PIO (Pilot Induced Oscillations) Criteria for
Rotorcraft Pilot Coupling (RPC) in roll axis investigation

Andreea AFLOARE *) Achim IONITA **)
STRAERO - The Institute for Theoretical and Experimental Analysis
of Aeronautical Structures
Bdul Iuliu Maniu 220, Bucharest 061126, Romania

*) afloare.andreea@straero.ro

**) achim.ionita@straero.ro

Abstract: *Advances in Flight Control System (FCS), cockpit controllers and aircraft effectors with a significant level of automation in generally have intention to relieve pilot workloads and to allow operations in degraded weather and visibility conditions. Fixed and rotary wing pilots are being confronted with potential instabilities or with annoying limit cycles oscillations, knowing that Aircraft- and-Rotorcraft-Pilot Couplings (A/RPC) that arise from the effort of controlling vehicle with high response actuators. Research experience concerning pilot-in-the-loop handling qualities show that understanding, predicting and suppressing of inadvertent or sustained rotorcraft oscillations has received less attention until the last two decades. This paper develops the existing bandwidth - phase delay PIO I Category criteria on aircraft to analyze rotorcraft oscillatory or divergent behavior from adverse pilot vehicle coupling. Bandwidth-phase delay criteria can be used to evaluate rotorcraft susceptibility to PIO Categories I. The proposed criteria are applied to the analysis of a medium weight helicopter model and a/the closed – loop parameter is assessed through numerical simulation.*

Key Words: Pilot Induced Oscillations, bandwidth, phase delay, roll axis criteria, pilot model, Bode diagram

Abbreviations/Nomenclatures:

ω_{BW}	"bandwidth" frequency
τ_p	phase delay parameter
ω_{180}	frequency for neutral stability
$\omega_{BWphase}$	bandwidth frequency as defined by phase
ω_{BWgain}	amplitude corresponding to ω_{180} plus 6 dB
Φ_M	phase margin
$\frac{p_{pk}}{\Delta\phi}$	roll attitude quickness
p	roll rate
A_1	lateral cyclic control
L_p, $L_{\theta_{1c}}$	damping and control derivatives
p_s	steady-state roll rate
$\Delta\phi$	discrete attitude change
$\hat{t}_1$	normalized time
φ	roll angle
K_p	pilot gain
T_L	lead
PIO	Pilot Induced Oscillations
AFCS	Automatic Flight Control System
A/RPC	Aircraft /Rotorcraft Pilot Coupling
PAO	Pilot Assisted Oscillations
RPC	Rotorcraft Pilot Coupling
PVS	Pilot Vehicle System

1. INTRODUCTION

The pilot-induced oscillation (PIO) is a particular type of oscillation that an aircraft can sustain, as a result of abnormally fast input from the pilot. These interactions have been present since the beginning of flight, and have since been carrying the status of the most important issue in aircraft controllability. At the appearance of this kind of phenomenon, it implicates corrective measures and studies, which contribute deeply to the design of the next generation of aircraft.

These phenomena occur only in the situation when the pilot tries to impose his command on the aircraft, by moving the control surfaces. The pilot, together with the airplane are operating in a so-called closed-loop control system, because of the fact that his actions and inputs depend on the aircraft's motion. Even though the aircraft by itself might be stable, the oscillations can be described as instabilities of such closed-loop control system.

Occasionally, some PIOs can be associated with abnormal changes in either the pilot's or vehicle's dynamics as a result of aggressive actions.

Generally, A/RPC phenomena are oscillations or divergent vehicle response that is a disagreement between vehicle characteristics and pilot control strategy. According to [1] some different definitions exist in the open literature and many times the aerospace community is unable to distinct upon whether or not it is an A/RPC. Presently PIO and PAO are considered subclasses of A/RPC.

