Prediction of the handling qualities and pilot-induced oscillation rating levels

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Abstract: *The basis for the aviation development is the ambition of increasing the efficiency and safety of flight. Improvements include flight performance and extended flight envelope, new flight regimes and tasks. However, all of these factors lead to the increase of pilot workload which can reduce the accuracy and safety of flight. Fixed and rotary wing pilots are being confronted with potential instabilities or with annoying limit cycle oscillations, known as Aircraft/Rotorcraft Pilot Couplings (A/RPC) that arise from the effort of controlling the vehicle with high response actuators.*
This paper deals with the unified theory of predicting handling qualities level (HQSF) and pilot-induced oscillation rating levels (PIOR) based on the structural model of human operator, developed by Hess. HQSF and PIOR are capable of capturing the prominent features of human pilot dynamics characteristics for a large class of aerial vehicles and tasks. The key element in this method is to unify the topics of vehicle handling qualities and RPC/PIO, applied to the analysis of a medium weight helicopter model.

Key Words: *flight performance, extended flight envelope, aircraft/rotorcraft pilot couplings, handling qualities level, pilot-induced oscillation rating level*

LIST OF ABBREVIATION

APC – Aircraft Pilot Coupling
A/RPC – Aircraft/Rotorcraft Pilot Coupling
ARISTOTEL – Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection
ASE – Aero-Servo-Elastic
AFCS – Automatic Flight Control System
HQ – Handling Qualities
HQSF – Handling Qualities Sensitivity Function
PIO – Pilot Induced Oscillation
PIOR – Pilot Induced Oscillation Rating
PSD – Power Spectral Density
RB – Rigid Body
RPC – Rotorcraft Pilot Coupling
SPM – Structural Pilot Model
u_m – proprioceptive feedback signal
c(t) – time evolution

τ_e – time delay

$Y_c(s)$ – transfer function of rotorcraft

$Y_p(s)$ – transfer function of pilot

ω_c – crossover frequency

1. INTRODUCTION

An adverse aircraft-pilot coupling (APC) or pilot-induced oscillation (PIO) can be defined as an unwanted, inadvertent, and a typical closed-loop coupling between a pilot and the response variables of an aircraft [1]. APC or PIO problems are not new phenomena; indeed, they have been around since the Wright Brothers and have been referred to as the senior handling qualities problem [2]. McRuer gives a concise historical perspective of the PIO problem, including a review and discussion of pilot behavior patterns. Because of a strong correlation between APC/PIO susceptibility and full-authority control systems employing fly-by-wire (FBW) technology, interest in studying the APC/PIO phenomenon has been increasing. For example, NATO's AGARD convened a special workshop on PIO [3], and NASA has sponsored a National Research Council committee to study the problem of APC/PIO [4]. U.S. Air Force interest in the APC/PIO problem has led to the publication of four reports under the general rubric of a Unified PIO Study [5-8].

Despite the amount of research that has been directed toward solution of the APC/PIO problem, there appears to be little consensus about the phenomenon itself in terms of the pilot behavior that initiates and sustains the APC/PIO. There is general agreement that the contributing factors are 1) a demanding flight task, 2) a vehicle with unsatisfactory dynamics, and 3) a triggering event. [2, 9]**.**

The Handling Qualities and Pilot Induced Oscillations criteria based on piloting models have been proposed over the past six decades. The analytical criteria for the specification of handling qualities have two forms: the first are the open-loop criteria such as limits on measured responses or on modes and the second are the closed-loop criteria assuming a pilot feedback structure which are dependent on the accuracy and adequacy of the pilot model forms. These models have been extensively developed to describe, understand and predict the pilot behaviour in many classes of vehicles including the aircraft and rotorcraft. The pilot model can be characterized through four basic categories of mathematical models: isomorphic, algorithmic, behaviour-based and qualitative [10, 11, 12, 13].

