Validation of a helicopter turbulence model on PUMA 330 dynamics

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Abstract: *Aircraft and algorithms used in automated flight control are always designed for calm atmospheric conditions; therefore, testing their behaviour in realistic atmospheric conditions implies the necessity for efficient turbulence models. The present paper tests the behaviour of a helicopter in turbulent atmospheric conditions, using two different, complex models and a mathematically derived CETI-type turbulence model, specific to the PUMA 330 helicopter.*

Key Words: *helicopter, automatic flight control system (AFCS), turbulence model*

ABBREVIATIONS AND NOTATIONS

AFCS	Automatic Flight Control System
ACAH	Attitude-Command Attitude-Hold)
CETI	Control Equivalent Turbulence Input
DOF	Degree Of Freedom
MIMO	Multi-Input Multi-Output
RC	Rate-Command
RCAH	Rate-Command Attitude-Hold
$\mathcal{H}_\infty$	H-infinity
x	State variables vector
u, v, w	Perturbational rates
p	Roll rate
q	Pitch rate
r	Yaw rate

β_{1c}	Lateral blade flapping angle
β_{1s}	Longitudinal blade flapping angle
θ	Blade pitch or feathering attitude angle
φ	Bank attitude angle
ψ	Azimuthal angular position of blade
θ_{1s}	Longitudinal cyclic pitch
θ_{1c}	Lateral cyclic pitch
θ_0	Collective pitch angle
θ_{0tr}	Tail-rotor collective pitch
T_r	Ideal model
Σg	Gust filter
y	Measured outputs vector
$\frac{\delta_{(\ldots),gust}}{W_{noise}}$	Transfer functions of gust filters

1. INTRODUCTION

An essential condition in designing and evaluating the effectiveness of an automatic flight control system is to determine an appropriate mathematical model that describes the behaviour of the actual plant. The complexity level of such a model depends on the application in which the resulting controller will be used; examples of such applications are: control law design considering flying qualities, disturbance rejection, stability at the flight envelope limits, development of control strategies for emergencies such as engine failure at particular flight phases, etc. If the aim is to design a flight simulator or to analyse aerodynamic phenomena, it is desirable to have a high-fidelity model, therefore one with a high level of complexity. As shown in [1] there are particularly complex models that miss important physical phenomena; also the increase in the level of mathematical complexity is not linear with the level of fidelity, becoming ineffective in terms of costs from a certain point. Therefore, usually simpler models [2] that reproduce complex behaviours are employed, the efficiency of the resulting controllers being tested in more challenging environments. The present paper aims to validate a turbulence model derived in [3] for the Puma SA330 helicopter, through tests carried out on two different level of complexity models of the helicopter. The first model is the ONERA model, stabilised for hover conditions, whilst the second one is based on the DRA (RAE) research Puma, SA330, XW241 model from [4] for which an $\mathcal{H}_\infty$ 2 DOF type of controller was designed in [5].

Comparisons between the behaviours of the two models subjected to the same gust field are delivered, and conclusions drawn.

2. THE FIRST MODEL OF THE PUMA HELICOPTER DYNAMICS

The first model is an ONERA developed RCAH (rate – command; attitude – hold) PUMA330 rigid body simulation model using Matlab software [6]. The simulation model includes 12 states: 6 translational and rotational body states velocities, 2 main rotor tilt (longitudinal and lateral) and 4 pseudo states (3 attitudes and height).

The state variables are: $x = u, v, w, p, q, r, \beta_{1c}, \beta_{1s}, \theta, \varphi, z, \psi$.

The command variables are: $u = \theta_{1s}, \theta_{1c}, \theta_0, \theta_{0tr}$.

A controller was implemented for vehicle corresponding to the 0 kts linearization, i.e. hover condition.

