HARMONIZING REAL-TIME OSCILLATION VERIFIER (ROVER) WITH HANDLING QUALITIES ASSESMENT FOR ENHANCED ROTORCRAFT PILOT COUPLINGS DETECTION

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Abstract

This paper introduces an improvement of existing Real-Time Oscillation VERifier (ROVER) by including rotorcraft handling qualities (HQ) assessment to achieve enhanced Rotorcraft Pilot Coupling (RPC) detection. First, the classical ROVER algorithm was implemented. Then, it was tested on desktop simulations. Next, it was evaluated by post hoc analysis of simulator test data of a single axis roll tracking task with a RPC trigger, which was the applied additional time delay on pilots lateral cyclic control path. Finally, degradation of HQ is proposed to be included in the final ROVER results. Classical ROVER results showed that with increasing severity of the applied time delay (100ms to 300ms), the number of detected RPC events increased and the application of classical ROVER was confirmed. The additional HQ detection feature of the improved ROVER benefits from correlation of the measured data with the frequency domain spectrum assessment of ADS-33E bandwidth-phase delay criterion. Offline desktop simulation and available simulator test data of roll tracking were post processed with the improved ROVER and capabilities of detecting HQ deviation were evaluated by various time delay applied configurations of Bo105 rotorcraft simulation model. Improved ROVER showed promising results of detecting degradation in HQ and a tentative method of converting this detection into a possible new HQ flag in ROVER is discussed in the paper.

SYMBOLS

A	System matrix
ampl	Relative amplitude of stick or body signal
B	Control matrix
freq	Frequency of stick or body signal
K	Gain between stick input and swashplate input command
p	Rotorcraft roll rate
peak_curr/prev	Current/previous stick or body peak value
phase	Phase delay between body and stick signal
tpeak _curr	Time of current/previous stick or body peak
Δt	The time lag between the body peak and stick peak
$\lambda\tau$	The time lag between the body peak and the stick peak
λ_ω	Bandwidth frequency distance from current mean HQ to next HQ level in ADS-33 requirement
μ_{HQ}	Final HQ deviation
τ_p	Phase delay
θ_{1c}	Swash plate input due to lateral cyclic
ω_c, ω_{2c}	Crossover frequency, double crossover frequency
ω_{BWg}, ω_{BWp}	Gain/phase bandwidth frequency
ξ_τ, ξ_ω	Region of HQ points consideration in frequency and phase delay axes in ADS-33

ACRONYMS

ADS-33E	Aeronautical Design Standard
A/RPC	Aircraft/ Rotorcraft Pilot Coupling
ARISTOTEL	Aircraft and Rotorcraft Pilot Couplings: Tools and Techniques for Alleviation and Detection
CH	Cooper-Harper rating scale
DHQ	Degraded Handling Qualities
HQ	Handling Qualities
HQR	Handling Qualities Rating
OLOP	Open-Loop Onset Point
PIO	Pilot Induced Oscillation
PIOR	Pilot Induced Oscillation Rating scale
ROVER	Real-Time Oscillation VERifer
TUD	Delft University of Technology

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1. INTRODUCTION

Aircraft and Rotorcraft Pilot Couplings (A/RPCs) are sustained inadvertent oscillations of aircraft or rotorcraft caused by an anomalous interaction between the pilot and vehicle [12]. To prevent A/RPCs to occur, vehicle A/RPC susceptibility should be detected as early as possible in the design process. But as this is difficult and cannot be guaranteed, it is logical to design a system capable to detect in real-time A/RPC and warn the pilot. Based on the warning, the pilot can decide to change his/her control strategy to prevent occurrence of fully developed A/RPCs.

For real-time detection, a Real-Time Oscillation VERifier (ROVER) was developed more than a decade ago for the U.S. Air Force [14]. This initial ROVER algorithm was applied only to fixed wing aircraft. Since the first development, ROVER has been refined and assessed in ground based simulation campaigns.

Recently, the ROVER concept has been applied to rotorcraft in Italy [11] and in the United Kingdom [7]. In these examples, simulation tests were performed along the longitudinal axis and the algorithm was able to detect RPCs and discriminate these detections from other oscillatory motions.

However, a drawback of ROVER is that it can be prone to false alerts. For example the classical ROVER algorithm was able to detect correctly only 34 per cent of the cases whenever the pilot did not observe an APC. Besides, both pilot and ROVER detected an APC in 91 per cent of the cases [1]. Perhaps a much cumbersome issue is the fact that users can select their own thresholds for PIO detection. If these are not set correctly, significant over/under prediction will occur.