The prediction of aeroservoelastic instabilities related to adverse interactions between pilot and vehicle is a subject that should considerably take part in the design process of modern/innovative air/rotor-craft configurations, but that cannot yet rely on a mature, well established technology. Starting with fixed-wing aircraft, in the last decades the scientific community has started a deeper analysis of this kind of phenomena, focusing the attention on the identification of the events that may be classified as resulting from pilot-vehicle interactions, as well as on the developments of appropriate computational tools suitable for predicting the proneness of modern aircraft and rotorcraft to A/RPC, and identifying suitable guidelines to designers of next generation aircraft such to avoid adverse A/RPC.

Concerning the rotor pilot coupling, Hamel, Ockier and others [C.J. Ockier, Flight evaluation of the new handling qualities criteria using the BO 105, AHS, Annual Forum, 49th, Saint Louis, Alexandria, VA: American Helicopter Society, United States, 1993] give the following characteristics that make rotorcraft prone to RPC:

- limited stability;
- significant delays in control effectors because of the time required for the rotor response (typically 70 msec) and power actuation (20 to 30 msec);
- coupling of rigid-body modes with rotor and transmission modes;
- significant inherent cross-coupling of control that is highly nonlinear;
- potential coupling with external slung loads.

The pilot modeling for rigid body RPC and servo-elastic for A/RPC must take into account the frequency range characteristics of rotorcraft and large aircraft dynamics [fig. 1]. The A/RPC phenomena involve the active and passive pilot participation with low frequency vehicle flight dynamics, low frequency air structural modes, frequently via flight control system interaction. Additionally, for rotorcraft, rotor dynamics with the swash plate mechanism may have a significant role in RPC encountering.

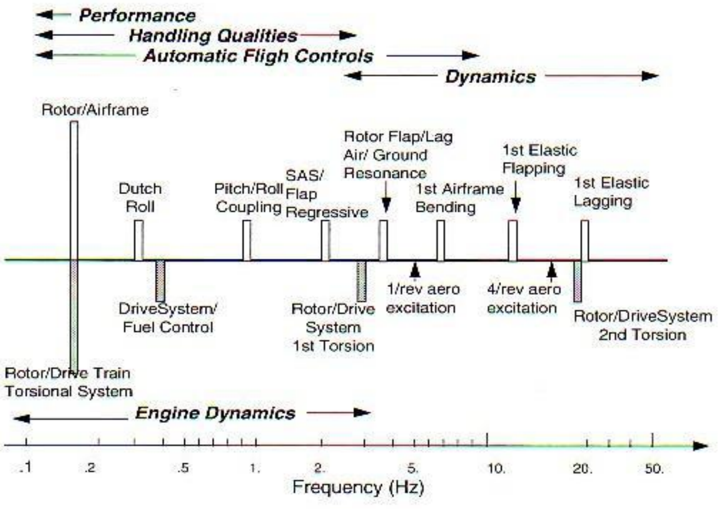


Fig. 1 Frequency range characteristics of rotorcraft dynamics [14]

This work uses the aero-servo-elastic (ASE) and rigid body (RB) models of the IAR PUMA 330 (fig. 2) helicopter and both models are taken into account for the pilot vehicle coupling Cat. I and II RPC analysis. Their dynamics include 6 rigid body modes, 8 structural modes of fuselage, 14 aero-elastic modes for the main rotor with additional axial dynamic inflow state. The rotorcraft dynamics is completed by 4 servo-actuators on main controls and 4 controllers' dynamics to improve stability performances. The control for rotorcraft model consist of main rotor collective pitch, longitudinal cyclic pitch, lateral cyclic pitch and tail rotor collective pitch. Additional controls are considered the external forces on CG location along their axes. Both hover and 80 kts speed forward flight condition at sea level have been considered.

Fig. 2 IAR PUMA 330

For the PUMA model, the complete linearization has carried on the developed rigid and elastic models, where the number of states depends on SCAS (OFF/ON) contribution. First step was to obtain a reduced order model especially to include the servo-elastic contribution of rotor and fuselage dynamics through simulation model of realistic complexity. The need for low order models is motivated by computational reasons for high complex vehicle where the model is described by a large number of first order differential equations. The effect on helicopter dynamics of constraining degrees of freedom can be modelled in different ways.