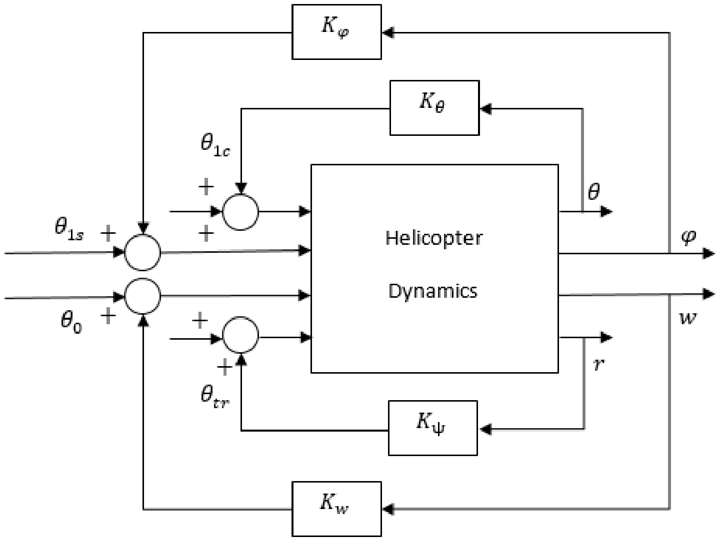


Fig. 1 – First PUMA 330 model, with RCAH flight control system included

3. THE SECOND MODEL OF THE PUMA HELICOPTER DYNAMICS

The base for the second model is the 6 DOF, 8 variable Helisim model described in [4]. An $\mathcal{H}_\infty$ 2 DOF controller (Figures 2 and 3) was designed [5] for the plant G corresponding to the 80 kts linearization. The main advantages of this method are that it guarantees robust stability in the face of an ideal step response model, without significantly increasing the controller dimensions, that the output tracks the ideal model (Tr) and that it allows for high levels of decoupling to be achieved [7], which is essential in the case of a highly coupled MIMO plant such as the helicopter.

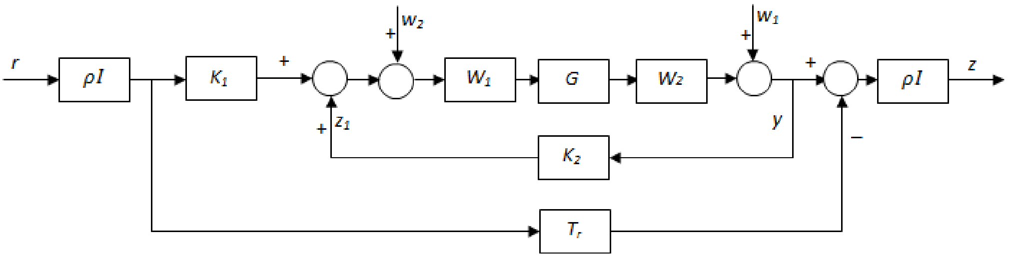


Fig. 2 – $\mathcal{H}_\infty$ 2 DOF loop-shaping configuration

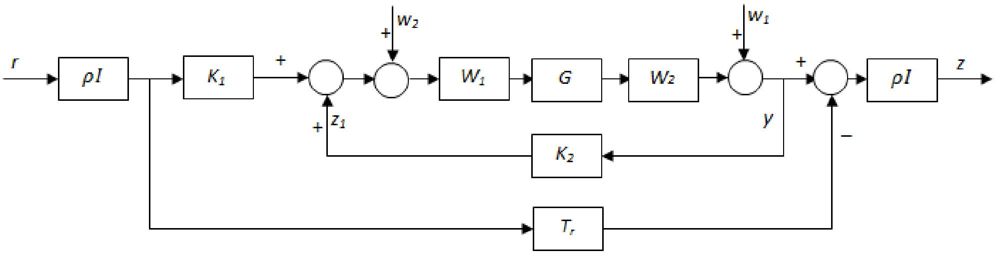


Fig. 3 – Final configuration (Σg represents the gust filter)

For tracking purposes, a value of ρ=2.5 was chosen, so that the obtained value for γ was 3.5296.

The measured outputs are the vertical velocity, pitch and bank attitude angles and yaw rate:

$$y = [w \quad \theta \quad \phi \quad r] \tag{1}$$

The ideal model was chosen so that the outputs are according to the ADS-33E standard, ACAH (attitude-command attitude-hold) type of response for the angles, and RC (rate command) for rates, respectively.

Afterwards, the behaviour of the resulting plant, i.e. controller coupled to the helicopter model, was verified at different airspeeds; Figures 4 to 7 show the results for the hover condition.