In ARISTOTEL [2], after an exhaustive discussion between the project partners, the following definition was proposed to be used through project: *"An Aircraft- or Rotorcraft-Pilot Coupling (A/RPC) is an unintentional (inadvertent), sustained or uncontrollable vehicle oscillation characterized by a mismatch between the pilot's mental model of the vehicle dynamics and the actual vehicle dynamics. The result is that the pilot's control input is out-of-phase with the response of the vehicle, possibly causing a divergent motion".*

Reconsidering the A/RPC definition according to Mc'Ruer [3] there should be met three simultaneous conditions for A/RPC event:

A/RPC = Vehicle Dynamics + Trigger + Closed Loop Control

Mc'Ruer divided PIO phenomena into three categories according to the degree of non-liniarity of the Pilot-Vehicle System as follows:

- Category I Essentially linear pilot-vehicle system oscillation;
- Category II Quasi-linear pilot-vehicle system oscillations with rate or position limiting;
- Category III Essentially non-linear pilot-vehicle system oscillations with multiple non-linear effects, transitions in the pilot behavior.

During the last five decades a multitude of criteria have been developed for these categories [4] but there are none applicable to Categories II and III A/RPC to satisfy three prerequisites: validity, selectivity and ready applicability. From all existing aircraft criteria only the bandwidth criterion have been adapted and added as adequate requirements in the ADS33 helicopter handling qualities specification for CAT I RPC prediction. Recent research [5] showed that the appropriateness of existing CAT I- APC criteria when applied to rotorcraft is questionable.

Adapted bandwith criteria code for fixed wing to rotorcraft will allow for a faster analyze and acceptance within ADS33 requests. The applicability of this criterion to roll mode makes this particularly attractive.

2. BANDWIDTH/PHASE DELAY CRITERION

The bandwidth criteria is an extension of the Neal-Smith criteria where the minimum closed loop pitch attitude tracking bandwidth is specified at 3.5 rad/sec.
A summary of the criterion is given by Hoh, et al. [6]:
"It follows that airplanes capable of operating at large values of bandwidth will have superior performance when regulating against disturbances. When flying an aircraft with low bandwidth, the pilot finds that attempts to rapidly minimize tracking errors result in unwanted oscillations. He is, therefore, forced to 'back off' and accept somewhat less performance (larger and more sustained tracking errors). It is not difficult to imagine a clear cut preference on the part of pilots for aircraft with increased bandwidth capabilities."

There are two definitions for bandwith used in the analysis of flying vehicles [7]: one is a classical definition of bandwith specified by electrical engineers (that region of frequency where the gain of closed loop system does not drop below -3 dB). The second definition adopted by flying qualities community, defines bandwith as the frequency at which the phase margin is 45 deg or the gain margin is 6 dB, whichever frequency is lower.

The bandwith/phase delay criterion that is presented in this paper shows that a measure of the handling qualities of an airplane represents its response characteristics, when operated in a closed loop compensatory task. This specific tracking task can take place within the stability limits at a maximum frequency, called bandwith (ω_{BW}).

Subsequently, airplanes capable of larger values of bandwith will have superior performance when regulating against disturbances. Moreover, the pilot will become aware of the fact that, when trying to fly at low bandwidths and to correct tracking errors rapidly at the same time, there will appear some unwanted oscillations. In this situation, he will be obliged to reduce the inputs and make use of a smaller level of performance, i.e. the maximum that the aircraft can produce.

The bandwith is, from a physical point of view, a measure of frequency. Above a certain limit, the aircraft will be unable to follow all the requests of the pilot, but it will be able to do so below that same value.

<u>Bandwidth definition</u>

The bandwidth is the highest frequency at which the phase margin is at least 45 deg and the gain margin is at least 6 dB is the bandwidth, as defined for handling quality criterion purposes.

Practically, this means the highest frequency at which the pilot can allow a 135˚ phase lag between control input and aircraft attitude response, or can double his gain, without affecting the stability of the system. ($\Phi \leq -180^{\circ}$ at the ω for 0 dB gain indicates instability).

To apply this definition, it must first be determined the frequency for neutral stability ω_{180}. This can be taken from the phase area, within the Bode plot. Afterwards, there must be identified the frequency corresponding to a 45˚ phase margin, ω_{135}. This is the bandwidth frequency as defined by phase, $\omega_{BWphase}$. In the end, there must be identified the amplitude corresponding to ω_{180}, at which a value of 6dB must be added. Then the frequency at which this value of response magnitude occurs must be found, and called ω_{BWgain}. The bandwidth is the minimum between $\omega_{BWphase}$ and ω_{BWgain}.

