# A SIMULATION MODEL FOR FLIGHT PERFORMANCE ANALYSIS OF HELICOPTER MID-LIFE UPGRADE DESIGNS

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## Abstract

*In this paper the development and evaluation of a software program that models and predicts the flight performance of upgrade design configurations is presented. The mathematical model is based on data input (operational, helicopter, mission systems) to predict and simulate the flight performance so to evaluate the performance and operating limits of the new upgrade design.*

*The assessment of flight performance by the simulation model is primarily based on momentum theory and other existing methodologies. This paper discusses the design of the software and presents a case study utilising an example helicopter to assess the performance of the simulation model.*

## Nomenclature

$A_i$ = component frontal area
$\alpha$ = rotor shaft tilt angle
$c$ = average blade chord
$c_d$ = fuselage drag coefficient
$c_{d0}$ = main rotor blade drag coefficient
est. = estimate
$h$ = altitude
hp = horse power
$k$ = induced power parameter
$\Omega$ = rotational speed
$P$ = power
$Q_{perc}$ = torque percentage
$R$ = radius
$s$ = vertical drag area
$T_{env}$ = environmental temperature
$V$ = velocity
$W_g$ = gross weight
$z$ = main rotor height

Subscripts
$A$ = available
$\max$ = maximum
$MR$ = main rotor
$SL$ = sea level
$sound$ = sound
$Tip$ = tip
$TR$ = tail rotor

## Introduction

To meet the demands of enhanced mission capabilities; mid-life upgrade of in-service aircraft is a cost-efficient option. The upgrade of the aircraft involves updating onboard mission systems to meet new mission requirements.

A software-based "Integrated Decision Support System" (IDSS) (Figure 1) that provides an automated analysis of mid-life upgrade process was developed by Sinha et al [1-3]. Capability enhancement through the IDSS provides decision support to formulate an optimum implementation strategy for a successful mid-life upgrade program. Flight performance evaluation is a critical part of this multi parameter-based design analysis and plays key role in the mid-life upgrade design process.

The development and evaluation of software that models and predicts the flight performance is required for the multi-parameter design analysis. The mathematical model, on which the software is based, will need data inputs (operational, helicopter, mission systems) to predict and simulate the flight performance for the evaluation of the performance and operating limits of the new upgrade design. In this paper the "Flight Performance Analysis and Simulation Model" is discussed (Figure 2).

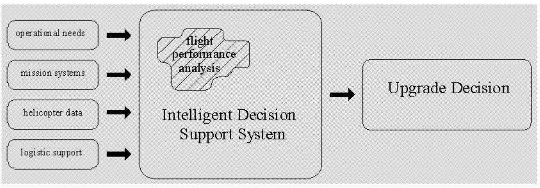


**Figure 1. Mid-life Upgrade System**

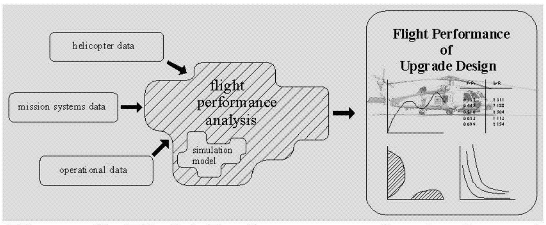


**Figure 2. Flight Performance Analysis and Simulation Model**

The assessment of flight performance by the simulation model is based on existing flight performance evaluation methodologies [4-7], in particular the momentum theory which models the rotor as an actuator disc.

<u>Flight Performance Simulation Software</u>

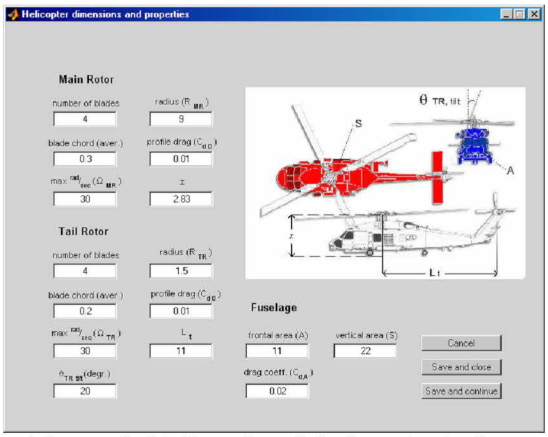
The power equations resulting from the application of momentum theory to model helicopter performance constitute the basis of the helicopter flight performance software. The simulation software was developed in MATLAB as it is a powerful engineering development tool with a comprehensive array of built-in mathematical and engineering algorithms, toolboxes and functions.

