, the operation within which would be less energy-demanding.

Consequently the development of a computational algorithm capable of determining the resources required (fuel and operational time) for a given helicopter trajectory, as well as assessing the environmental impact in terms of emissions produced associated with the helicopter's operation within the specific trajectory, is essential. The algorithm has to be able to obtain optimal flight paths for any user-defined constraints in order to configure innovative operational procedures within the optimal calculated flight paths. For this purpose an integrated tool has been developed capable of modeling and assessing the properties of interest of any user-defined helicopter trajectory. This work presents the initial steps of a methodology developed for the purpose of acquiring optimal trajectories of a given helicopter configuration under certain user-defined operational or environmental constraints. The objective is met by applying a specific optimization strategy on the aforementioned integrated tool and the optimal mission profiles for any given user-defined, operational or environmental constraints are obtained.

INTEGRATION OF TOOLS

Description of tools

The integrated tool, created for the scope of this work, consists of three computational models developed at Cranfield University. These models are: 1) a helicopter performance simulation model (HELIX), 2) an engine performance simulation model (TURBOMATCH) and 3) an emissions prediction tool (HEPHAESTUS). The linking of the above-mentioned models has been performed with the deployment of LMS OPTIMUS with NLR contributing their expertise on helicopter mission analysis. The optimizations carried out were based on OPTIMUS' integrated optimizing algorithms.

Performance modeling represents indisputably the economically most efficient way to analyze the performance of existing helicopter configurations at a range of flight conditions. Its scope is to participate in the development of new designs and to assess the feasibility of various design alternatives for the purpose of satisfying the growing environmental requirements – e.g. defining mission profiles requiring lower fuel consumption and reduced emissions etc. Helicopter performance models with a choice of fidelity and with varying capabilities have been developed in the past, however they are typically not available in the public domain. To address this issue a generic helicopter performance model (HELIX) has been developed in standard FORTRAN 90. The helicopter properties susceptible to user-specification include the geometrical and weight break-down distribution data of the helicopter.

The helicopter mission to be assessed in terms of engine power required is defined by the user. The mission profile is truncated in user-specified number of flight segments. The user needs to define the flight conditions occurring for each and every one of the mission profile's segments. The flight conditions are defined in terms of initial and final altitudes, the segment duration/range and the forward velocity of the helicopter.

With the exception of a strictly forward flight segment where variations in altitude are non-existent, it is acceptable to say that HELIX is most suitable in the limit:

$$\lim_{dR \to 0} PW_{req}(Alt)$$

Having an infinitely small segment range will result in a very smooth and accurate representation of the helicopter trajectory where variations in atmospheric parameters with altitude can be accurately represented. However in this case, the number of segments which will represent the trajectory will have to be infinitely large resulting in a restrictive increase in computational time. On the other hand, a small number of segments will result in highly finite and discrete altitude steps which will compromise the accurate representation of an actual trajectory. It is therefore realized that the number of segments in which a flight profile is truncated, has to be carefully specified, bearing in mind that a compromise between accurate trajectory representation – accuracy in calculations and computational time is inevitable.

The engine performance model (TURBOMATCH) used for the present work has been developed and refined at Cranfield University over a number of decades [4]. TURBOMATCH is capable of simulating the performance of an extensive range of aero and industrial gas turbine engines with cycles ranging from a simple single shaft turbojet to complex multi-spool turbofans with mixed exhausts and secondary air systems as well as novel engine configurations. The performance simulations range from simple steady state (design and off-design point) to transient performance computations. For the scope of this work the engine is assumed to be working at steady state conditions so TURBOMATCH has been set up appropriately.

The emission indices are calculated using the emissions prediction model HEPHAESTUS developed at Cranfield University [5]. It is generally accepted that three broad strategies can be adopted for the purpose of combustor emissions prediction which are the following: 1) empirical correlations, 2) stirred reactor models and 3) comprehensive numerical simulations (CFD) calculations. The use of empirical correlations implies that the fine details of the combustion chemistry and internal flow are degenerated to global expressions, having been established directly from measurements. The deployment of detailed numerical simulations of the turbulent reacting flow inside the combustor (CFD simulations) represents the other extreme of the approaches to gas turbine emissions prediction. However, it is generally acceptable that this approach is both time consuming and requires a high-fidelity definition of the combustor geometry, which may be difficult to obtain for certain combustors designs. Stirred reactor models, in which the turbulent flow is sufficiently idealized and the time-dependent chemistry of pollutant formation is computed with sufficient accuracy, represent an efficient compromise between the two aforementioned extreme approaches and it the method deployed by HEPHAESTUS in order to calculate gas turbine emissions. The critical zones within the combustor are represented by individual stirred reactors, incorporating the processes of mixing, combustion heat release, and pollutant formation. In order to take into account inhomogeneities in gas composition and temperature which influence directly the rates of pollutant formation, a stochastic representation of turbulent mixing in the combustor primary zone is utilized.

The linking of the aforementioned simulation algorithms was carried with the deployment of LMS OPTIMUS as a simulation framework. OPTIMUS is a flexible design environment which can be used to evaluate multiple design alternatives. OPTIMUS can be used to link simulation codes or legacy systems in a graphical and user-friendly environment. Having its own integrated variety of optimization sequences ranging from single-objective - local optimization to multi-objective - global optimization methods, the integrated tool's potential can be fully evaluated.