In the case when $\omega_{BWphase}$ is equal to ω_{BWgain}, the system is called gain-margin limited. This means that the rotorcraft reaches its neutral stability when the pilot increases his own gain by a factor of 2 (6dB). This kind of aircraft may have a big value of the phase margin, Φ_M . These systems are characterized by flat frequency response-amplitude plots, together with phase plots that roll off rapidly, such as shown in the following figure:

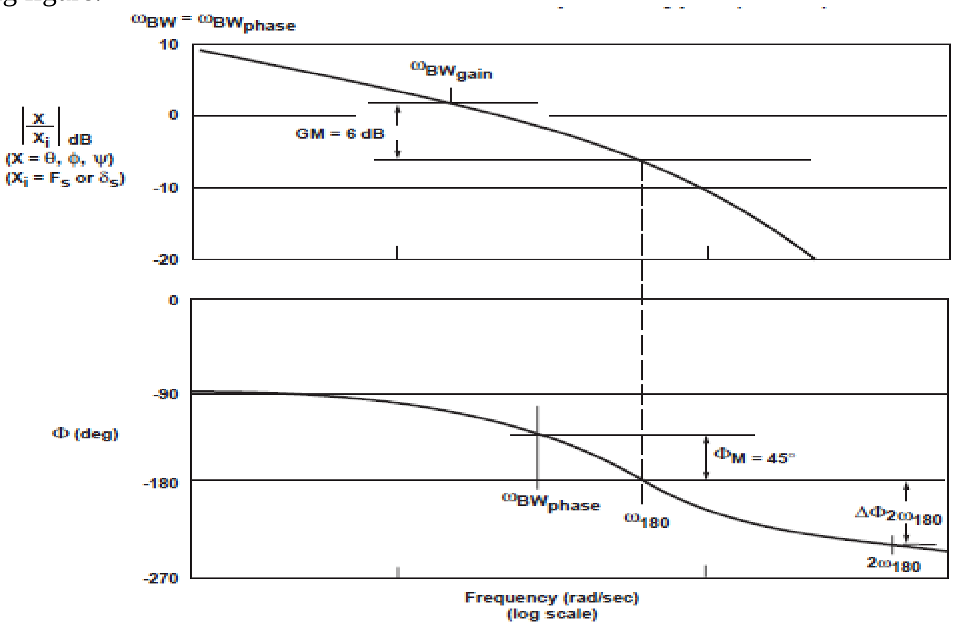

Figure 1. Definitions of bandwidth and phase delay

The shortcomings to the bandwidth criteria have been underlined by Hodgkinson [7] where a small increase in pilot gain results in a large change in crossover frequency and a corresponding decrease in phase margin for attitude control with τ_p moderately large (0.1 – 0.2 sec).

3. APPLICATION OF BW CRITERIA TO ROTORCRAFT-PILOT SYSTEM

Generally the roll moments can have multiple purposes on an aircraft. Among these, there is the trimming out of the residual moments, the reorientation of the thrust vector, and the counteracting of the atmospheric disturbances. These can have different demands on the aircraft, the flying qualities criteria have to be developed in order to best satisfy them.

Over the years, most of the attention has probably been drawn towards the roll axis, possibly as a result of extensive research in rotary-wing flying qualities. Still, another possible cause could be the fact that the most amendable to analysis and pure characteristics of an aircraft are identifiable in the roll control.

The bandwidth criteria closed in ADS 33PRF does include several of the flying qualities criteria find in MIL-HDBK-1797 [8] and is recommended to serve as the basis for the pitch/roll flying qualities of rotorcraft.

Mainly the handling qualities study for fixed and rotary wing aircraft has fixed attention on the short term inputs and in our case the roll axis is deeply oriented.

