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# AN ATMOSPHERIC TURBULENCE MODEL FOR THE PUMA SA 330 HELICOPTER

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*Testing robustness and disturbance rejection properties of complex automatic flight control algorithms designed for aircraft flying in calm atmospheric conditions, means verifying their behaviour in the actual atmosphere, thus modelling atmospheric turbulence becomes necessary. The present paper gives a mathematical solution that makes use of existing gust models for specific helicopters, derived from real flight test data, permitting the development of similar models for other types of helicopters.*

**Keywords**: helicopter, automatic flight control system (AFCS), turbulence modelling, CETI, EC 135, Puma.

## 1. Introduction

Aircraft, and implicitly, automatic flight control systems (AFCS) design considers only the calm atmosphere, i.e. conditions described by the International Standard Atmosphere (ISA). Therefore, in order to properly evaluate the performances of the designed object, one must test its behaviour in more realistic atmospheric conditions, either in flight or through simulations, the latter being more common for initial phases of design. Since the mathematics that describe atmospheric phenomena are very challenging and also imprecise, the use of turbulence models is generally considered sufficient.

Turbulence is due to convection, windshear or clear air turbulence (CAT) [1], special cases being the wake vortices and turbulence generated by ground obstacles, natural or man-made; with regard to intensity, turbulence may be categorised as light, medium, severe and extreme [2]. Turbulence is characterised by large variations of atmospheric parameters (such as pressure, density, velocity, etc.) in a structured local flow, but part of a pseudo-random global flow [3]. The effect that turbulence has on an aircraft depends on its construction type (aeroplane, helicopter, etc.) and on the dimensions of lifting surfaces (wing length, respectively rotor diameter). Hence, the aerodynamic forces and moments

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generated by each surface of the aircraft deviate from the steady-state values in a pseudo-random manner, turbulence affecting the entire dynamics of the aircraft.

The following section of the paper will briefly present the classical turbulence models, followed by the Control Equivalent Turbulence Input (CETI) models, much more convenient in the helicopter case; then, based on a methodology which allows for scaling an existing helicopter model, to another *same type* of helicopter, a *new* methodology will be derived that allows that scaling to take place for *different* types of helicopters. The existing model is the one developed for the EC 135 helicopter by DLR, and the study-helicopter is the Puma SA 330.

## 2. Classical modelling of atmospheric turbulence

The traditional method of evaluating aircraft behaviour in turbulent conditions relies on statistical mathematical models such as the von Karman (*"Progress in the Statistical Theory of Turbulence*"[3]) and Dryden (*"A Review of the Statistical Theory of Turbulence"*[4]) models, these two models representing the base for the widely used statdards *MIL-SPEC F-8785B* [4], respectivelly *MIL-STD-1797A* [5]. The turbulence derived using these two models depends on the height and speed of the aircraft.

These two models have produced excellent results, especially for fixed wing aircraft, but, as shown in [6], they are not truly suited for helicopter simulation and testing. Piloted helicopter flight tests have proven the lack of realism when simulating turbulent flights using the classical models, this being due to the different characteristics of the helicopter compared to the aeroplane, and to the differences in flight parameters, such as much lower speeds and hights, these flights taking place mainly in the lowest layer of the troposphere, i.e. the friction layer, where turbulent phenomena are quite common. Also, another characteristic of the helicopter flight is the low speed ($< 20kts \approx 10m/s$) and hover near obstacles; in these cases the classical models are not useful, since the flow of the air loses its statistical properties [3].

Considering all the above, it was considered that it the aforementioned CETI model, developed specifically for helicopters, is much more appropriate for testing helicopter AFCSs, as demostrated in [7], [8], [9], [10].