Workflow Configuration

The three aforementioned simulation tools (HELIX, TURBOMATCH and HEPHAESTUS) have been linked in order to communicate linearly with each other. The experiment is carried out for each and every flight segment. The segment workflow is illustrated in Fig. 1. The experiment is initiated by defining the flight conditions of the segment which are input into the helicopter performance model (HELIX).

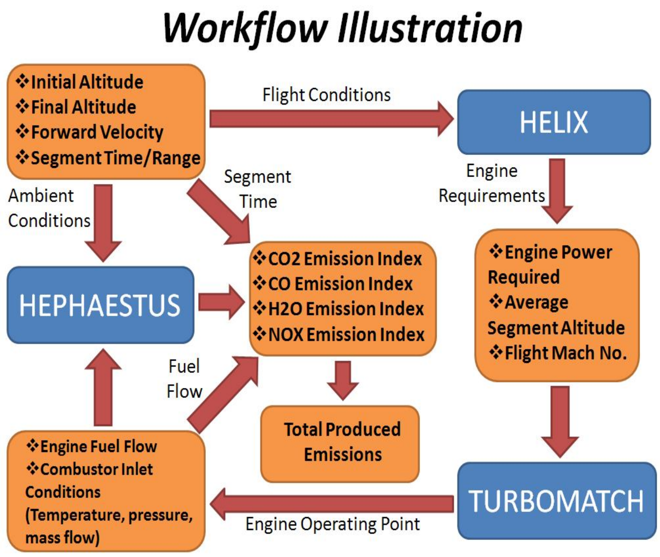

Fig. 1 Segment workflow illustration

HELIX is capable of accepting initial and final segment altitudes, forward velocity, and segment horizontal range/operational time as well as any reduction in the helicopter total mass (fuel consumption or drop of ordnance) as inputs. Based on these user-defined flight conditions HELIX will calculate the helicopter engine shaft power required for the duration of the aforementioned pre-defined flight segment, in order for the helicopter to reach the final segment conditions while maintaining the user-defined forward velocity.

After the successful execution of HELIX, OPTIMUS automatically reads HELIX's output file, and extracts the necessary output data in a pre-determined way that has been set up by the user. OPTIMUS then re-writes the output data in the appropriate format so that it can then be input into the performance simulation tool (TURBOMATCH). TURBOMATCH then determines the engine operating point for the given flight conditions (average segment altitude and flight Mach No. based on the helicopter's forward velocity) and engine shaft power requirement. Therefore the fuel flow and the combustor inlet conditions such as air mass flow, total inlet pressure and total inlet temperature are acquired.

After the engine performance simulation is complete, OPTIMUS reads the results and extracts the fuel flow, the aforementioned combustor inlet conditions and calculates the ambient temperature for the given average segment altitude. These are the required input data for the emissions prediction model (HEPHAESTUS). The data is then re-written in the appropriate format so that it can be read by HEPHAESTUS. After the execution of HEPHAESTUS, the predicted emission indices for several types of emissions regarding the specified flight segment are calculated

Having calculated the fuel flow per engine and having a user-defined segment operational time, the fuel burn per engine during the specific flight segment can be calculated. Since the fuel burn per engine and the emission indices are now known, the total production of each emission per engine for the given flight segment is calculated. The helicopters mass at the segment’s final state can also be calculated simply by deducting the total fuel burn from the initial helicopter mass. The segment workflow as developed in LMS OPTIMUS is illustrated in Fig. 2.

The segment’s initial altitude, final altitude, horizontal range/operational time have been defined and the flight conditions in terms of flight Mach No. and average segment altitude have been set. The associated operational resources requirements in terms of fuel burn and operational time have been evaluated and the environmental impact in terms of emissions produced has been assessed for the given segment. Since all the parameters that can fully define the position of the helicopter have been acquired, and the respective properties of interest have been calculated, it is therefore reasonable to say that the problem in hand has been defined and solved for the specified flight segment.

Having defined and solved the problem within one flight segment, the new flight conditions in terms of final altitude and new helicopter mass are known. The calculations can therefore proceed to the next flight segment using as initial conditions, the previous segment’s final conditions in order to ensure flight path continuity. The former segment’s final altitude will be input in the new calculations as the new segment’s initial altitude and the initial helicopter mass for the new segment will be the former segment’s initial mass minus the former segment’s total fuel burn. A new final altitude, forward velocity and horizontal range/operational time are now defined for the new segment and the previously described calculations are performed for the newly defined flight conditions. The aforementioned process will be reiterated for each and every flight segment in which the helicopter trajectory has been truncated.

The environmental impact associated with the helicopter’s operation within any user-specified, or calculated optimal trajectory, can be assessed either in terms of total produced emissions, or by means of higher fidelity such as the emissions trail. The emissions trail for each pollutant of interest is acquired by evaluating the emissions produced within each flight segment only. Thus, the different trails of emissions left behind in the helicopter wake during the operation within different trajectories can be evaluated.