One of them is to set to zero or to some prescribed value, the portions of model corresponding to the constrained degree of freedom. This is the simplest technique, but it tends to be inaccurate, especially for extreme couplings between the longitudinal and lateral modes like rotorcraft with articulated rotors [15]. Another possibility is to use the model reduction techniques, like Balanced Stochastic Truncation or algorithms based on singular Hankel value decompositions, which are implemented in the Robust Toolbox of Matlab.

Analyzing the matrix A of the state space models for simulator we observe the occurrence of a large domain on frequency scale.

This makes difficult to develop a rigid body reduced model. A widely used technique is the quasi-static reduction of the constrained degree of freedom. This is acceptable for us because there is a clear frequency separation between the dynamics to be left free and the dynamics to be constrained [16, 17] (fig. 3).

The objective of the reduced-order realization is that the states of reduced model approximate the behaviour of the states of ASE model and the outputs of the reduced order model match the output response of the initial system.

Consider the system in linearized form and divide the state vector into partition x_1 to be retained and a partition x_2 to be removed:

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u \tag{1}$$

If it can be assumed that the states x_2 are infinitely fast, so that one can write $\dot{x}_2 = 0$, then the lower partition of Eq.(1) can be solved for x_2 and the solution substituted back into the upper partition. This results in the reduced order model:

$$\dot{x}_1 = \tilde{A}x_1 + \tilde{B}u \tag{2}$$

with

$$\tilde{A} = A_{11} - A_{12}A_{22}^{-1}A_{21} \tag{3}$$

$$\tilde{B} = B_1 - A_{12}A_{22}^{-1}B_2 \tag{4}$$

The measure of “goodness” of reduced order model may be some error criteria in the frequency and/or time domain and is highly dependent on the purpose for reduced order model and particular application.

From the results displayed in figure 3 a distinct separation between the frequency at 10 Hz and 3 Hz can be noticed.

The distribution of the modal frequency at 80 kts flight condition is similar. In addition the Eigenvalues of the ASE model and RB model are plotted in figure 4.

Furthermore the eigenvalues of reduced linear system and those of the original linear one agree up to 5 Hz.

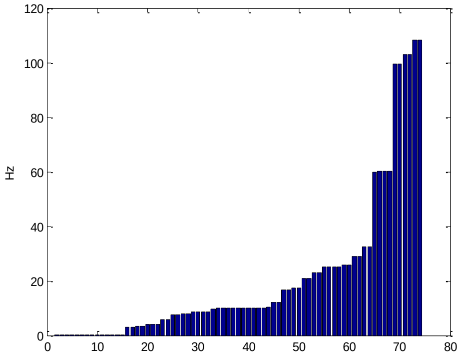


Fig. 3 Frequency map at sea level and V=80 kts

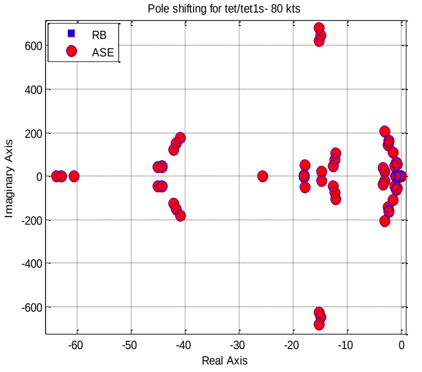


Fig. 4 Eigenvalues at 80kts flight speed

2. STRUCTURAL PILOT MODEL ANALYSIS

The human pilot model so-called "structural pilot model" developed by R. Hess (derived from a theory introduced by Smith) is able to capture the prominent features of the human pilot dynamics characteristics for a large class of aerial vehicles and tasks [18, 19, 20, 21, 22]. Figure 5 presents the structural pilot model which consists of two parts: the central nervous system and the neuromuscular system. In the following analysis the individual blocks are presented as described below:

$$Y_{pn} = \frac{\omega_n^2}{s^2 + 2\xi\omega + \omega_n^2}; \quad Y_f = \frac{K_1 s}{s + 1/T_1}; \quad Y_m = \frac{K_2}{(s + 1/T_2)^{k-1}}; \tag{5}$$

where $Y_c(s)$ and $Y_p(s)$ are the transfer function of the rotorcraft and pilot.