[3] von Karman, Theodore, "Progress in the Statistical Theory of Turbulence," Turbulence – Classic Papers on Statistical Theory, New York: Interscience Publishers, Inc., 1961

[4] Dryden, Hugh L., "A Review of the Statistical Theory of Turbulence," Turbulence – Classic Papers on Statistical Theory, New York: Interscience Publishers, Inc., 1961

## 3. The CETI method

This method was introduced in [11], respectivelly [12] bearing a similarity to the Dryden and von Karman models in the use of linear filters that transform white noise into perturbation signals; unlike the classical models, these filters do not modify the atmosphere surrounding the aircraft, i.e. the states of the aircraft, but their outputs are command signals that lead to the same response from the aircraft as the equivalent turbulence would produce. The disadvantages of this method are the impossibility to simulate gusts larger than the maximum range of controls, and that the filters are empirically derived or from flight test measurements – a method to initially tackle the latter problem being presented in this paper.

The general model is represented by the following transfer functions, presented in [9]:

$$\frac{\delta_{lon,gust}}{W_{noise}}(s) = K_{lon}\sigma_w^{x_1}\sqrt{\frac{U_0}{(\pi L_w)}}\cdot\frac{1}{\left(s+U_0/L_w\right)}\cdot f_2(s) \tag{1}$$

$$\frac{\delta_{lat,gust}}{W_{noise}}(s) = K_{lat}\sigma_w^{x_1}\sqrt{\frac{U_0}{(\pi L_w)}}\cdot\frac{1}{\left(s+U_0/L_w\right)}\cdot f_2(s) \tag{2}$$

$$\frac{\delta_{col,gust}}{W_{noise}}(s) = K_{col}\sigma_w^{z}\sqrt{\frac{3U_0}{(\pi L_w)}}\cdot\frac{\left(s+20\,U_0/L_w\right)}{\left(s+0.63\,U_0/L_w\right)\left(s+5\,U_0/L_w\right)}\cdot f_2(s) \tag{3}$$

$$\frac{\delta_{ped,gust}}{W_{noise}}(s) = K_{ped}\sigma_w^{x_2}\sqrt{\frac{U_0}{(\pi L_v)}}\cdot\frac{1}{\left(s+U_0/L_v\right)}\cdot f_2(s) \tag{4}$$

where:

- $W_{noise}$ - white noise input
- $\delta_{i,gust}$ - equivalent input on control $i$ due to gust (collective main rotor *MR*, longitudinal and lateral cyclic, collective tail rotor *TR*, i.e. pedals)
- $K_{col}, K_{lon}, K_{lat}$ and $K_{ped}$ - coefficients depending on characteristics such as rotor radius and blade inertia
- $U_0$ - flow field mean wind velocity
- $\sigma_w, \sigma_v$ - standard deviation in lateral and vertical directions
- $L_w$, $L_v$ - lateral and vertical characteristic lengths

- $f_2(s)$ - second-order low pass filter, legacy implementation from flight testing, preventing unwanted high-frequency commands to actuators.

Equations (1) - (3) represent the simulated responses in roll, pitch, and heave to a vertical velocity gust field impinging on the main rotor, whilst equation (4) represents the yaw response of the tail rotor response to a lateral velocity field. Parameters $K$ are derived empirically either from flight test measurements or from existing non-linear models of the helicopter.

As previously mentioned, the input to our study was the EC 135 [7], [13] CETI model valid for hover and low speed flights. The aim was to derive an equivalent model for the Puma SA 330 helicopter, in order to test the disturbance rejection properties of an AFCS designed for the subject helicopter[5], *without the need* of costly flight tests. It is also worth mentioning that although in the literature there are cases of direct use of the EC 135 model for testing an AFCS developed for another type of helicopter (e.g. R44) [14], the authors considered that in support of scientific accuracy, the use of a model specific to the study-helicopter is better suited.

The filters developed by the DLR team are similar to those described by equations (1)-(4):

$$\frac{\delta_{lon,gust}}{W_{noise}}(s) = A_{lon}\frac{1}{\left(s+U_0/L_w\right)} \tag{5}$$

$$\frac{\delta_{lat,gust}}{W_{noise}}(s) = A_{lat}\frac{1}{\left(s+U_0/L_w\right)} \tag{6}$$

$$\frac{\delta_{ped,gust}}{W_{noise}}(s) = A_{ped}\frac{1}{\left(s+U_0/L_v\right)} \tag{7}$$

$$\frac{\delta_{col,gust}}{W_{noise}}(s) = A_{col}\frac{\left(s+20\,U_0/L_w\right)}{\left(s+0.63\,U_0/L_w\right)\left(s+5\,U_0/L_w\right)} \tag{8}$$

where the values corresponding to parameters $A_i$ (gust amplitude), and $U_0/L_w$, respectively $U_0/L_v$ depend on the intensity of the turbulence.