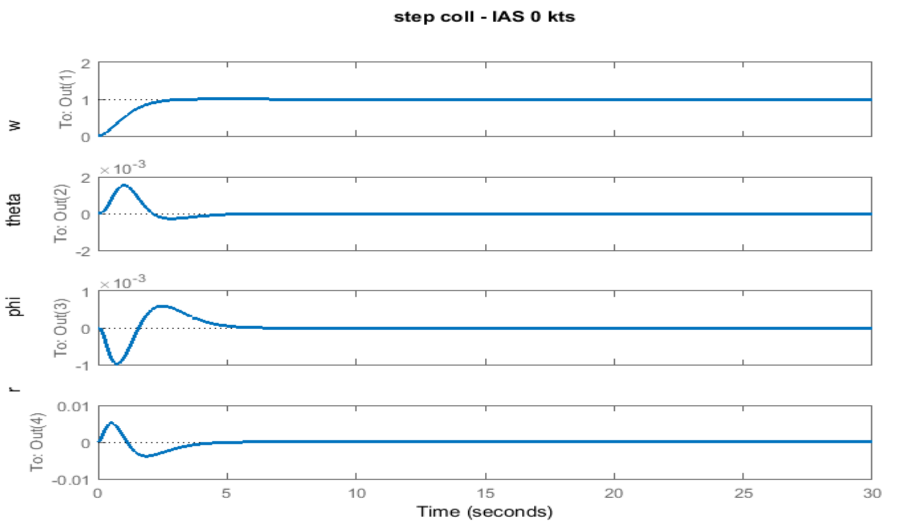


Fig. 4 – Step input on collective

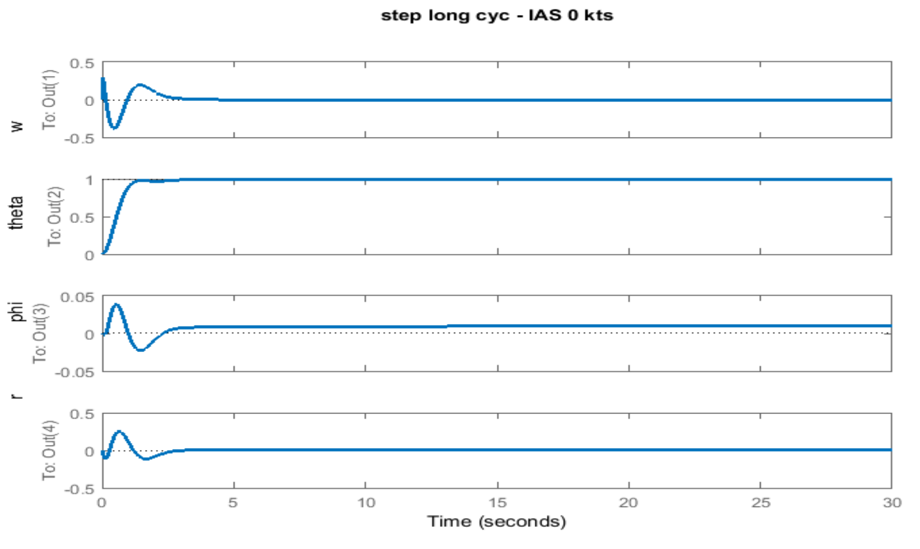


Fig. 5 – Input on longitudinal cyclic

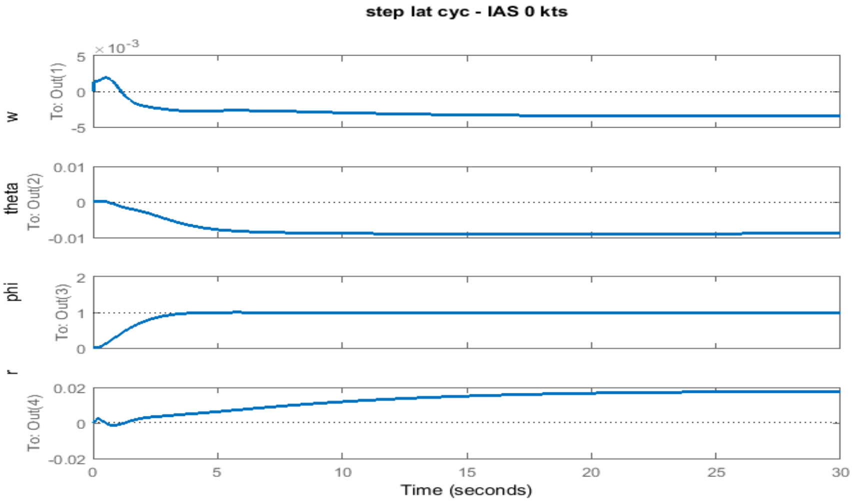


Fig. 6 – Step input on lateral cyclic

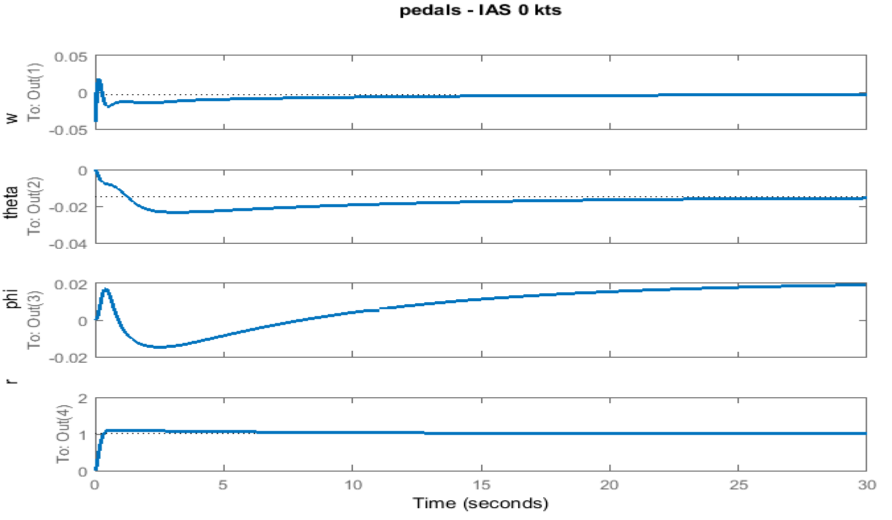


Fig. 7 – Step input on pedals

4. VALIDATION OF TURBULENCE MODEL FOR THE PUMA SA330 HELICOPTER

In order to test the validity of the previously presented models and efficiency of controllers, realistic atmospheric conditions need to be simulated.

Although classical models, such as the von Karman and the Dryden models, have produced excellent results, especially for fixed wing aircraft, they are not truly suited for helicopters.

The CETI (Control Equivalent Turbulence Input) method is much more appropriate for modelling turbulence effects on helicopters. A method for scaling the CETI model derived through flight testing for the EC-135 helicopter [8] was presented in [3].

The resulting transfer functions of the gust filters have the following forms:

$$\frac{\delta_{lon,gust}}{W_{noise}}(s)=\frac{6.0714(s+0.61)}{(s+3)(s+0.4148)}$$
$$\frac{\delta_{lat,gust}}{W_{noise}}(s)=\frac{6.1525(s+0.61)}{(s+3)(s+0.4148)}$$
$$\frac{\delta_{ped,gust}}{W_{noise}}(s)=\frac{21.708}{s+7.28} \tag{2}$$
$$\frac{\delta_{col,gust}}{W_{noise}}(s)=\frac{0.67132(s+60)(s+0.61)}{(s+1.89)(s+0.4148)(s+15)}$$

The turbulence signals generated by the filters from Eq. (2) were applied as inputs to both Puma models, the results being shown in Figures 8 to 11, where Model 1 stands for the ONERA based model and Model 2 stands for the Helisim, stabilised with the $\mathcal{H}_\infty$ 2 DOF controller.