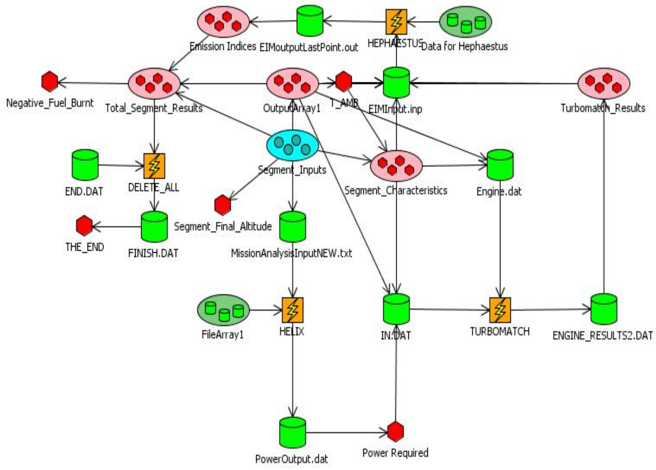

Fig. 2 Segment workflow illustration in LMS OPTIMUS

CASE STUDY

Problem Definition

In order to evaluate the potential and assess the limitations of the developed integrated tool, a simple case study has been selected. The overall helicopter model that has been implemented is a generic, twin engine, medium utility helicopter modeled after the EUROCOPTER Super PUMA AS332. The AS332 is equipped with two Turbomeca Makila 1A1 engines rated at 1.3 MW each. Therefore the respective engine model for TURBOMATCH has been developed. The trajectory type selected for the purpose of this work is a typical climb profile for a helicopter of similar specifications. The mission objective is to climb from sea-level altitude (set to 0m) to a typical cruise altitude (set to 2530m) while covering a horizontal range of 30 kilometers.

The mission profile has been truncated into 5 segments, them being 1 initial hover segment and 4 remaining climb segments. The specific number of segments is insufficient when it comes to an accurate representation of a realistic helicopter mission. However for the purpose of the present work, which is mainly to evaluate the potential of the integrated tool and assess its limitations, it was decided that the accuracy level achievable by such a truncation would suffice. For the specific case study which consists of 5 segments, a complete experiment requires the integrated tool to perform its calculations 5 times separately, one for each flight segment. After the calculations of all the segments have been completed, the calculated produced emissions, fuel burn and operational time are summed up and the total emissions produced, fuel burn and operational time required for the entire climb profile are calculated. A graphical representation of the simulation framework developed in OPTIMUS for the specific case study is illustrated in Fig. 3.

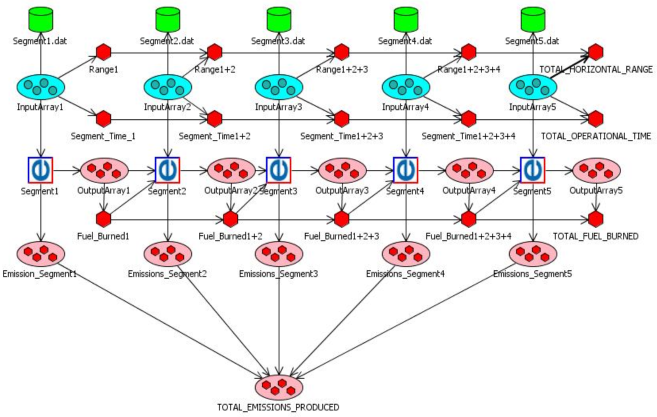

Fig. 3 Case Study workflow illustration in LMS OPTIMUS

As mentioned earlier, the initial states of only the first flight segment are set to be constant. These consist of the segment initial altitude, which is the ground altitude set at sea level (0m) and the initial helicopter mass, which is set to a typical gross weight of an AS332 with standard and additional fuel tanks, a payload of 700 kilograms and two crew members. For each and every one of the rest of the segments, the values of the helicopter gross weight and the segment initial altitude will be calculated based on the results of the calculations of its previous segments. Each and every one of the flight segments has 2 variables. These variables are: a) final segment altitude and b) segment operational time with the exception of the first segment which, as previously mentioned, is set to be a fixed 'hover' segment as is typical for any helicopter mission. During this segment the helicopter is hovering at an altitude of 30 meters for a time of 0.083 hours. Hence, the parameters are held constant. The last segment's final altitude is also set to a fixed value of 2530m which is the mission objective. The forward velocity of the remaining climb segments is held constant as well. The objective is to find the optimal values of the segment duration and the final altitude for every 'non-hover' segment under given single or multiple constraints. The constraint can be either an operational constraint such as minimum total fuel burn or minimum operational time, or it can be an environmental constraint, such as minimum NOX or CO2 emissions, or any imposed ATC constraint. In order to maintain a sense of realism within the problem, it would make sense to impose an arbitrary ATC constraint of a fixed total climb horizontal range. Therefore, as mentioned earlier, a fixed climb horizontal range constraint of 30 kilometers has been imposed.

For the purpose of quantifying the optimization results in terms of operational resources economy, or emissions reduction, a sub-optimal baseline trajectory has been defined, with which the results of the optimal flight paths can be compared. The characteristics of the baseline trajectory in terms of initial and final segment altitudes, forward velocities and segment durations are presented in Table 1. It is noted that segment forward velocity distribution as shown in Table 1 for the baseline trajectory, is held constant throughout the optimization processes.

Table 1: Baseline Climb Profile

Segment No.	Initial Altitude (m)	Final Altitude (m)	Forward Velocity (m/sec)	Segment Duration (hrs)
1	30	30	0	0.083
2	30	655	35	0.03
3	655	1600	40	0.04
4	1600	1800	45	0.05
5	1800	2530	50	0.06

Performed Optimizations

Two OPTIMUS integrated optimization algorithms were deployed for the purpose of this work. It was decided that the most suitable optimization strategy for the given case study, would be the initial execution of a global optimization algorithm and the finalization with a local optimizer. The starting point of the global optimization is set to be the point defined by the variables and constants as set in the arbitrarily defined baseline climb profile. The starting point of the local optimization is set to be the optimum obtained from the global optimization. The algorithms selected were 'Self-Adaptive Evolution' and 'Sequential Quadratic Programming' respectfully.