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[5] The AFCS methods of design represent the topic of the first author's PhD thesis.

## 4. Scaling the initial model

Paper [15] presents an approximate method for scaling the equivalent turbulence induced transfer functions from one helicopter to another. Even though this method provides only a simplified solution to the problem, this solution is well suited to flight control system initial design, and especially for verifying its disturbance rejection properties (conclusion 6 in [15]).

It is important to highlight that the resulting model is valid for flights in the very same conditions, i.e. same gust field, as those for which the initial model was identified.

Also, a key point for our study is based on conclusion 5 of [15]: the scaling is possible only for aircraft having *similar configurations*, namely if the initial helicopter is main rotor and *shrouded* tail rotor, as is the case for the EC 135, that the scaled model will be realistic only for a similar type of helicopter. This is not the case for the Puma SA 330 [13] which is a *open* tail rotor helicopter. Therefore we propose in the following section a methodology that permits deriving *equivalent open rotor* characteristics for the *fenestron* (shrouded tail rotor), in order to employ these characteristics in the scaling functions from [15].

## 5. Deriving equivalent antitorque rotor characteristics

The formulae that allow the scaling of the initial EC 135 gust control equivalent transfer functions into those corresponding to the study-helicopter, use four physical aircraft parameters, namely: main and tail rotor diameter (radius) and their respective angular velocities; hence, the two parameters that need to be equivalated are the radius and angular velocity for the tail rotor.

The following hypotheses have been employed:

1. The real and the equivalent antitorque rotors use equal amounts of power;
2. The real and the equivalent antitorque rotors produce equal thrust forces.

*Note:*
*Shrouded tail rotors are always characterised by a smaller diameter, but a higher number of blades when compared to open tail rotors. Since the equivalence of rotors is based on the actuator disc (Froude) theory, the number of blades has no importance in this calculations* [17].

3. Main rotor tip speed is equal to tail rotor tip speed.

Main rotor tip speed is a very important parameter in helicopter construction and design. In case of turbine helicopters, with blade number $N_b \geq 3$ it has a value of approximately $200\,m/s\left(\approx 700\,ft/s\right)$; this parameter has a very low margin, since a large value implies high Mach number, and subsequent blade compressibility problems, respectively a low value leads to high angles of attack, and possible loss of lift for certain blade azimuths [18].

The antitorque rotor is subject to the same aerodynamic limitations as the main rotor, operating in rougher conditions, i.e. wake of the main rotor, its blade having fewer degrees of freedom when compared to the main rotor blade (only pitch angle).

Taking into account the above considerations and data from Table 1, hypothesis 3 is considered justified.

*Table 1*

**Comparisons of different helicopter operating parameters**

| *Helicopter* | *PUMA SA 330* [16] | *Bo 105* [16] | *Agusta A 109E* [19] | *S-61 Sikorsky* [20], [21] | *Lynx XZ17* [22] |
|---|---|---|---|---|---|
| *Main rotor radius (m) =* $R_{MR}$ | 7.5 | 4.91 | 5.5 | 9.45 | 6.4 |
| *Tail rotor radius (m) =* $R_{TR}$ | 1.56 | 0.95 | 1 | 1.57 | 1.105 |
| *Main rotor angular velocity (rad/s) =* $\Omega_{MR}$ | 27.75 | 44.4 | 40.21 | 21.26 | 33.33 |
| *Tail rotor angular velocity (rad/s) =* $\Omega_{TR}$ | 133.94 | 232.5 | 218.34 | 130.27 | 193.1 |
| *Main rotor RPM(rpm) =* $NR_{MR}$ | 265 | 424 | 384 | 203 | 318 |
| *Tail rotor (rpm) =* $NR_{TR}$ | 1279 | 2220 | 2085 | 1244 | 1844 |
| *Main rotor tip speed (m/s) =* $V_{MR}$ | 208.13 | 218 | 221 | 200.86 | 213.36 |
| *Tail rotor tip speed (m/s) =* $V_{TR}$ | 208.94 | 220.85 | 218.34 | 205.15 | 213.36 |
| **$V_{MR}/V_{TR}$ (%)** | **99.61%** | **98.71%** | **101.29%** | **97.91%** | **100.00%** |