Therefore, there is a need for improvement of the ROVER algorithm to cope with false alerts due to over detecting A/RPC events. Section 3.1 states a proposed method as a remedy. However, the aim of this study is predominantly to merge handling qualities (HQ) assessment with ROVER detection capabilities and enhancing the detection algorithm and increasing the pilot awareness of a RPC event.

Mitchell reported that the subjective rating and interpretations of A/RPC solely depends on the pilots experience and skill [16]. There is no specific A/RPC-prone pilot, but there are certain conditions that most probably drive majority into undesirable couplings with the vehicle dynamics during the active task [17]. This brings the issue of alerting the pilot to the status of the vehicle, more specifically RPC trace of the current situation. At this point, classical ROVER just tells the problem to be the “resultant” effect of having an out-of-phase, excessive control and helicopter body rate, but it could not specify the source of the problem. An enhancement to increase the awareness of the pilot to the source of an A/RPC would be beneficial to perform any pilot strategy to cope with the developing A/RPC. In this study, the aim is to provide the degradation of HQ as a new ROVER alert. The pilot will therefore know if the alert is due to degradation of HQ or due to his/her instant piloting technique. This study does not aim to provide remedy to “suppress PIO”, but rather extends the information that pilot would receive during a RPC event. One would argue that during a chaotic event like RPC, pilot would need less distraction and disorienting alerts, and thus he/she could achieve higher concentration levels. But it must be noted that, especially the continuity of a RPC also depends on that long lasted close-loop tight control of the pilot rather than a simple “back-off” strategy, which would possibly solve the occurring RPC issue. Hence, letting the pilot know about the status of the RPC is still believed to be a beneficial feedback to prevent, or suppress the on-going RPC.

A moderately developed A/RPC event generally provides sufficient information to ROVER to detect the occurrence of A/RPC, because aircraft or rotorcraft responses and the pilot inputs are becoming distinctive from normal flight. For example, oscillations and phase lag between pilot input and aircraft or rotorcraft response start to grow. However, an A/RPC event in the initiation phase is difficult to discriminate from normal flight. Therefore, one of the improvements which can be made to ROVER is the capability of providing additional information on A/RPC danger at the starting phase of an A/RPC. The goal of the paper is to connect HQ criteria analysis with ROVER in order to improve the detection capability of A/RPC events. In other words, any detection in noticeable HQ level degradation will be supplied through the warning system to the pilot before getting involved in a fully developed RPC. As a consequence the pilot is warned first about the possible HQ change and he/she can adapt their control strategy accordingly. This feature will be used to inform the pilot if they are over-controlling or that the rotorcraft has degraded handling qualities (DHQ).

In this paper, the analysis is limited to Category I Pilot Induced Oscillations (PIOs), a common linear A/RPC event which is defined in reference [9] as follows:

> *“Cat. I assumes linear behaviour of the pilot and control system. The oscillations are associated with high gains and increased time delay effects, typically resulting in a destabilization of the closed loop pilot-vehicle system.”*

The US Army Aeronautical Design Standard – 33 (ADS-33E [1]) is the current document applicable to assess the HQ of rotorcraft. The ADS-33E standards contain an extensive combination of specific HQ criteria and a variety of specified manoeuvres that can be used to validate the level of HQ of a specific helicopter class and configuration.

In ADS-33E, one specific requirement is the bandwidth criterion. This is a frequency domain criterion based on the bandwidth frequency (ω_{BW}) and phase delay (τ_p) (see Section 6.1 for a more detailed explanation). The criterion is aimed at short-term control response. An indicative measure is that a system with good HQ will have a high bandwidth and a system with poor HQ will have a low bandwidth. Physically, low values of bandwidth indicate a need for pilot's control adjustment in the control loop (lead equalisation) to achieve the required mission performance. Excessive demands on pilot's control adjustments (lead equalisation) result in degraded DHQ. Ref. [13] states that the bandwidth criterion is the most reliable measure for A/RPC Category I prediction which was introduced in ADS-33E

2. WHAT DOES A/RPC PHYSICALLY MEAN

In Ref. [13] a definition is given for A/RPC:

> *"A PIO exists when the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 degrees out of phase with the pilot's control inputs, and when the input control and output state are large enough to care."*

From this definition four conditions must be present to say that an event is an A/RPC event [15]:

(1) There must be an oscillation. Though, an oscillation as sole criterion is not sufficient for declaring an event as an A/RPC, because oscillations happen often during flight.

(2) The aircraft must be out of phase with the pilot input. It means that there is a lag of 180 degrees between the stick input and the roll or pitch angle for example.

(3) The frequency of the oscillation must be in the A/RPC frequency range where the pilot has active control (Approximately 1-8 rad/s).