The flight performance software consists of three main sections as follows. a) Pre Processing, where parameters are defined, units are set and the required data and values are entered, b) Analysis, where the helicopter flight performance is calculated and c) Results, where the analysis outcomes are displayed and stored.

The following is an overview of the main component of the pre processor:

- <u>Units:</u> Units for geometry, altitude, velocity, mass, power and distance can be set by the unit selection menu, thereby allowing users to work in their preferred units.

- <u>Helicopter data</u>: The helicopter data required for performance evaluation is provided by the user. This includes airframe and rotor geometry, drag coefficients and the maximum rotational speed of the rotors. The input of data is via the helicopter property window (Figure 3)


Helicopter dimensions and properties

Main Rotor
number of blades: 4
radius ($R_{MR}$): 9
blade chord (aver.): 0.3
profile drag ($C_{d0}$): 0.01
max $^{rad}/_{sec}$ ($\Omega_{MR}$): 30
z: 2.83

Tail Rotor
number of blades: 4
radius ($R_{TR}$): 1.5
blade chord (aver.): 0.2
profile drag ($C_{d0}$): 0.01
max $^{rad}/_{sec}$ ($\Omega_{TR}$): 30
$L_t$: 11
$\theta_{TR\ tilt}$ (degr.): 20

Fuselage
frontal area (A): 11
vertical area (S): 22
drag coeff. ($C_{dA}$): 0.02

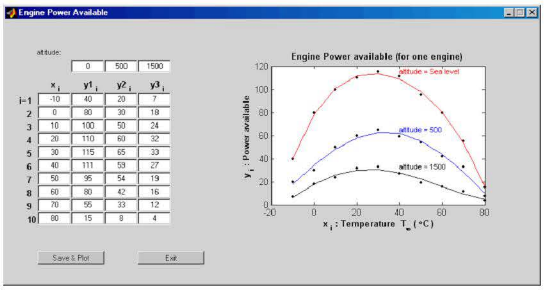
**Figure 3. Helicopter data input window**

- <u>Engine data:</u> In the engine property window the engine data is entered including the number of engines. The software only supports multi-engine helicopters with identical engines. The important engine properties of available power and fuel consumption are entered separately.

- <u>Available Power</u>: Temperature and altitude both influence the density of the air. Air density exerts great influence on engine performance thus on power available. Data regarding available power is often given by engine manufacturers in the form of performance diagrams. These diagrams display the power that the engine is able to generate at a certain environmental temperature, for a range of altitudes.

  The simulation software requires the user to input ten data points obtained from original engine performance diagrams for three different combinations of temperature and altitude (Figure 4).

Based on this input the simulation software interpolates using a fourth order polynomial to reconstruct the original performance curves. Based on the power available for three different combinations of altitude and temperature, the software further interpolates to determine the effect of temperature and altitude. These interpolated engine performance diagrams are then used in the evaluation of flight performance.

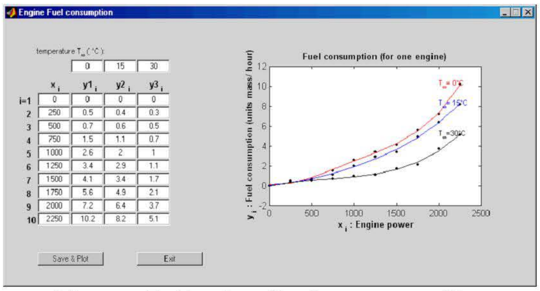


altitude: 0 500 1500

|  | $x_i$ | $y1_i$ | $y2_i$ | $y3_i$ |
|---|---|---|---|---|
| i=1 | -10 | 40 | 20 | 7 |
| 2 | 0 | 80 | 30 | 18 |
| 3 | 10 | 100 | 50 | 24 |
| 4 | 20 | 110 | 60 | 32 |
| 5 | 30 | 115 | 65 | 33 |
| 6 | 40 | 111 | 59 | 27 |
| 7 | 50 | 95 | 54 | 19 |
| 8 | 60 | 80 | 42 | 16 |
| 9 | 70 | 55 | 33 | 12 |
| 10 | 80 | 15 | 8 | 4 |