The method described in [17], and conditions from hypotheses 1 and 2 where used in order to find the equivalent radius and rotor angular speed values. Therefore, the ratio of the real shrouded rotor (*SR*) radius to the equivalent open rotor (*OR*) radius will be $\frac{R_{SR}}{R_{OR}} = \frac{1}{\sqrt{2\sigma_d}}$ where $\sigma_d$ stands for diffuser expansion ratio, effective value, after correction for blockage by rotor hub. Using the geometric value for the diffuser expansion ratio $\sigma_d^* \approx 1$ [17], a value of $\sigma_d = 1.27$ was determined, permitting the calculation of the equivalent open rotor values (Table 2).

*Table 2*

**Radius and angular speed for equivalent open rotor**

| *Helicopter* | $R_{MR}$ | $R_{TR}$ | $\Omega_{MR}$ | $\Omega_{TR}$ | $NR_{MR}$ | $NR_{TR}$ | $V_{MR}$ | $V_{TR}$ |
|---|---|---|---|---|---|---|---|---|
| EC 135 SR | 5.1 | 0.5 | 41.36 | 371.23 | 395 | 3545 | 210.96 | 185.62 |
| EC 135 OR | 5.1 | **0.8** | 41.36 | **264.73** | 395 | **2528** | 210.96 | **210.96** |

## 6. Gust filters for the Puma SA 330 helicopter

The initial model was that of the EC 135 for hover/low speed flight in heavy turbulence [13]:

$$\frac{\delta_{col,gust}}{W_{noise}}(s) = \frac{0.974\cdot(s+60)}{(s+1.89)(s+15)} \tag{9}$$

$$\frac{\delta_{lon,gust}}{W_{noise}}(s) = \frac{5.99}{s+3} \tag{10}$$

$$\frac{\delta_{lat,gust}}{W_{noise}}(s) = \frac{6.07}{s+3} \tag{11}$$

$$\frac{\delta_{ped,gust}}{W_{noise}}(s) = \frac{21.5}{s+7.28} \tag{12}$$

As previously stated, paper [15] gives a method for developing scaling transfer functions, which are then multiplied by the initial filters in order to obtain the final transfer functions for the study helicopter.

For the first three controls, i.e. main rotor collective, longitudinal and lateral cyclic, the general form of the scaling function is [15]:

$$H\left(s,R,U_0\right)=\frac{\left.\dfrac{\pi U_0/8R}{s+\pi U_0/8R}\right|_{final\_helicopter}}{\left.\dfrac{\pi U_0/8R}{s+\pi U_0/8R}\right|_{initial\_helicopter}}\cdot A_x \tag{13}$$

where $A_x$ is a parameter that depends on physical characteristics of each helicopter, such as radius and angular speed of main rotor; for $x=\delta_c$, main rotor collective:

$$A_{\delta_c}=\left.\left(R\Omega_{rot}\right)\right|_{initial\_helicopter} \Big/ \left.\left(R\Omega_{rot}\right)\right|_{final\_helicopter}$$

(14)

and for $x=\delta_B$, longitudinal cyclic, or $x=\delta_A$, lateral cyclic:

$$A_{\delta_B}=A_{\delta_A}=\left.\left(\Omega_{rot}\right)\right|_{initial\_helicopter} \Big/ \left.\left(\Omega_{rot}\right)\right|_{final\_helicopter} \tag{15}$$

For the last control, i.e. the antitorque rotor collective, the scaling transfer function is:

$$H(s)=\left.\left(R\Omega_{rot}\right)\right|_{initial\_helicopter} \Big/ \left.\left(R\Omega_{rot}\right)\right|_{final\_helicopter} \tag{16}$$

in this case the values for the radius and angular speed being the ones corresponding to the tail rotors.