Roll axis response criteria from ADS33PRF

The roll response to lateral cockpit control position input shall meet the limits specified bellow according to bandwidth (ω_{BW}) and phase delay(τ_p) parameters:

The PIO proneness of an helicopter can be analyzed within the following classification:

- If the phase delays parameter $\tau_p \leq 0.12\sec$ and $\omega_{BW} \geq 2.5 rad/\sec$, the aircraft has no PIO.
- If the phase delay parameter $0.2\sec \geq \tau_p \geq 0.12\sec$ and $0.15\sec \leq \omega_{BW} \leq 2.5 rad/\sec$, there is a possibility for PIO but not a severe PIO.
- If the phase delay parameter $\tau_p \geq 0.2\sec$ and $\omega_{BW} \leq 1.5 rad/\sec$, aircraft is prone to PIO.

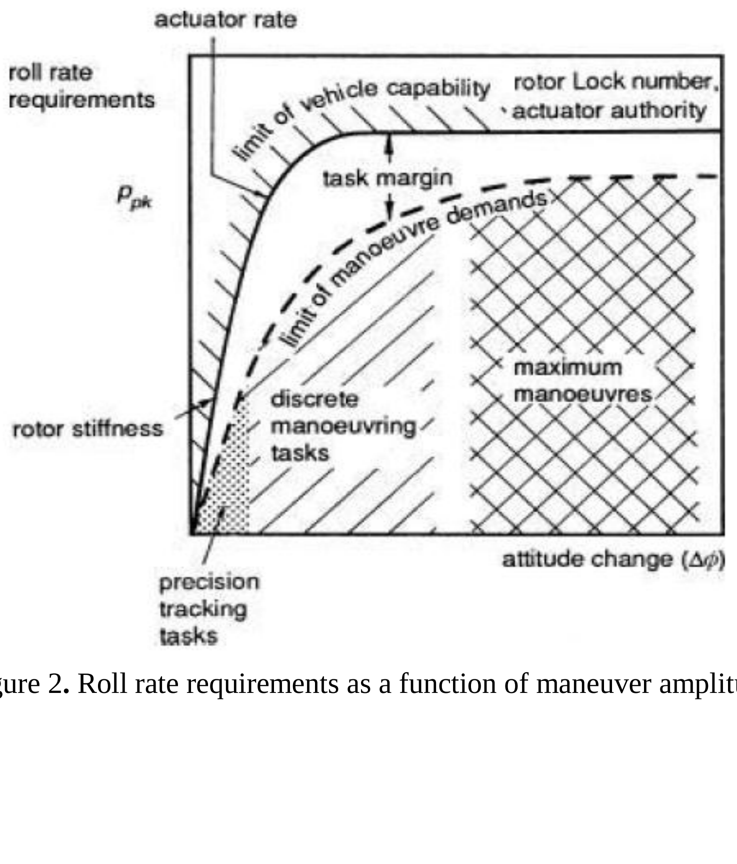

Figure 2. Roll rate requirements as a function of maneuver amplitude

4. DISCUSSION AND RESULTS

The helicopter analyzed is Sikorsky CH-53D, a twin-turbine heavy assault transport helicopter with a rotor system consisted of a six-bladed, fully-articulated main rotor and is powered by two T64-GE-412 engines rated at 3695 shaft horsepower. The vehicle features a highly augmented flight control system with an electronic automatic flight control system (AFCS) that is primarily used, which includes command augmentation of the longitudinal cyclic control, rate damping about all axes, attitude and heading stabilization and turn coordination at airspeeds above 60 kt. [11]

Transfer function data are associated with level flight conditions at 610m and 40 knots. Thus, the helicopter transfer functions used are:

- AFCS OFF

$$\frac{\varphi(s)}{A_1(s)} = \frac{0.5\left(s^2+1.33s+0.4998\right)\left(s^2-0.3978s+0.3745\right)\left(s^2+0.5951s+0.61\right)}{\underbrace{(s+1.64)}_{R}\underbrace{(s+.145)}_{S}\underbrace{\left(s^2+1.369s+0.5373\right)}_{SP}\underbrace{\left(s^2-0.382s+0.354\right)}_{P}\underbrace{\left(s^2+0.3197s+0.8064\right)}_{D}}$$