**Figure 4. Engine power available window**

- Engine Fuel Consumption: This is commonly expressed as 'specific fuel consumption' (SFC), which is the amount of fuel (in units of mass) per unit power per unit time. This is an average rate of fuel consumption, based on certain engine operating characteristics. The simulation software is able to interpolate SFC for any given operating characteristics from data input by the user. (Figure 5).



temperature $T_\infty$ (°C): 0 15 30

|  | $x_i$ | $y1_i$ | $y2_i$ | $y3_i$ |
|---|---|---|---|---|
| i=1 | 0 | 0 | 0 | 0 |
| 2 | 250 | 0.5 | 0.4 | 0.3 |
| 3 | 500 | 0.7 | 0.6 | 0.5 |
| 4 | 750 | 1.5 | 1.1 | 0.7 |
| 5 | 1000 | 2.6 | 2 | 1 |
| 6 | 1250 | 3.4 | 2.9 | 1.1 |
| 7 | 1500 | 4.1 | 3.4 | 1.7 |
| 8 | 1750 | 5.6 | 4.9 | 2.1 |
| 9 | 2000 | 7.2 | 6.4 | 3.7 |
| 10 | 2250 | 10.2 | 8.2 | 5.1 |

**Figure 5. Engine fuel consumption window**

Similar to the method used to interpolate available engine power, the user needs to input ten pairs of data points, representing the amount of fuel (unit mass/hour) the engine combusts for generating a certain amount of power at three ambient temperatures. A polynomial function is then introduced to these data sets and from these the SFC at any operating condition is interpolated.

- Mission Systems: The software defines a mission system as any load (device, crewmember, cargo) that the aircraft carries onboard in order to accomplish the mission objective. The performance analysis software allows the user to add mission systems to the aircraft in order to analyse and compare the flight performance of different upgrade configurations. The system has a built in database of state-of-the-art mission systems, that the user can select.

- Mission Flight Path: The flight path or mission to be analysed is entered into the 'waypoint editor' of the flight performance software. For each waypoint the coordinates, altitude and the type of manoeuvre (hover, land, take off, cruise) are required. Changes in mission system configuration can also be entered. This enables the simulation model to simulate “real life” missions so that the suitability of different upgrade configurations can be quickly analysed

Following the user input of the required information into the pre-processor the simulation model then performs the analysis. The performance analysis is based on existing flight performance evaluation methodologies [4-7], in particular momentum theory which models the rotor as an actuator disc. The software offers two different types of analysis as follows. a) General performance analysis which calculates the performance limits of the aircraft based on a specific configuration; or b) Mission performance analysis, which is calculated based on the mission's flight path, manoeuvres and the helicopter configuration. For this analysis, the variation in gross weight during the mission, fuel consumption and the development of the power required during flight are taken into account. The mission performance can be calculated for maximum flight speed (minimum mission time) or for minimum fuel consumption.

Finally the results of the performance analysis are expressed in diagrams and tables, which can be viewed, stored and printed by the user. To illustrate the results of an analysis is presented in Figure 6.

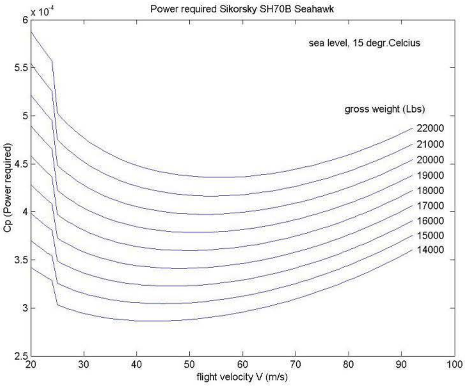


**Figure 6. An example result diagram, generated by the flight performance simulation software: Power required coefficient for flight velocities up to 92 m/s**

Evaluation of Results: A Case Study

The simulation model relies primarily on momentum theory to calculate the flight performance of an upgrade design configuration. In order to evaluate the results of such analysis a case study was undertaken using the performance simulation model to calculate the climb rate of an example helicopter.