(4) Finally the amplitude of the control inputs and the aircraft response must be large enough to care. If for example the body response is within the A/RPC region of interest, but the amplitude of the stick and body responses are small, the pilot will not classify the event as being an A/RPC.

3. THE CLASSICAL ROVER ALGORITHM

The ROVER algorithm for fixed wing aircraft was first developed by Mitchell et al. in 2000 [14]. ROVER can detect oscillations of the pilot input and response of the aircraft in a real-time fashion. The algorithm has two inputs: the pilot stick input (for example the lateral stick) and the body rate response (for example the roll rate).

Within the ROVER algorithm, first the stick and body input are filtered to remove high frequency oscillations and prevent issue of unrealistic large phase delay detection.. This is done using a third order Butterworth filter with a cut-off frequency of 8 rad/s to be able to observe oscillations of the body up to 8 rad/s. An example of a filtered and corresponding unfiltered signal is shown in Figure 1. As can be seen, high frequencies are removed and the extreme values are slightly reduced at some points. Although the Butterworth filter smoothens part of the signal, still the issuing of false flags is possible. To reduce this even further thresholds are applied for frequency of the body, amplitude of stick input and body and phase delay. Further peak selection logic is implemented to reduce false alerts. The next subsections give a brief explanation on this peak selection logic.

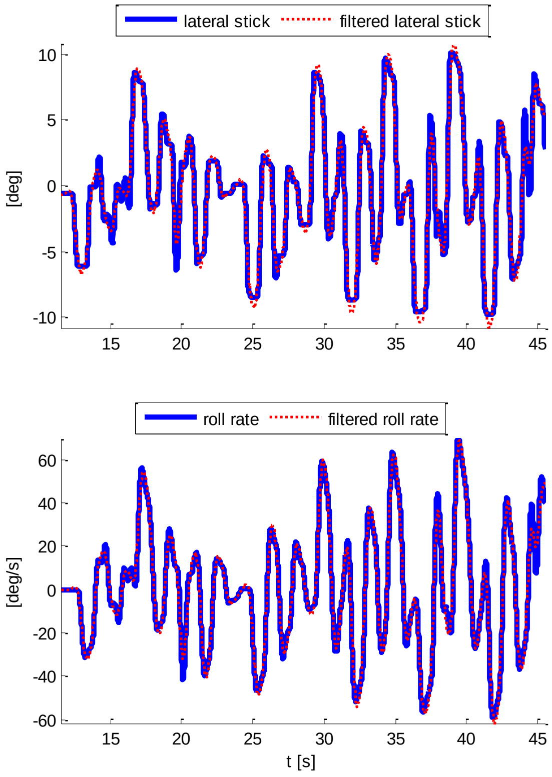

Figure 1: Original data (blue) and filtered data (red dotted)

In the classical ROVER algorithm the body rate response is used rather than the body attitude response. The reason to use rate response is two fold. First, the body angular response is small at the initiation phase of an A/RPC event making it difficult to detect motion of the body. Second, the angular response has non-zero mean. It is noted though that the phase delay during an A/RPC event is 90 degrees if the body angular rate is taken instead of the body angular motion [13].

Using the stick input and the rotorcraft response as inputs, the algorithm calculates outputs: the amplitude and the frequency of the rotorcraft response and also the phase delay between the pilot and the rotorcraft response. Next, a short explanation is given how ROVER algorithm calculates these outputs.

3.1. Amplitude

The amplitude of the stick input and rotorcraft motion is calculated using the peaks of the motion with the following relation:

$$ampl = \frac{peak_{curr} - peak_{prev}}{2} \quad (1)$$

In this equation the amplitude of either the stick input or body rate response is based on the current and previous peak values of the signal.

The peak values are determined by comparing consecutive extremes with so called *peak selection thresholds* for the time between extremes and difference of the magnitude of two successive extremes. When the *peak selection thresholds* are met the current extreme is considered a peak. Else the algorithm rejects the current peak and tries to find the next extreme value. This is how the calculation in the classical ROVER works.

A simple method to reduce false flags is already accomplished by applying the following method. If the threshold values are met, the extreme is stored as a peak of the signal. If, on the other hand, successive extremes are within the limits for peak selection, then they are stored in an array after which the average becomes the peak value. This logic is applied in the ROVER algorithm implemented by Delft University of Technology (TUD).Although, this is not the innovative part of improving RPC detection accuracy (See chapter 7), it improves the detection quality of ROVER especially around peak values which oscillate around a maximum or minimum value.