The following procedure is adopted to select the appropriate values of different parameters used in the above transfer function and to evaluate the measure of the workload and the handling qualities sensitivity function (HQSF)[23]:

- a specified vehicle and flight tasks to be simulated are established,
- the mathematical model for the rotorcraft is obtained,
- a crossover frequency ω_c is selected as a measure of the specified performance level characterizing the task,
- the parameter 'k' in the structural model is selected based on the vehicle transfer function and the specified crossover frequency. The value of 'k' will depend upon whether gain (k=1), lead (k=2), or lag (k=0) compensation is required,
- the nominal parameter values for the structural pilot model are selected from table 1 depending on 'k' value,
- the value of parameter T_2 is chosen to ensure 1/s like open – loop pilot vehicle characteristics around ω_c,
- the relation

$$K_e = \frac{1}{|Y_p(j\omega_c)|}\,\frac{1}{|Y_c(j\omega_c)|} \tag{6}$$

is calculated to ensure that the desired ω_c is obtained.

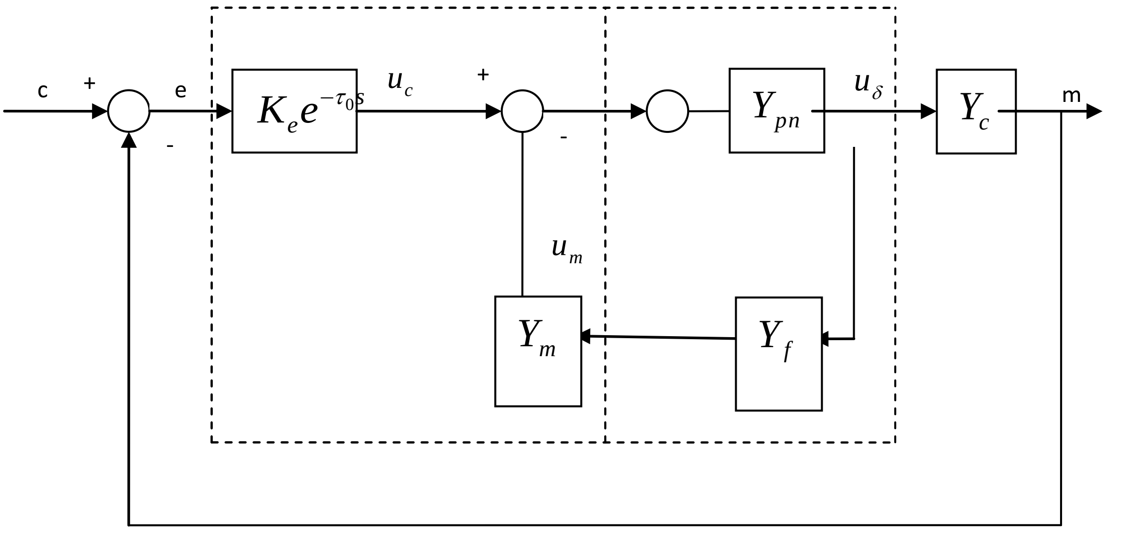


Fig. 5 Structural Pilot Model

Table 1

k	K_1	K_2	T_1(sec)	τ_0 (sec)	ς_n	ω_n (rad/s)
0	1.0	2.0	5.0	0.15	0.707	10.0
1	1.0	2.0	5.0	0.15	0.707	10.0
2	1.0	10.0	2.0	0.15	0.707	10.0

The pilot vehicle system will be simulated using the disturbance or/and command signals for u_m.

The measure of the pilot workload is computed as root mean square value (rms) of u_m/K_e for the study of flight speed effect on the band width phase delay criterion.

The handling qualities sensitivity function (HQSF) will be estimated at the crossover frequency ω_c that the magnitudes of the transfer function u_m/c.

3. ANALYSIS OF HANDLING QUALITIES

A theory for handling qualities based on the original structural model has been proposed and discussed elsewhere [24, 25]. The theory postulates that the power in the proprioceptive feedback signal $u_m(t)$ of fig. 5 is the determining factor in a pilot's perception of a vehicle's handling qualities. The signal $u_m(t)$ can be shown to be proportional to the output rate $m(t)$.