R S SP P D

- AFCS ON

$$\frac{\varphi(s)}{A_1(s)} = \frac{-1.5\cdot s\cdot(s-200)(s+7.45)(s+1.95)(s+0.714)(s+0.532)(s+0.0115)}{s\cdot\underbrace{(s+200)}\underbrace{(s+1.49)}\underbrace{(s+0.714)}\underbrace{(s+0.533)}\underbrace{(s+0.12)}\underbrace{(s+0.0669)}}\cdots$$

$$\cdots\frac{\left(s^2+0.4197s+0.1747\right)\left(s^2+1.777s+2.657\right)}{\underbrace{\left(s^2+4.831s+5.905\right)}\underbrace{\left(s^2+0.5397s+0.2016\right)}\underbrace{\left(s^2+1.884s+2.657\right)}}$$

where R- Roll ; S- Spiral; SP- Short Period; P- Phugoid; D- Dutch Roll.

To perform closed loop analyses it is necessary to have available a mathematical model of the human pilot.

The pilot transfer function used was postulated to be:

$$Y_p(s) = K_p e^{-sT}\left(T_L s + 1\right)$$

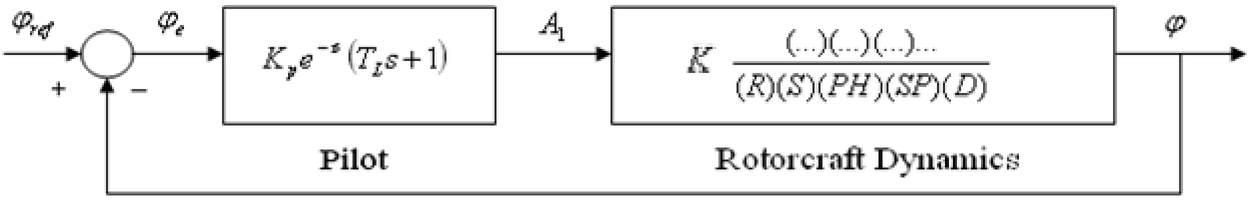

Figure 3. Bandwidth roll control block diagram

Control systems with dead-time are difficult to analyze and simulate, and it is also difficult to determine all the system poles. Thus, to analyze these systems we use Padé approximations that approximate a dead-time by a rational function.[10]

The most recommended Padé approximation is of 1st order with equal numerator and denominator degree:

$$e^{-sT} \approx \frac{2 - sT}{2 + sT}$$

and the 2nd order Padé approximation with:

$$e^{-sT} \approx \frac{12 - 6sT + (sT)^2}{12 + 6sT + (sT)^2}$$

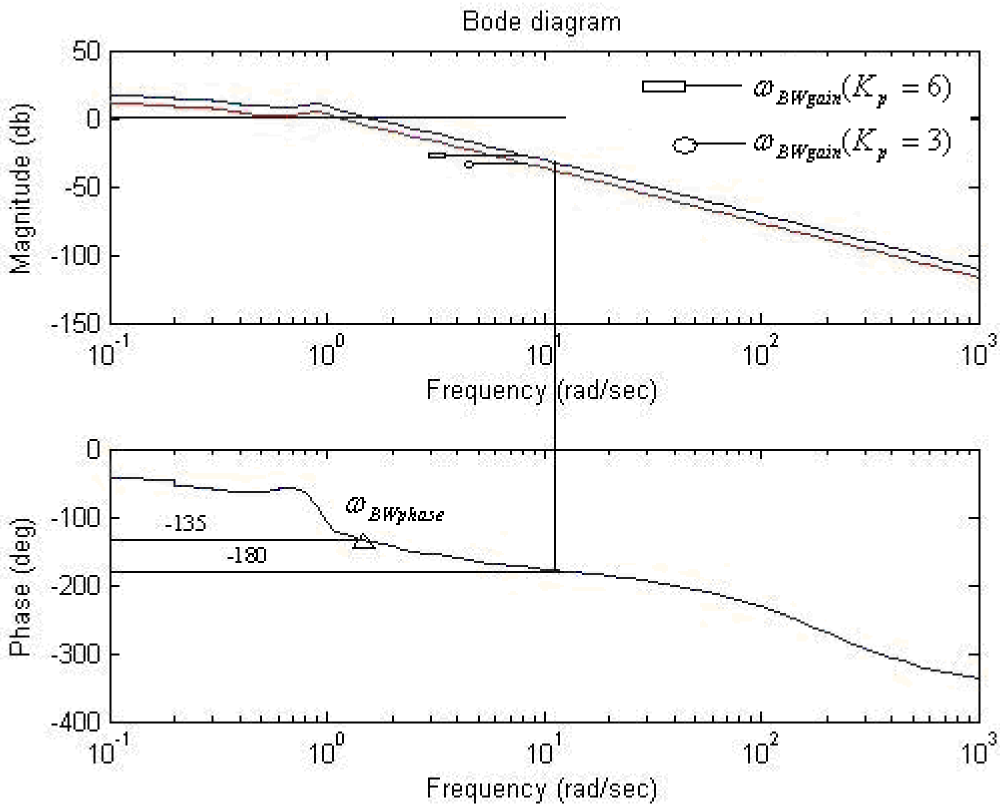

Figure 4. Bode diagram for closed loop with AFCS off

Using automatic flight control system (AFCS) OFF and ON for 1st order Padé approximation we obtained the following results:

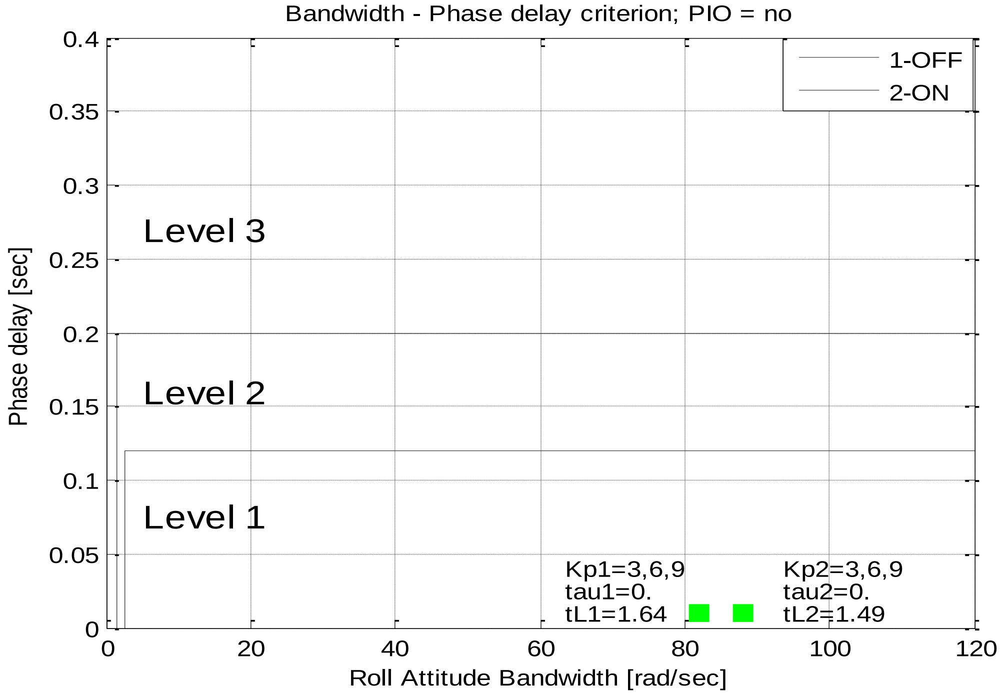

Figure 5. Pilot gain (K_p) variation

Fig. 5 shows the variation of the K_p parameter but these numerical simulations give us no information about changes in flying qualities level because varying K_p will obtain acceptable values for $\omega_{BWphase} < \omega_{BWgain}$ (see Fig.4).

In the next plot, the phase delay parameter τ_p was increased.