Self-Adaptive Evolution (SAE) is an 'Evolutionary Scheme'. These schemes are nature-inspired and imitate biological mutation and natural selection in a simplified way with the purpose of finding the 'fittest' solution to multi-dimensional technical problems [6]. The main advantage of using Evolutionary schemes in complex, multi-dimensional experiments is that they do not require the calculation of the sensitivities of the variables and the objective function. SAE is based on a population of designs. The members of this population are created by recombination and mutation from a set of parent designs. These parent designs are selected from the total initial population of designs. Parents with better fitness have a larger probability of being selected. SAE is multi-recombinant scheme, meaning that multiple parents are selected in order to generate a single offspring. Each design is independently mutated according the following scheme:

$$\boldsymbol{x_{m,i}^{(k)} = x_{p,i}^{(k)} + d_m^{(k)} S_i^{(k)}}$$

After the new generations have been acquired, their fitness is evaluated and then a new offspring-population is produced. As a rule of thumb, the population size is selected to be 4 or 5 times the number of the variables that the experiment consists of.

The convergence criteria can be the number of iterations, the execution time, the maximum fitness or any intermediate combination. For the purpose of this work a maximum number of 25 iterations has been set as a convergence criterion. It is generally not recommended to set the number of iterations below 20. However, since a local optimization algorithm has been scheduled to follow the optimization process, it was decided that it would be acceptable to stop the global optimization after 25 iterations.

Sequential Quadratic Programming (SQP) methods are considered as the standard general purpose algorithms for solving smooth, non-linear optimization problems [7]. They have evolved from Quasi-Newton methods, by taking constraints into account. They belong to the most powerful non-linear programming algorithms that have been developed so far for solving differentiable non-linear problems.

The basic idea is to establish a quadratic approximation based on second order information for the purpose of achieving local convergence. The quadratic sub-problem is obtained within each iteration by linearizing the constraints and approximating the Langrangian function quadratically [8]. The problem is then solved within the specific iteration with linearized constraints following Newton's method [9]. The aforementioned process is re-iterated until the user defined convergence criteria have been met. Since the local optimization (SQP) is carried out strictly for the finalization of the total optimization process and has as a starting point, the optimal set of variables, acquired by the previously conducted global optimization (SAE) it is acceptable to set a maximum number of 20 iterations.

The main disadvantage of local optimization methods is that they cannot escape local optima. This is the primary reason why it is of essence to execute a global optimization algorithm beforehand. The purpose of the initial global optimization execution is to establish the best candidate starting point capable of maximizing the probability of finding the absolute best optimal solution to given user-imposed problem.

RESULTS AND DISCUSSION

Two different optimization cases with different objectives, but under identical constraints, have been carried out for the purpose of this work. The first case objective is an operational constraint with regards to fuel consumption. The helicopter has to perform the previously described mission having consumed the least amount of fuel possible. The second case objective is an imposed environmental constraint with regards to NOx emissions. The exact same mission needs to be carried out but the total NOx produced emissions need to be minimal. The required operational resources and the total emissions produced associated with the acquired optimal trajectories are compared with the results of the baseline sub-optimal trajectory, as well as with each other.

The environmental impact of the helicopter operation within the baseline and within the optimized trajectories is evaluated in terms of total produced emissions as well as in terms of the helicopter's emissions trail. The trail of emissions for each pollutant of interest is acquired for the arbitrarily selected baseline trajectory and the calculated optimal ones, and are sub-sequentially compared and evaluated.

Operational Resources Quantification

Table 2 presents a comparative evaluation of the operational resources and overall produced NOx emissions between the calculated optimal mission profiles and the arbitrarily defined baseline trajectory, as well as with each other. The percentage differences '*D*' presented in Table 2 are defined as follows:

$$\boldsymbol{D} = \left(\frac{\boldsymbol{Property\ X}}{\boldsymbol{Property\ Y}} - \mathbf{1}\right)\%$$

Table 2: Total Operational Resources and NOX Emissions evaluation

Compared Mission Profiles	Total Fuel Consumption	Required Time	Total NOx Emissions
FUEL-Opt./ BASELINE	**-6.52%**	**-3.23%**	**0.18%**
NOX-Opt./ BASELINE	**-4.07%**	**-1.56%**	**-7.29%**
NOX-Opt./FUEL-Opt	**2.61%**	**1.72%**	**-7.46%**

The optimizations revealed a substantial reduction margin available regarding the total fuel consumption approaching almost 6.52% compared to the baseline profile's demanded fuel burn. The fuel-optimized profile is also accompanied by a reduction in operational time of the order of 3.23%. A small increase in NOx emissions of approximately 0.18% in relation to the baseline profile also occurs. The respective feasible NOx emissions reduction margin relative to the baseline trajectory approaches 7.29%. The NOx-optimal trajectory is accompanied by a considerable reduction of overall fuel consumption which reaches approximately 4.07% relative to the baseline fuel burn while the demanded operational time is also reduced by a total of 1.56%. A direct comparison between the fuel-optimized and the NOx-optimized trajectories reveals a percentage difference in overall fuel burn of 2.61% while the overall percentage difference in NOx emissions production reaches a substantial 7.46%. However the difference in demanded operational time for the 2 optimal mission profiles is only 1.72%.