Because the power in $u_m(t)$ is dependent on $|(U_M / C)(j\omega)|$, it was found that this function itself could be used to predict handling qualities levels and was referred to as the handling qualities sensitivity function (HQSF) [24, 25].

The HQSF definition is:

$$HQSF = \left| (U_M / C)(j\omega) \right| \tag{7}$$

In calculating the HQSF, it is necessary to remove the effects of the control sensitivity.

By this it is meant that the model results are forced to be independent of control and force-feel system sensitivity.

This sensitivity includes command path gains between the inceptor and the actuators and the static gain of the pertinent vehicle transfer function, i.e., the gain appearing in the vehicle transfer function when written in "time-constant" form.

Removing the effects of uncertainty from the vehicle transfer function, the HQSF is accomplished as follows:

- Displacement-sensing inceptor

$$HQSF = \left| \frac{M}{C}(j\omega) \cdot \frac{1}{K_e} \cdot \frac{1}{Y_c(j\omega)} \cdot Y_f \cdot Y_m(j\omega) \right|$$

- Force-sensing inceptor

$$HQSF = \left| \frac{M}{C}(j\omega) \cdot \frac{1}{K_e} \cdot \frac{1}{Y_c(j\omega)} \cdot Y_f \cdot Y_m \cdot Y_{pn}(j\omega) \right| \tag{8}$$

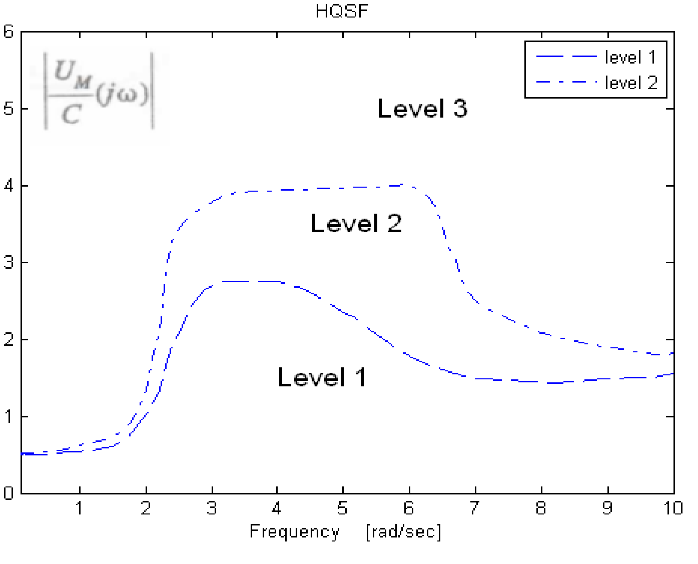


Fig. 6 Handling Quality Sensitivity Function

4. ANALYSIS OF PIO RATINGS

An analysis of the vehicle configurations using the pilot-vehicle analysis procedure described in the preceding was conducted with the goal of developing a theory for APC/PIO.

Again, the characteristics of the proprioceptive feedback signal $u_m(t)$ were investigated in this context. It was found that a sensitive metric for APC/PIO susceptibility was the power spectral density (PSD) of the signal $u_m(t)$ when a filtered white noise command $c(t)$ was applied.

The PSD of $c(t)$ was selected as:

$$\Phi_{u_m u_m}(\omega) = \frac{2^4}{\omega^4 + 2^4} \cdot \left| HQSF \right|^2 \tag{9}$$

It was found that, similar to the HQSF, plots of $\Phi_{u_m u_m}(\omega)$ could be used to delineate "levels" of pilot-induced oscillation ratings (PIORs) using the scale of fig. 7 and Table 2.

Table 2 PIOR Scale description

Description
No tendency for pilot to induce undesirable motions.
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.