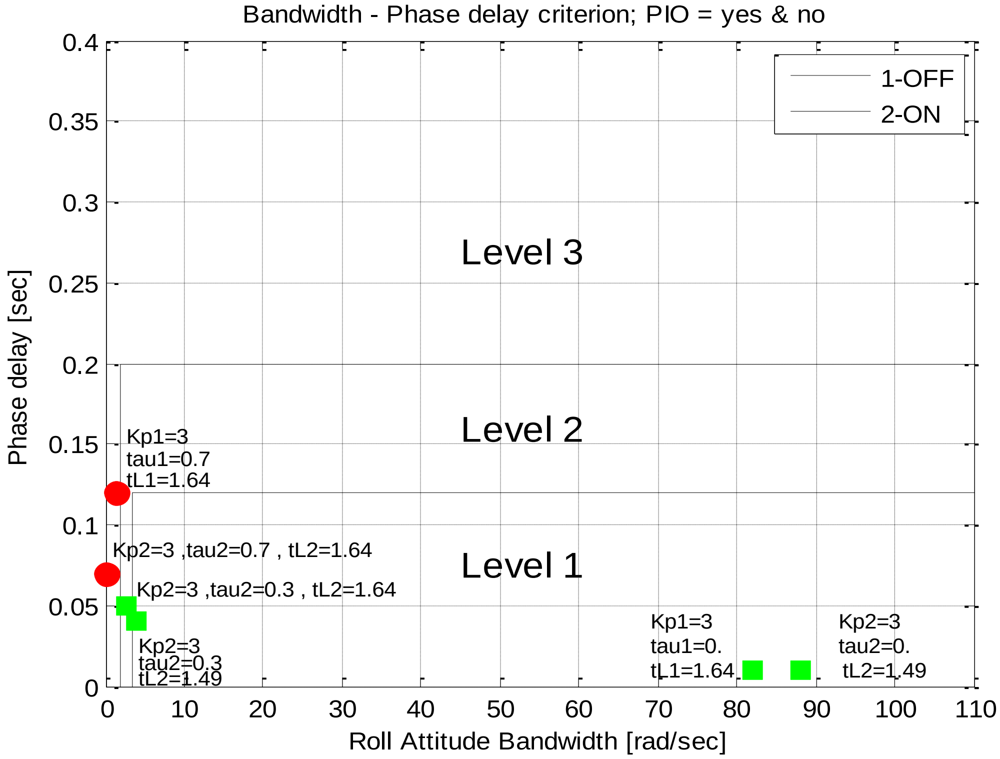

Figure 6. Phase delay (τ_p) variation

In this case the increase of the delay causes a deterioration of the lateral directional flying qualities.

The following figure shows a variation of the lead parameter, (T_L) that has a very good Level 1 PIO response.