Fig. 4 presents an illustration of the baseline along with the calculated optimal helicopter flight paths. As mentioned earlier, the fuel consumption is solely dependent on the engine fuel flow and the demanded operational time. Hence, the optimal fuel burn flight path needs not only to be accompanied by rather small values of segment engine fuel flow, but of relatively limited segment operational time as well. However small segment operational times require increased forward velocities and climb rates, thus increased engine shaft power settings leading to high values of engine TET and fuel flow. Therefore the optimal compromise between those two contradicting factors needs to be established in the process of total fuel consumption minimization.

It can be observed in Fig. 4 with regards to the fuel-optimized trajectory, that the optimization process suggests the incorporation of a high climb rate value for the first climb segment followed by its gradual reduction during the rest of the mission. The final climb segment eventually ends with a rather 'gentle slope' FPA. It is also observed that the suggested calculated segment ranges start with a rather low value for the initial climb segment and then they gradually increase. Therefore the optimization process suggests for the helicopter to try and climb as fast as possible while covering only approximately 1 km of horizontal distance, and then to deploy a gradually FPA reducing 'gentle-slope trajectory' for the rest of mission. It is understood that very high values of climb rate will have as a direct result very high shaft power requirements from the engine, leading to increased values of engine TET and fuel flow. However, a very high value of climb rate will also lead to the faster completion of a segment, meaning the reduction of demanded operational time.

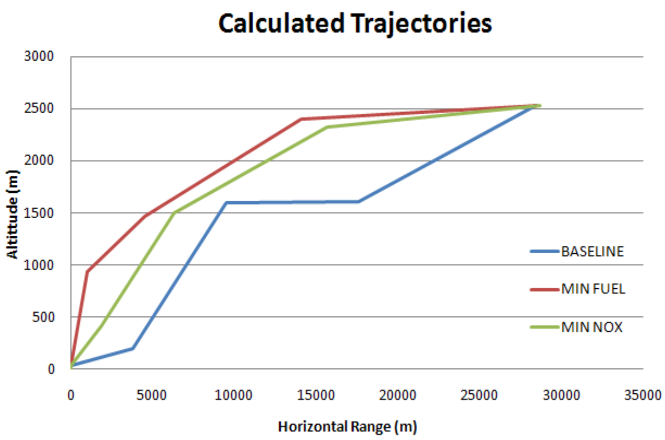

Fig. 4 Illustration of baseline and optimal trajectories

Considering the case of NOx minimization a somewhat similar behavior can be observed. This is because in the case of any pollutant minimization the overall fuel consumption must be as low as possible. Thus, the NOx-optimized trajectory resembles the fuel-optimized trajectory simply because minimum fuel consumption can be a prerequisite of minimum NOx production. This is why the percentage difference in the overall fuel consumption between the fuel-optimized and the NOx-optimized trajectories is only 2.61% as shown in Table 2.

However some major differences between the two mission profiles can be observed at the initial segments. Specifically, the very high climb rate observed at the first climb segment of the fuel-optimized trajectory does not appear in the NOx-optimized mission profile. This is because of the direct connection between the helicopter's operational climb rate and the engine operating conditions. As explained earlier, in order for the helicopter to maintain a high value of climb rate, the shaft power required will be rather significant and the engine will be operating with an increased TET. NOx emissions are mainly produced due to the oxidation of atmospheric nitrogen in the high-temperature regions within the combustor. The formation rate is highly accelerated when temperatures exceed 1800K. Therefore the combustor primary zone temperatures must be kept at relatively low values. Hence the engine TET needs to be kept at rather low values, but still high enough for the engine to be able to perform sufficiently thus ensuring rather low values of operational time, that are demanded in order to keep the engine total fuel consumption at sufficiently low values. Therefore the optimizations process suggests the avoidance of the initial high climb rate values for the NOx-optimized trajectory.

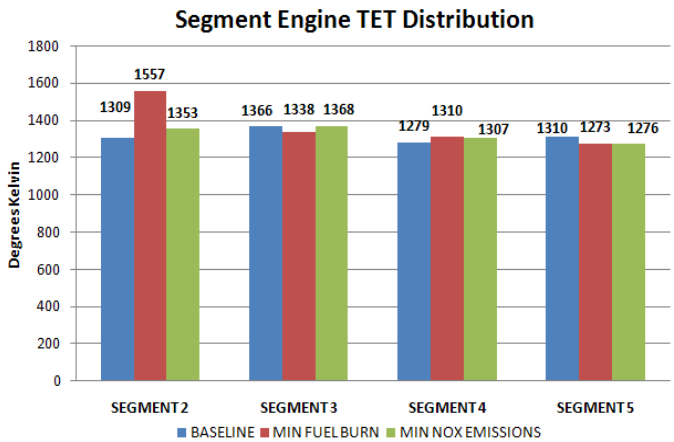

Fig. 5 Engine TET distribution among mission profile climb segments for the baseline and the optimal trajectories