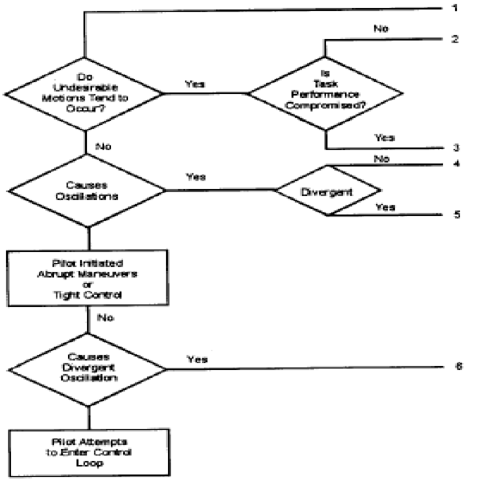


Fig. 7 PIOR Scale

The levels were defined herein as:

$$1 \le \text{PIOR} \le 2,\ 2 < \text{PIOR} < 4,\ \text{PIOR} \ge 4 \tag{10}$$

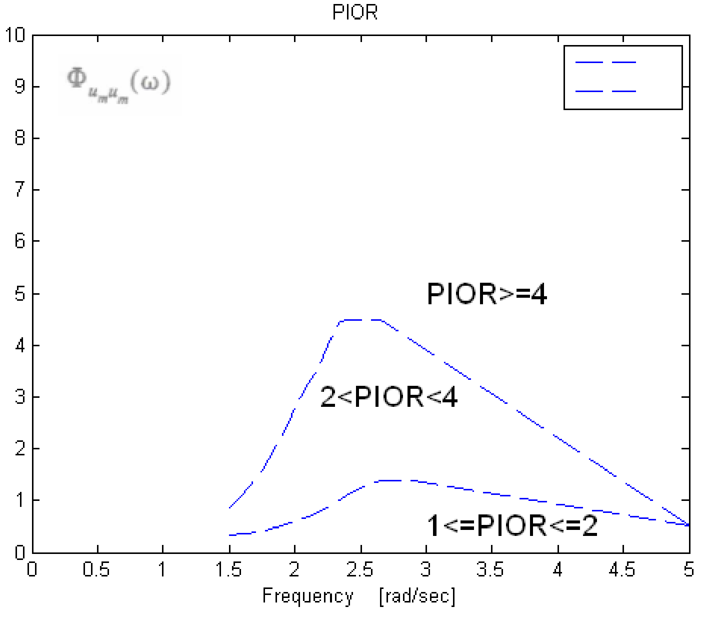


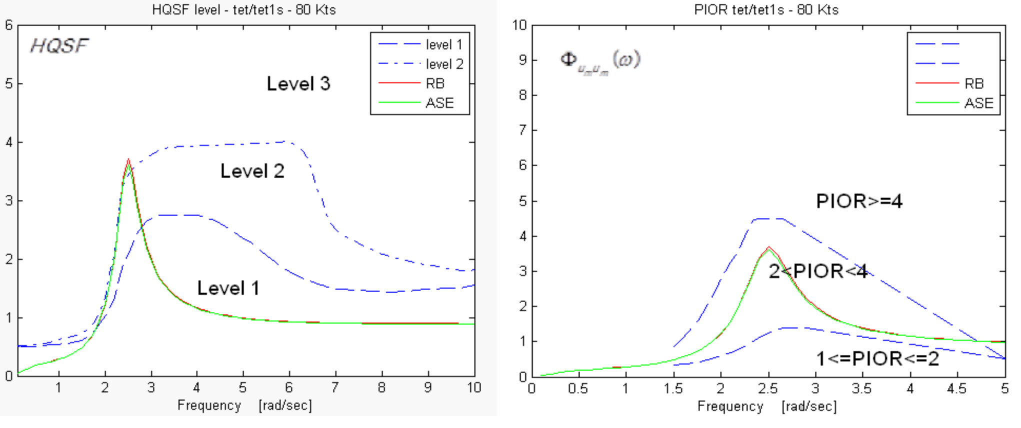
Fig. 8 Pilot Induced Oscillation Rating

The prediction of handling qualities level in single axes task with linear or nonlinear dynamics to study the category I and II RPC/PIO susceptibility is developed by selecting different configuration of linearized rotorcraft dynamics with additional displacement limits element in servo-actuators of control chains. The bounds on HQSF and the normalized

$\Phi_{u_m u_m}(\omega)$ define the HQ levels and PIOR levels established for linear systems and demonstrate their utilities as well as for nonlinear systems.