This case study required the simulation model to calculate the climb rate at sea level and 15°C for a range of gross weights. The available engine power was determined from the example helicopter flight manual. However, the flight manual gives available power in units of 'indicated torque percentage' (Figure 7) which is linearly related to available power. From the 'Engine power, indicated torque diagram' (Figure 8) this relationship between power *P* and torque percentage $Q_{perc}$ was determined as:

$$P \approx \frac{12}{85} Q_{perc} \qquad \text{Eqn 1}$$

Ten data points which defined the available engine power at sea level were entered into the simulation softwares pre- processor (Figure 9). The simulation then interpolated from this the function defining engine performance function as:

$$P_A = -0.2T_{env}^{\;2} - 1.6T_{env} + 1742.6 \qquad \text{Eqn 2}$$

For $T_{env} = 15^{\circ}C$ at sea level the simulation model calculates the available power as 1673.6hp.

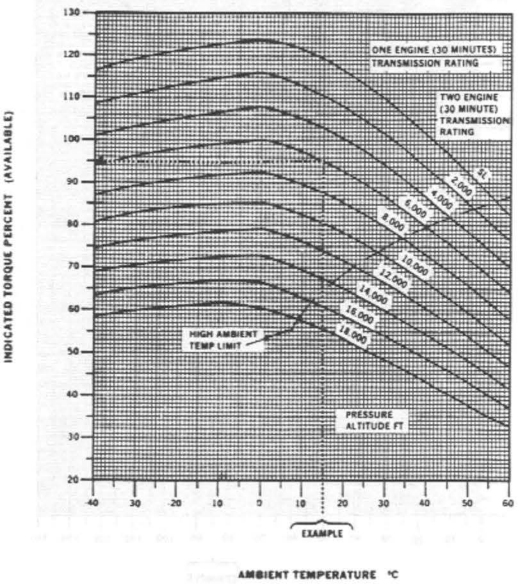


**Figure 7. Indicated torque, ambient temperature diagram from the example helicopter flight manual**

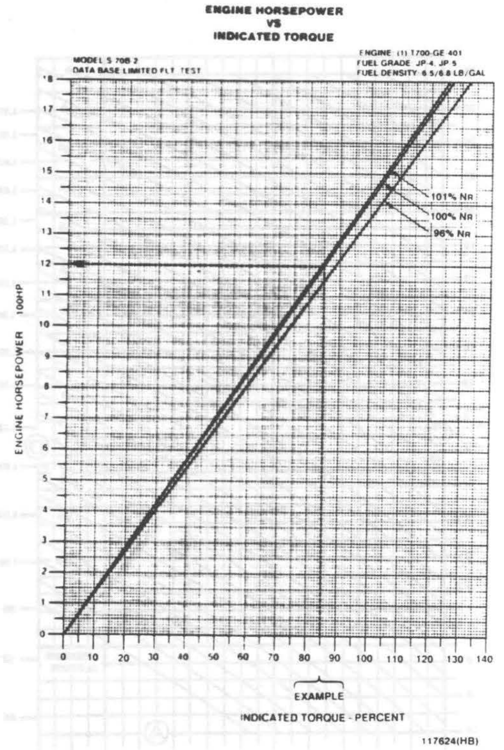
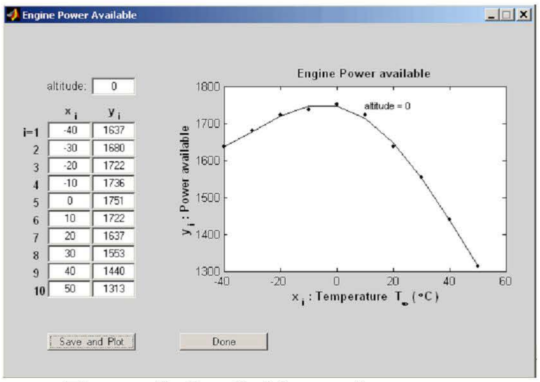