Fig. 5 illustrates the engine TET distribution among the mission profile climb segments. The highest value of TET to be observed lies within segment 2 of the fuel-optimized trajectory, reaching approximately 1557 K. As explained earlier, this is due to the deployment of a very high climb rate during this segment, leading to quite significant engine shaft power requirement. Seeing that the segment 2 TET value regarding the fuel-optimized trajectory reaches 1557 K, it is implied that the combustor primary zone temperatures will be rather higher, leading to increased NOx formation. Following segment 2, the engine TET is gradually reduced for the rest of the segments regarding the fuel-optimized profile, which is the direct result of the incorporation of a rather gentle-slope flight path after segment 2. A somewhat similar engine handling can be observed for the NOx-optimal trajectory as well, which as explained earlier, is the outcome of the optimizer trying to keep the overall fuel consumption at low levels. However regarding segment 2, the engine TET value reaches only approximately 1353 K. This is due to the fact that the optimizer is trying to keep the engine TET at low levels in order to minimize the associated NOx emissions. At this point it is noted that, as shown earlier, the percentage difference between the NOx-optimized and the fuel-optimized mission regarding the overall NOx emissions production reaches a substantial 7.46%.

Environmental Impact Assessment

The environmental impact of the helicopter operation within the baseline and within the optimized trajectories is evaluated in terms of total produced emissions as well as in terms of the helicopter's emissions trail. The trails of emissions of various pollutants of interest for the various mission profiles are sub-sequentially comparatively evaluated.

Fig. 6 presents a comparative evaluation of the total CO2, CO, NOx and H2O produced emissions between the baseline and the optimal flight paths, as well as between the optimal flight paths themselves.

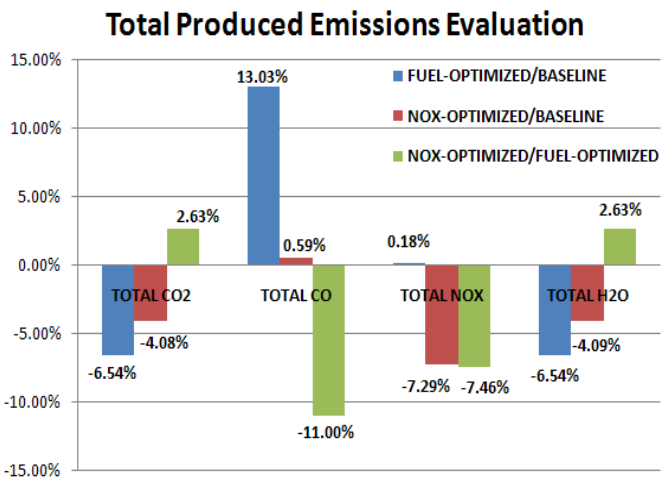

Fig. 6 Comparative evaluation of the total produced emissions between the arbitrarily defined baseline and the optimal mission profiles.

Regarding the CO2 and H2O emissions it is noted that the aforementioned pollutants leave the engine exhaust in chemical equilibrium conditions. The total production of CO2 is solely dependent on the overall engine efficiency. Thus for a given amount of fuel burn, the CO2 emission index will vary only very slightly depending on the combustor efficiency as well as on the fuel to air ratio in the combustor primary zone. Fig. 6 illustrates that the percentage differences with respect to CO2 and H2O total emissions between the baseline and the optimal mission profiles are almost identical to the values of total fuel consumption percentage differences illustrated in Table 2 earlier in this paper. Hence, it is reasonable to say that a trajectory optimized for minimum fuel consumption, in all probability would be associated with minimum total CO2 and H2O emissions as well.

Regarding the total CO production it can be observed that the fuel-optimized trajectory is accompanied by a substantial increase in overall CO emissions of the order of 13%. The overall observed increase is mainly due to the operating conditions suggested for flight segment 2, in which a very high rate of climb is deployed. As explained earlier, the very high climb rate inevitably demands high engine shaft power settings, hence increased engine TET and fuel flow. The aforementioned increase could either indicate fuel-rich operation of the combustor primary zone leading to CO production due to incomplete combustion, or moderately fuel lean mixture strength and CO2 dissociation because of high primary zone temperatures. In practice CO emissions are found to be highest at low power conditions, this being in conflict with equilibrium theory. However due to the fact that the engine TET for segment 2 is approximately 1557K, implying a much higher combustor primary zone temperature, it is more reasonable to conclude that the predicted increase in CO emissions is due to CO2 dissociation rather than incomplete fuel combustion. The percentage difference in CO production of the NOx-optimized trajectory in relation to the baseline is a negligible 0.59% which is probably due to the fact neither trajectory includes flight segments with rather high values of engine TET which could lead to CO2 dissociation.