Employing the above mentioned scaling functions, which were built according to the method from subsection 5, the following transfer functions for the study-helicopter were obtained:

$$\frac{\delta_{col,gust}}{W_{noise}}\left(s\right)=\frac{0.67132\left(s+60\right)\left(s+0.61\right)}{\left(s+1.89\right)\left(s+0.4148\right)\left(s+15\right)} \tag{17}$$

$$\frac{\delta_{lon,gust}}{W_{noise}}\left(s\right)=\frac{6.0714\left(s+0.61\right)}{\left(s+3\right)\left(s+0.4148\right)} \tag{18}$$

$$\frac{\delta_{lat,gust}}{W_{noise}}\left(s\right)=\frac{6.1525\left(s+0.61\right)}{\left(s+3\right)\left(s+0.4148\right)} \tag{19}$$

$$\frac{\delta_{ped,gust}}{W_{noise}}\left(s\right)=\frac{21.708}{s+7.28} \tag{20}$$

Figures 1 to 4 show the equivalent responses for the two helicopters, subjected to the same gust field, in control range percentages[6].

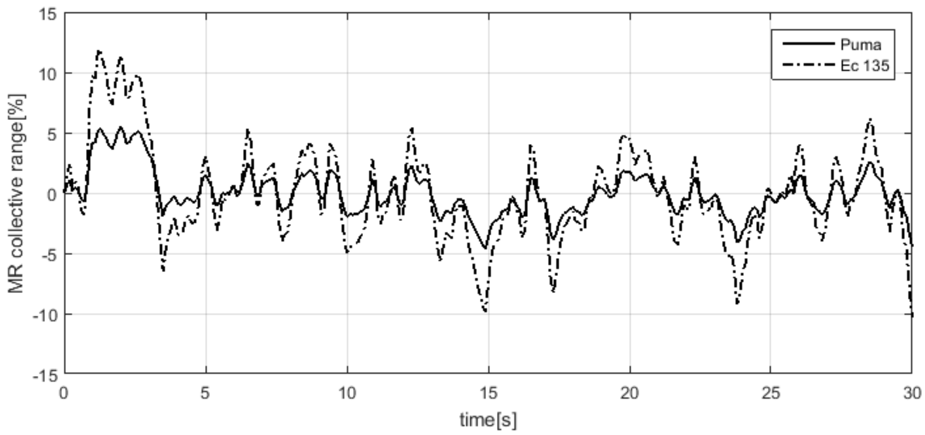


Fig. 1. Output of gust filters as collective inputs

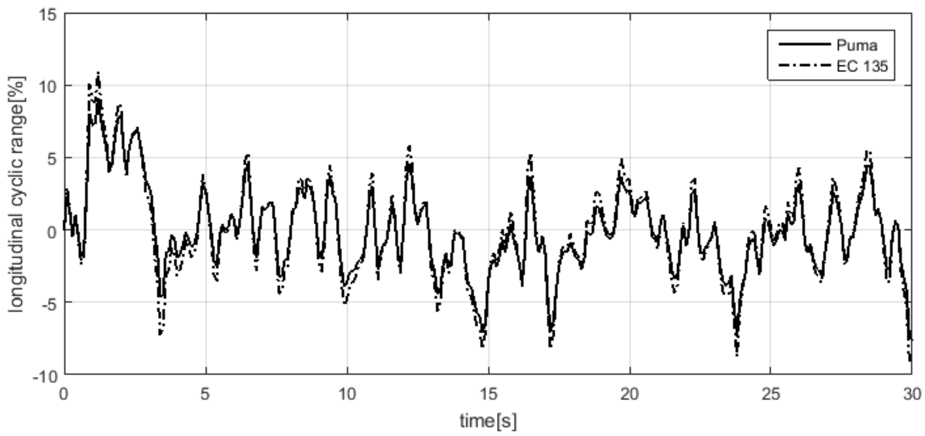


Fig. 2. Output of gust filters as longitudinal cyclic inputs

[6] Values for the control ranges are derived from [23], [24].