**Figure 8. Engine power, indicated torque diagram from the example helicopter flight manual**



altitude: 0

| i | $x_i$ | $y_i$ |
|---|---|---|
| i=1 | -40 | 1637 |
| 2 | -30 | 1680 |
| 3 | -20 | 1722 |
| 4 | -10 | 1736 |
| 5 | 0 | 1751 |
| 6 | 10 | 1722 |
| 7 | 20 | 1637 |
| 8 | 30 | 1553 |
| 9 | 40 | 1440 |
| 10 | 50 | 1313 |

Figure 9. Available engine power interpolation

The climb rate is directly related to the excess power of the helicopter, which itself is defined as the available power minus the power required. The maximum excess power is achieved when the helicopter is flying at the speed for minimum power. The simulation model analyses the power required for a range of flight speeds, at any given altitude, and based upon these results the speed for maximum excess power is evaluated. The following conditions and parameters are those used for modelling the example helicopter climb rate:

Conditions

Altitude *h:* sea level
Speed *V* : 2 to 92 ms$^{-1}$
Gross Weight $W_g$: 14000 to 22000 lbs

Input parameters

$\alpha = 10^\circ$ (est.)
$z = 5.23m$
$c_{d0} = 0.01$ (est. from Johnson [7])
$c_d = 0.05$ (est. from Johnson [7])
$c_{MR} = 0.30m$ (est.)
$c_{TR} = 0.20m$ (est.))
$k_{MR} = k_{TR} = 1.15$ (est. from Johnson [7] )
$R_{MR} = 1.675m$
$R_{MR} = 8.175m$
$s = 15m^2$ (est.)
$\sum A_i = 12m^2$ (est.)
$\Omega = 30 rad.s^{-1}$ (est. see derivation)

Derivation of $\Omega$

$$V_{\max, SL} = 92m.s^{-1}$$

$$V_{sound,SL} \approx 343m.s^{-1}$$

$$V_{tip} = V_{sound,SL} - V_{\max,SL} = 251m.s^{-1}$$

$$\Omega = V_{tip} \times R_{MR} \approx 30 rad.s^{-1}$$

The results of the climb rate analysis by the simulation model and the published climb rates of the example helicopter are presented in Table 1 and Figure 10.

**Table 1. Comparison of calculated and published climb rates of the example helicopter.**

| *Sea Level* | *Power available = 1673.6hp* | |
|---|---|---|
| $W_G$ (lbs) | Calculated Climb rate (ft per min) | Published Climb Rate (ft per min) |
| 14000 | 2384.602 | 2850 |
| 15000 | 2023.272 | 2650 |
| 16000 | 1705.127 | 2500 |
| 17000 | 1422.836 | 2300 |
| 18000 | 1170.238 | 2150 |
| 19000 | 942.8214 | 1950 |
| 20000 | 736.7578 | 1800 |
| 21000 | 549.1252 | 1700 |
| 22000 | 377.2738 | 1280 |

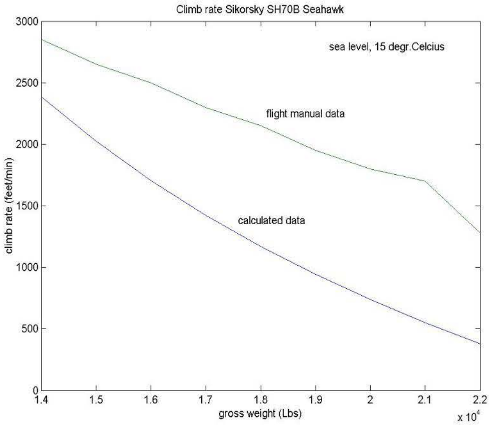


Figure 10. Comparison of calculated and published climb rates of the example helicopter.