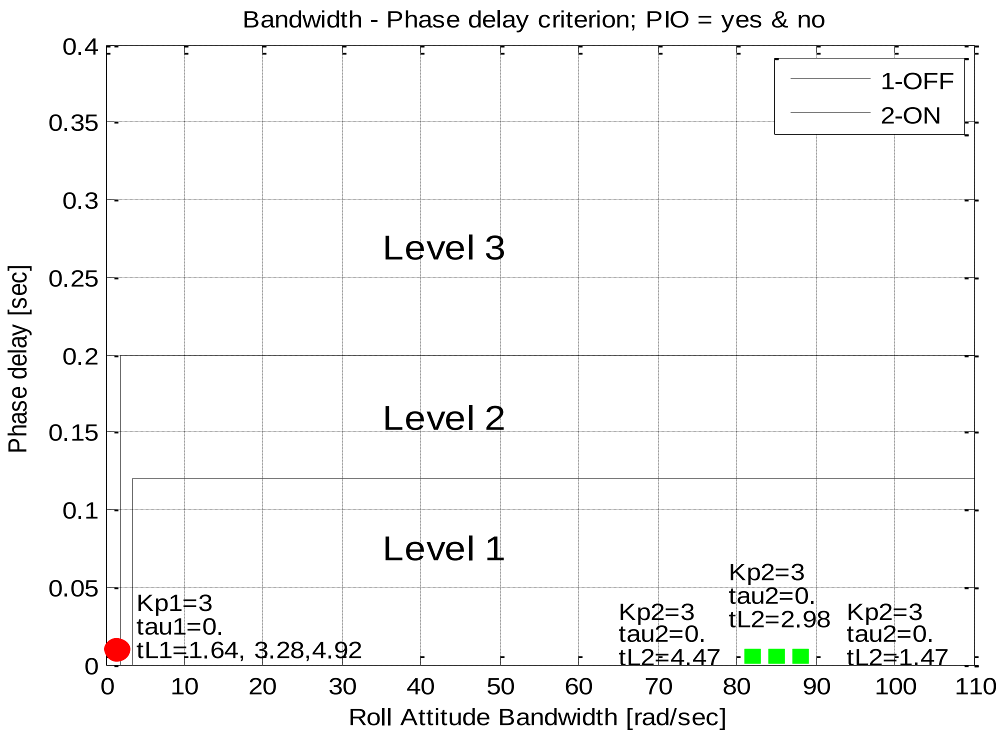

Figure 7. Lead (T_L) variation

In the last case we have analyzed the difference between 1st and 2nd order Padé approximation using the same transfer function for the helicopter.

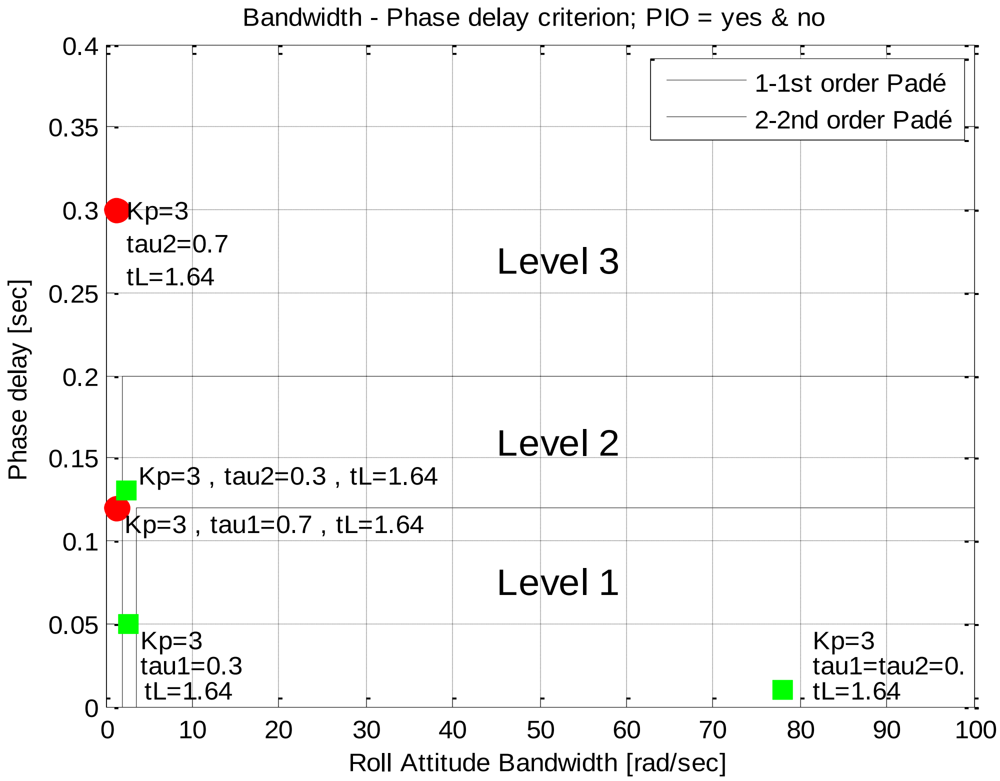

Figure 8. 1st order Padé approximation vs. 2nd order Padé approximation

Fig. 8 illustrates a comparison between 1st and 2nd Padé approximation on closed loop system with AFCS off. The differences appear only in phase delay with no change in bandwidth.

5. CONCLUSION

The bandwidth criterion is a representative approach to evaluate Cat. I – RPC phenomena. The bandwidth and phase delays have been shown to be effective parameters to discriminate between level 1, 2 and 3 handling qualities on the CH53D helicopter example closed loop system with AFCS off and on. The shape of the phase curve above ω_{BW} is the key factor.

This article presents numerical simulations on the PIO problem and how it is tackled in handling qualities criteria. Regards to estimation of ω_{BW} and τ_p parameters, an "in home" code has been developed in flying qualities HQ toolbox inside of HELISTRA program.

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