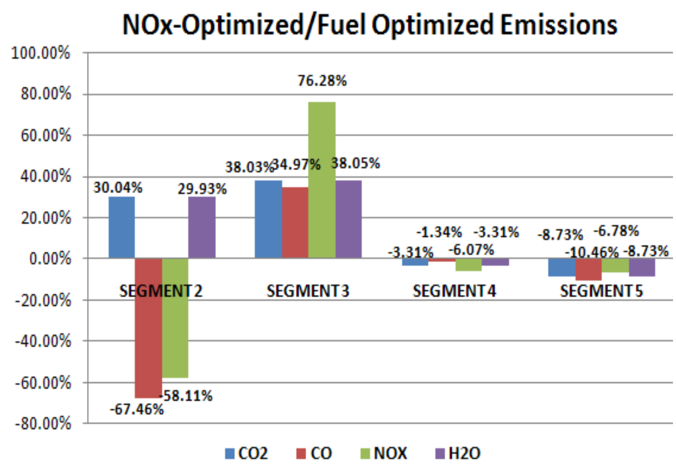

Fig. 7 Comparative evaluation of the emissions trails between fuel-optimized and NOx-optimized mission profiles

A comparative evaluation of the environmental impact regarding the optimal mission profiles is presented in Fig. 7. Fig. 7 illustrates the percentage differences between the CO2, CO, NOx and H2O emissions trails created by the helicopter's operation within the NOx-optimized and the fuel optimized trajectory respectively. The substantial difference in total CO and NOx emissions between the optimal profiles previously observed in Fig. 6, is now distributed along the flight paths deployed respectively. It can be observed that within segment 2, large percentage differences present themselves with respect to CO and NOx emissions production reaching approximately 67.46% and 58.11% respectively. These differences are the direct outcome of incorporating a high climb rate for the fuel optimized trajectory, thus having increased values of engine TET and fuel flow.

It can also be observed that the NOx-optimized mission profile is accompanied by a substantial increase in NOx production within segment 3 in relation to the fuel optimized trajectory, which is in conflict with the purpose of the optimization process. As seen earlier, with respect to the fuel-optimized trajectory, the optimization process suggests the deployment of a very steep FPA for the segment 2 accompanied by a large engine TET, followed by a rather gentle-sloped segment 3 with a rather low value of engine TET. However, regarding the NOx-optimized trajectory, a rather smooth combination of FPAs and climb rates is suggested for both segments 2 and 3. Both means achieve more or less the same result of climbing 1500m within a total horizontal distance of approximately 5km. However, with respect to the fuel-optimized trajectory, most of the work takes place within segment 2, while segment 3 is a very gentle-sloped 'finishing-touch' to the aforementioned climb having a rather low engine TET. The exact opposite behavior is observed for the NOx-optimized trajectory where most of the work is carried out within segment 3 where the engine has to work harder with an increased TET being approximately 1368 K. However, as previously shown, the overall result is the diminished overall NOx production for the NOx-optimized mission profile

Regarding segments 4 and 5 it can be seen that the percentage differences in produced emissions are rather low. This is because of the resemblance of the 2 optimized trajectories within these segments, observed previously in Fig. 4. This behavior is due to the optimization process trying to keep the lowest possible fuel consumption in the NOx-optimized trajectory as well.

CONCLUSIONS

In the current study an integrated tool has been developed capable of evaluating the required operational resources for any user-defined helicopter mission profile as well as assessing the associated environmental impact of the helicopter operation within the defined trajectory. A simplified case study regarding a commercial helicopter climb profile from ground to cruise altitude has been defined for the purpose of assessing the potential and the limitations of the developed integrated tool. The objective has been met with the application of a specific optimization strategy. The optimal flight paths for minimum fuel consumption and overall NOx emissions respectively have been acquired and a comparative evaluation regarding their overall environmental impact has been waged. The main conclusions that can be drawn can be summarized as follows:

- The calculated percentage difference in fuel consumption between a mission profile optimized for minimum fuel burn and one for minimum NOx emissions is of the order of 2.61% for the presented simplified case study.
- The predicted percentage difference in overall NOx emissions production between trajectories optimized for minimum fuel burn and minimum NOx emissions respectively can reach approximately a value of 7.46%. The associated operational time penalty when operating for minimum NOx emissions is of the order of 1.72%.
- When optimizing for minimum overall NOx emissions the optimization process will try to also minimize the overall fuel consumption due to the direct connection between those two quantities. Therefore the acquired optimal trajectories might resemble one another. However, flight conditions imposing increased engine shaft power settings leading to high combustor primary zone temperatures will be penalized.
- When optimizing for total fuel consumption, the two main contradicting factors to take into account are the engine fuel flow, and the total operational time. Therefore the most efficient compromise between these two properties has to be acquired for every flight segment. This is achieved by establishing the optimal engine operating point that will achieve sufficient engine shaft power ensuring a rather low operational time at satisfyingly low values of engine fuel flow
- The main factor affecting the formation of pollutants leaving the engine exhaust in a state of chemical equilibrium is the overall engine efficiency. Hence it is reasonable to say that a flight path optimized for total fuel consumption will also be accompanied by minimized CO2 and H2O pollutant formation.

This work illustrates the initial steps of a methodology developed for the purpose of performing helicopter mission analysis and acquiring the optimal flight paths for any given helicopter configuration under any user-defined operational or environmental constraints. Throughout the progress of this work it has been assessed that further refinement regarding the developed integrated tool is necessary. The process of obtaining higher fidelity geometrical data with regards to a generic medium utility helicopter engine combustor is already a work in progress. Thus the accuracy in the calculation of the various combustion zones residence times can be enhanced and the emission indices prediction significantly improved. The application of the aforementioned methodology using engine models corresponding to different engines, though belonging in the same class, is also considered. Thus the effect of the engine selection on the acquired optimal flight paths can be evaluated and the respective reduction in fuel consumption and emissions quantified. The simulation of higher fidelity mission profiles is also a future plan. By incorporating a larger number of segments, higher resolution trajectories can be obtained and greater accuracy levels in the calculations established.