## Discussion of Case Study Results

The results presented in Table 1 and Figure 10 show a significant difference between the actual published climb rate of the example helicopter and that calculated by the simulation model. However, the shape of the climb rate curve for both the published and calculated climb rate are approximately the same.

Since the simulation model is primarily based on momentum theory, it would be expected that the assumptions associated with momentum theory would be responsible for this discrepancy. Momentum theory models the rotor as an actuator disc which is 'ideal', hence it under-estimates the power loss of the rotor. Based on this it would be expected that the simulation model would over-predict the climb rate, and not under-predict as is the case with the results. It is therefore likely that the discrepancy between calculated and actual climb rates is based on other assumptions.

The climb rate is directly related to the excess power of the helicopter, which itself is defined as the available power minus the power required. Therefore it is likely that the simulation model is either under-estimating the available power or over-estimating the required power. Since the simulation model interpolates the available power from the published flight manual, a small discrepancy is expected but not to the extent shown in the results. Therefore it is likely that the discrepancies result from the calculation of the power required.

In calculating the climb rate the simulation models the required power as a function of induced rotor power, rotor profile power and parasite power. The value of each of these components being calculated from the input parameters used in the case study. However at the time of the case study, the actual or real values of many of the parameter was not known and had to be estimated (with assumptions). Therefore it is most likely that the significant discrepancy between actual and calculated rates of climb is due to any combination of the estimations.

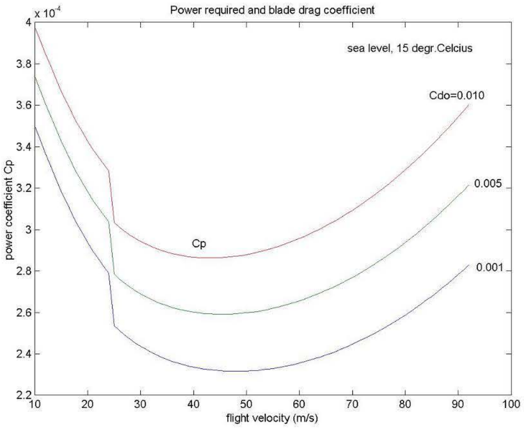


**Figure 11. Power required coefficient for different values of blade drag coefficient.**

The effect of inconsistency between real and estimated input parameters is shown in Figure 11 and Figure 12 which contrast the power required coefficient for different values of blade and fuselage drag

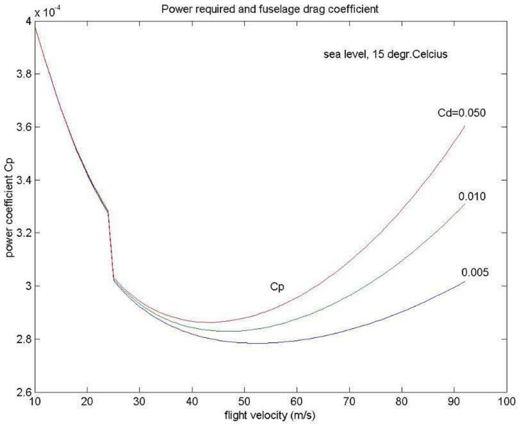


**Figure 12. Power required coefficient for different values of fuselage drag coefficient.**

## Concluding Remarks

A software simulation model for the flight performance analysis of helicopters has been developed. The mathematical model, on which the software is based, requires user inputs regarding helicopter specifications, operational environment and mission systems. The assessment of helicopter flight performance by the simulation model is based on existing helicopter performance evaluation methodologies [4-7], in particular the momentum theory which models the rotor as an actuator disc.

The performance of the simulation model was evaluated using a case study which examined the helicopters climb rate. This study was based on an example helicopter and utilised published data and specifications. The results of this case study (Figure 10 and Table 1) demonstrate that the simulation model significantly under evaluated the climb rate of the example helicopter. However, examination of the performance analysis suggests that the significant difference in results is due to the inaccurate helicopter specifications used in the evaluation. Therefore no conclusions can be made regarding the performance of the simulation model without further testing that utilises accurate helicopter specifications.

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