5. RESULTS

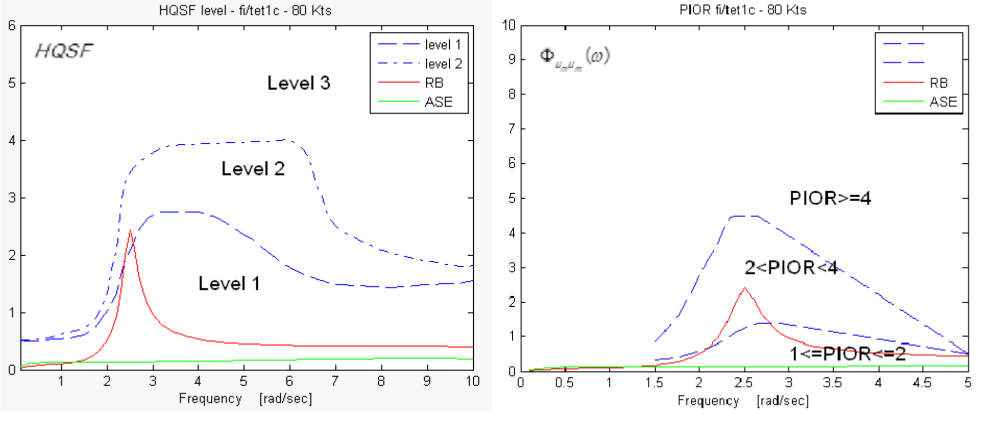
Figures 9 – 10 present HQ and PIO levels for the IAR 330 PUMA helicopter at flight level 80 kts conditions. Obviously, the boundaries plotted in this figures are valid for the fixed wing but they have been plotted to understand where the helicopter reference model shows different levels in above specified conditions. In our study cases we choose the time delay τ_e and error gain K_e in structural pilot model obtained from [26].



a) b)

Fig. 9 (RB) - a) HQSF for flight level configuration with longitudinal cyclic displacement limit; b) Normalized $\Phi_{u_m u_m}(\omega)$ for flight level configuration with longitudinal cyclic displacement limit

In flight level conditions with effect of sensitivity**,** the HQ rating shows a region of level 3 for RB and ASE configurations. The PIO rating shows a region of level 2<PIOR<4 for RB and ASE configurations, if not taking into consideration the 0.1 - 1.5 rad/sec frequency region.



a) b)

Fig. 10 (RB) - a)HQSF for flight level configuration with lateral cyclic displacement limit; b) Normalized $\Phi_{u_m u_m}(\omega)$ for flight level configuration with longitudinal cyclic displacement limit

In flight level conditions with effect of sensitivity the HQ rating shows a region of level 2 for RB and level 1 for ASE configurations, and the PIO rating shows a region of level 2<PIOR<4 for RB and level $1 \leq \text{PIOR} \leq 2$ for ASE configurations.

6. CONCLUSIONS

Based on the research that has been described, the following conclusions can be drawn:
1) Using a well-defined pilot-vehicle analysis technique and flight-test results, it was possible to categorize the following: i) handling quality levels using a handling qualities sensitivity function, easily derived from the pilot model; and ii) PIOR levels using the PSD of a signal easily derived from the pilot model.
2) A unified theory for aircraft handling qualities and APC/PIOs is possible. The theory is based on a structural model of the human pilot and the central importance of a proprioceptively derived signal in that model.
3) The transfer function between the collective, longitudinal cyclic pitch and lateral cyclic pitch controls and longitudinal and lateral attitude, vertical and lateral displacements have been considered in order to evaluate the rotorcraft dynamic behaviour in the active pilot bandwidth.
4) The structural pilot model is suitable to estimate the pilot work measure and HQSF parameter and will be required in estimation of handling qualities level.
5) The advantage of the structural model compared with the crossover model is that it involves a refined observation of the human central nervous and neuromuscular systems.

7. ACKNOWLEDGEMENTS

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