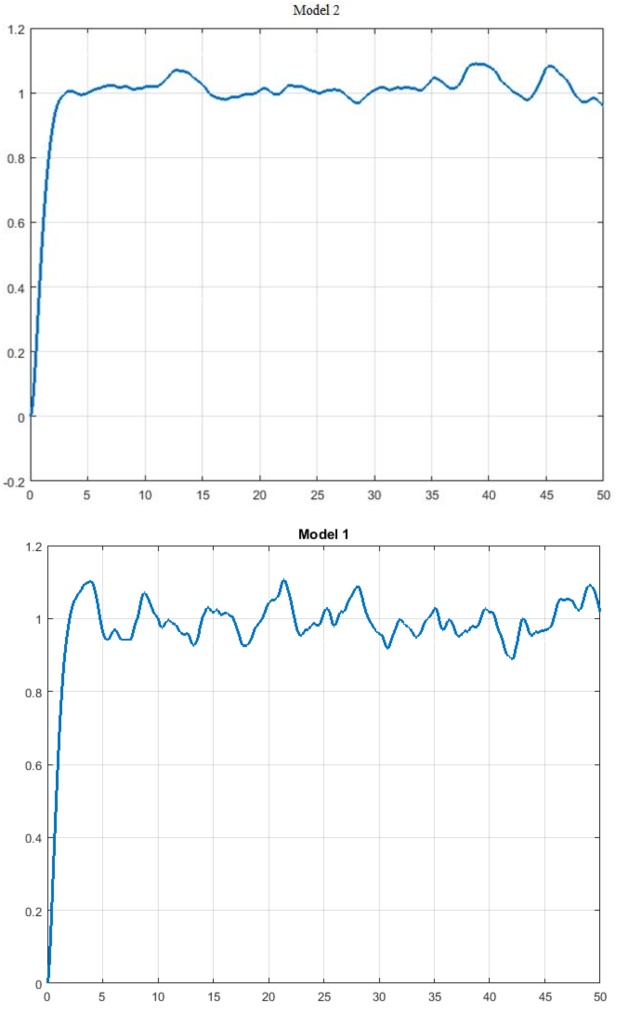


Fig. 8 – Gust effect on vertical speed; input – main rotor collective, output - w

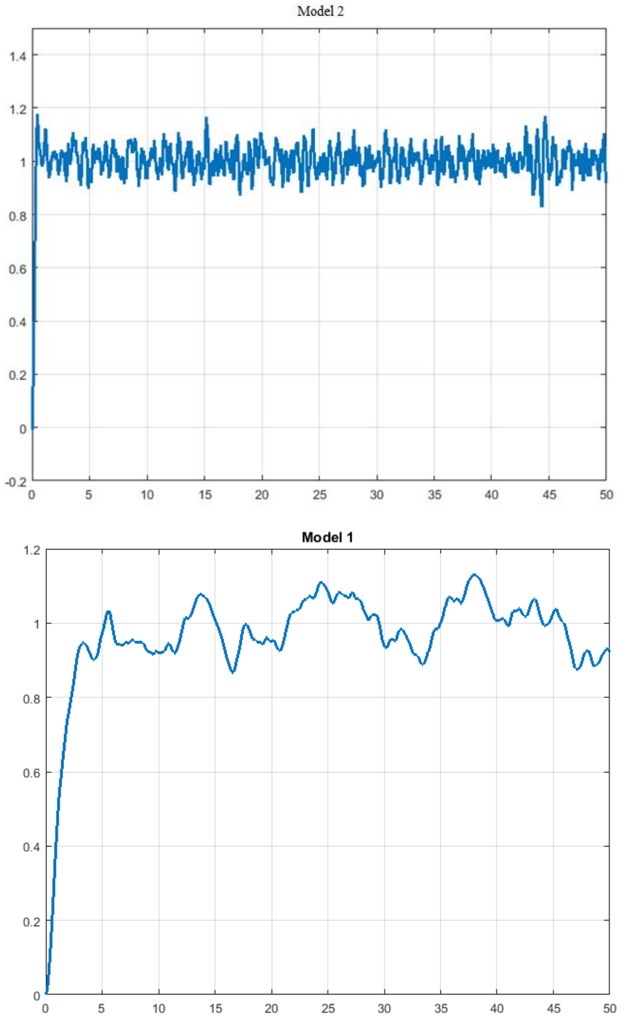
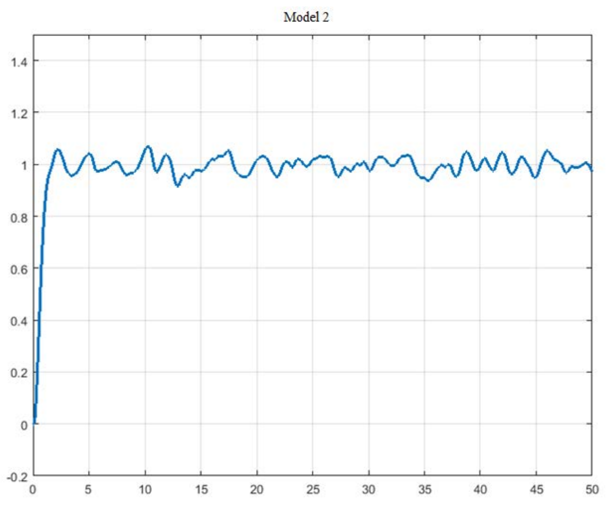