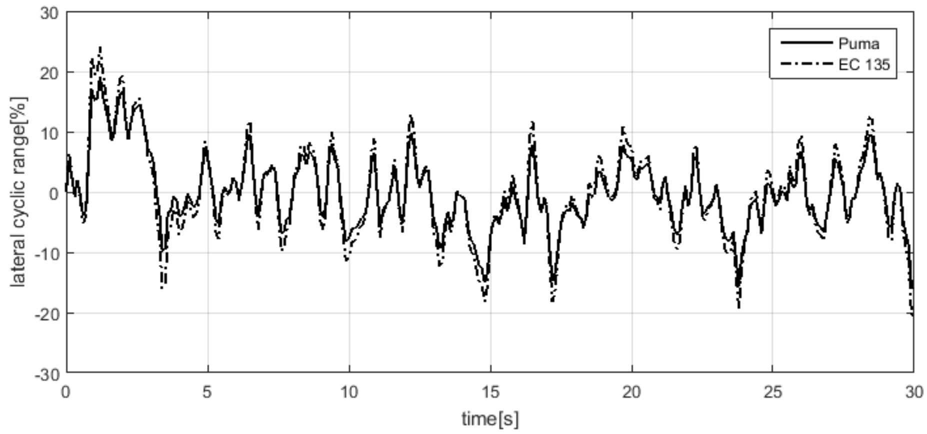


Fig. 3. Output of gust filters as lateral cyclic inputs

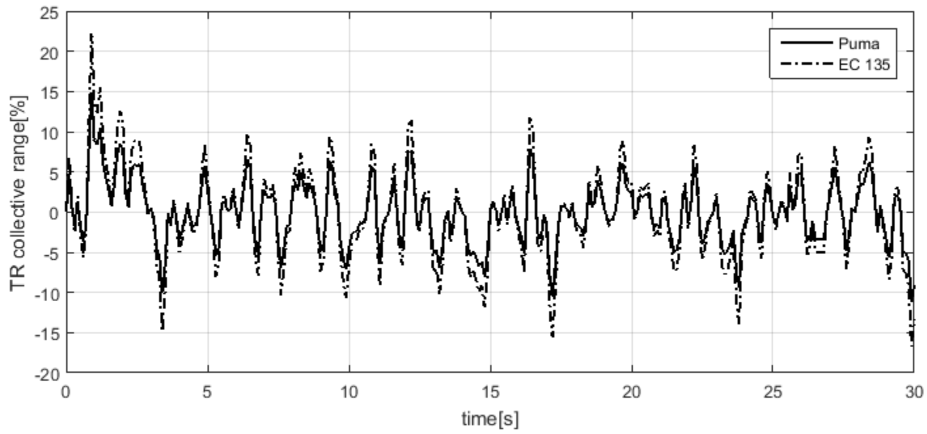


Fig. 4. Output of gust filters as antitorque rotor collective inputs

As expected, the heavier helicopter (Puma – class 7 tons) has a reduced response to the same gust field when compared to the lighter helicopter (EC 135 – class 2.5 tons). This difference is more obvious for the turbulence equivalent collective responses for main and tail rotors, figures 1 and 4; for the cyclic case, lateral and longitudinal, figures 2 and 3, the responses are quite similar due to similar blade loading for both helicopters [13].

## 7. Conclusions

The present paper presents a method for developing a CETI type gust model for the Puma SA 330 helicopter. It makes use of a numerical model for the EC 135 helicopter, derived from flight test data, and with the aid of an existing method for scaling the initial transfer functions, an original methodology was presented that allows equivalating between two different types of rotorcraft.

The result is a gust model specific to the study helicopter, developed without actual flight tests, appropriate for AFCS robustness and disturbance rejection testing.

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