ACKNOWLEDGMENTS

The authors would like to acknowledge Professor Pericles Pilidis and Dr. Vishal Sethi, from the department of Power & Propulsion of Cranfield University for their insightful advice and their continuing support. Thanks are also due to Mr. Cesar Celis from the department of Power & Propulsion (Cranfield University) for his valuable contribution and technical support.

NOMENCLATURE

Alt = Altitude
ATC = Air Traffic Control
CO2 = Carbon Dioxide
EI = Emission Index (indices)
PW = Shaft Power
FPA = Flight Path Angle
H2O = Water (vapor)
NOX = Oxides of Nitrogen
TET = Turbine Entry Temperature
No. = Number
D = Percentage Difference
R = Range
SAE = Self Adaptive Evolution
SQP = Sequential Quadratic Programming
d = Step Length
x = design variable
S = random search direction

Subscripts

m = member
i = direction
p = parent index
k = generation number
req = required

REFERENCES

1) Clarke, J. P., 2003, "The Role of Advanced Air Traffic Management in Reducing the Impact of Aircraft Noise and Enabling Aviation Growth", Journal of Air Transport Management, 9(3), pp. 161-165.
2) Brooker, P., 2006, "Civil Aircraft Design Priorities: Air Quality? Climate Change? Noise?, The Aeronautical Journal, 110(1110), pp. 517-532.
3) Clean Sky JTI (Joint Technology Initiative) home page: http://www.cleansky.eu.
4) Palmer, J. R., 1990, "The TURBOMATCH Scheme For Aero/Industrial Gas Turbine Engine Design Point/Off Design Performance Calculation," SME, Thermal Power Group, Cranfield University
5) Celis, C., Moss, B., and Pilidis, P., 2009, Emissions Modelling for the Optimisation of Greener Aircraft Operations, Proceedings of GT2009, ASME Turbo Expo 2009, Power for Land, Sea and Air, Orlando, Florida, US.
6) H.-P.Schwefel, Numerical Optimization of Computer Models, John Wiley & Sons, Chicester, New York, 1981.
7) Stoer J. (1985): Foundations of recursive quadratic programming methods for solving nonlinear programs, in: Computational Mathematical Programming, K. Schittkowski, ed., NATO ASI Series, Series F: Computer and Systems Sciences, Vol. 15, Springer.
8) Panos Y. Papalambros and Douglas J. Wilde: *Principles of Optimal Design,* Cambridge University Press.
9) Schittkowski K.: On the convergence of a sequential quadratic programming method with an augmented Lagrangian search direction, Optimization, Vol. 14, 197-216, 1983.
10) Cesar Celis, Richard Long, Vishal Sethi, David Zammit-Mangion, 2009, On Trajectory Optimization for Reducing the Impact of Commercial Aircraft Operations on the Environment, 19th ISABE Conference, ISABE-2009-1118, Montreal, Canada.
11) NOESIS SOLUTIONS, November 2008, OPTIMUS REV 8- Manual, User's Guide, LEUVEN, Belgium
12) NOESIS SOLUTIONS, November 2008, OPTIMUS Theoritical Backround, LEUVEN, Belgium
13) The Jet Engine, Rolls-Royce, 5th edition, 2005
14) Chen, R.T.N., Zhao,Y., Optimal trajectories for the helicopter in One-Engine-Inoperative terminal-area operation, AGARD/CP-592
15) Gill P.E., Murray W., Wright M.H.: *Practical Optimization*, Academic Press, 1981
16) Cooke, A. and Fitzpatrick, E.(2002), Helicopter Test and Evaluation, Blackwell Publishing, Oxford, UK
17) Fletcher, R., 1987, Practical Methods of Optimization, 2nd Edition, John Wiley, Chichester, UK
18) Rogero, J. M., 2003, JGA Optimisation Toolbox Documentation, User's Guide, Cranfield University, Cranfield, UK
19) Young, C.(1978), A User's Guide to Some Computer Programs for Predicting Helicopter and Rotor Performance, Technical Memo/Structures 924, RAE, May 1978
20) Leishmann, J.G.(2000), Principles of helicopter aerodynamics, Cambridge University Press, UK
21) Filippone, A. (2004), Flight Performance of Fixed and Rotary Wing Aircraft, Elsevier, Oxford, UK
22) Ogaji, S.O.T., Pilidis, P., and Sethi, V., 2008, Advanced Power Plant Selection: The TERA Techno-economic Environmental Risk Analysis) Framework, 19th ISABE Conference, ISABE-2009-1115, Montreal, Canada.
23) Lefebvre, A. H. and M. V. Herbert, Heat-Transfer Processes in Gas Turbine Combustion Chambers, Proc. Inst. Mech. Engrs. Vol. 174, No. 12, 463-473, 1960
24) Seddon, J.(1990), Basic Helicopter Aerodynamics, AIAA, USA
25) Walsh P.P., Fletcher P. (2004). Gas Turbine Performance – 2nd edition, Blackwell Science, Oxford
26) Clarke, J. S. and S. and H. E Lardge, Performance and Reliability of Gas Turbine Combustion Chambers, Canadian Aircraft Industry, Vol. 2, 1958
27) Walsh P.P., Fletcher P. (2004). Gas Turbine Performance – 2nd edition, Blackwell Science, Oxford

2010-12-22

Simulation framework development for helicopter mission analysis

Goulos, Ioannis

American Society of Mechanical Engineers (ASME)