Fig. 9 – Effect of gusts on yaw rate; input – tail rotor collective (pedals), output - r



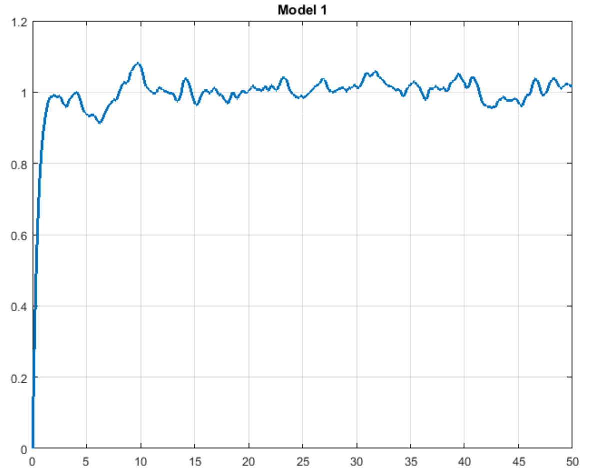


Fig. 10 – Effect of gusts on pitch angle; input – longitudinal cyclic, output Θ

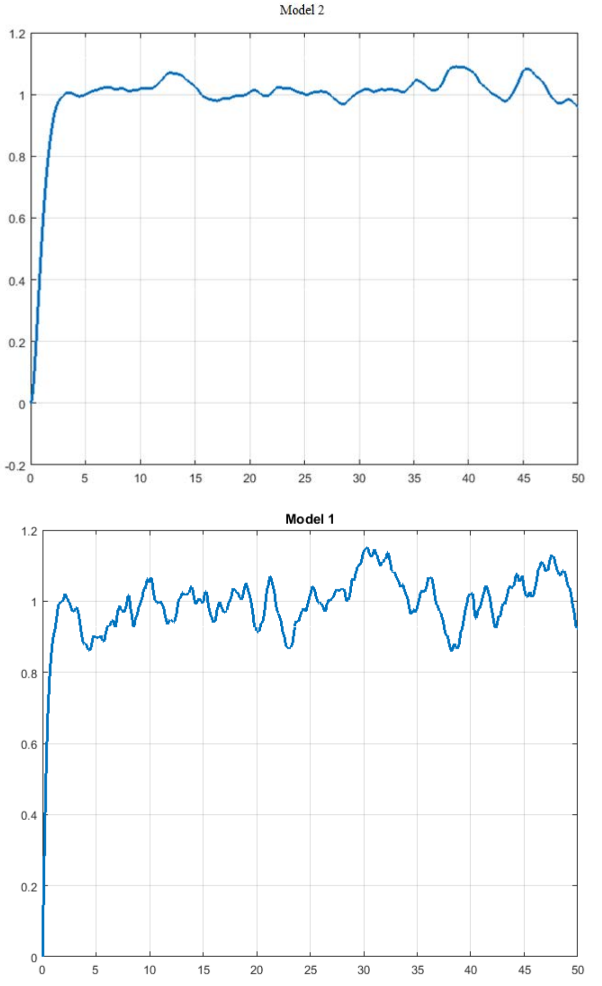


Fig. 11 – Effect of gusts on bank angle; input – lateral cyclic, output - Φ

5. CONCLUSIONS

The last section shows the effect of turbulence on the two different models for the stabilised Puma helicopter dynamics.

Although the two models are different and the AFCS were designed using different methods – Model 1 identified from the actual aircraft dynamics and the one for Model 2 designed mathematically - it can be seen that the results are quite similar when considering the same gusty conditions.

These findings allow us to consider that the method employed in the design of the turbulence model is validated by this similarity of responses, therefore in future work such a methodology could be extended to other aircraft.

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