3.2. Frequency

The frequency of the body motion is calculated by using equation (2). Note that the frequency is based on the time of the current and previous peak. The calculation of the stick frequency can be calculated in an analogous way.

$$freq = \frac{2\pi}{t_{peak\_curr} - t_{peak\_prev}} \quad (2)$$

3.3. Phase delay

The phase delay is determined by calculating the time difference between corresponding minimum or maximum peaks of body and stick. Because of actuators in the system and the rotorcraft dynamics like low pass filters, not all stick frequencies result in a body response. The stick input is therefore noisier than the body response.

During simulation it is possible that multiple peaks of stick correspond to only one certain peak of the body. In this situation the average time of occurrence of the stick peaks are taken to perform the phase calculation.

The phase delay is calculated using:

$$phase = \frac{2\pi \cdot \Delta t}{freq_{body}} \quad (3)$$

In which Δt is the time lag between the body peak and the stick peak.

The calculated values of amplitude, frequency and phase delay are checked against threshold values and a score is issued dependent on the number of thresholds met. Thus, a maximum score of four is achievable and corresponds to a fully developed RPC detected event. If at two consecutive instances the score is three, the score is changed to 3.5 so a warning can be given to the pilot that he/she is approaching a RPC event.

4. SIMULATION EXPERIMENT SET-UP

ROVER was tested and evaluated using offline simulations on a desktop computer. Moreover, simulator trials were conducted in the SIMONA research simulator at TUD within the ARISTOTEL project [10]. A full description of facility can be found in ref.18. Helicopter pilots from the Royal Netherlands Air Force and UK airlines were involved in the ARISTOTEL RPC trials. The simulator data were post-processed using ROVER to assess the RPC detection capability.

4.1. The simulation model

From frequency analysis of the model, the HQ rating can be determined as stated in ADS-33E. For this purpose, an in-house developed linear model of the Bolkow 105 (Bo105) was used. The ultimate simulation model contains 16 states; 6 translational and rotational body states, 3 flapping states, 3 lead-lag states, 3 Pitt-Peters dynamic inflow states and 1 tail rotor inflow state. But to achieve simplicity for the analysis and to be able to compare with the simulator test campaign roll tracking task, only the lateral degree of freedom was considered for the further analysis.

In addition to the helicopter roll model, the following simple low pass filter model for the actuator between the pilot lateral cyclic input and the swashplate was used with the time constant of 0.04 seconds:

(4) $$\frac{\theta_{1c}(after\_acuator)}{\theta_{1c}(before\_acuator)} = \frac{1}{0.04s+1}$$

One important detail for A/RPC studies is the rate limiting effects of such main rotor actuators. Numerous studies and criteria focus on actuator rate limiting issues [12] (e.g. CAT II A/RPCs, OLOP criteria, etc). But in this study, there was no rate limit acting on the actuator. Excluding such nonlinearities from the proposed post process analysis aided to narrow down the RPC trigger element in the comprehensive assessment.

Finally, to simulate a Category I RPC event, a time delay was implemented between the pilot input and the resultant command to the swashplate angle. In this way, the helicopter HQs are degraded artificially. In Figure 2 the resultant model of the simulation set-up is presented.

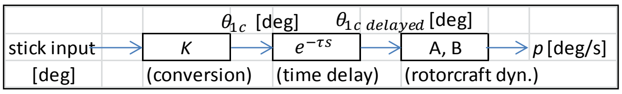

Figure 2: Mathematical simulation model with applied time delay

4.2. Simulator experiment

The simulator trials consisted of a roll tracking task flown at 60 knots. Using the linear model for the roll tracking task, the yaw and longitudinal axes were locked.

Figure 3 shows the roll command tracking task to be completed which was first used in GARTEUR activities [5].

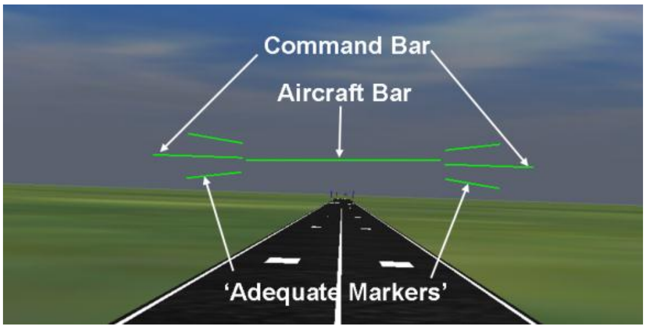

Figure 3: Roll command tracking symbology [5]

- Aircraft Bar. This bar remains fixed to the aircraft body axis and provides an indication to the pilot of the aircraft roll angle in relation to the outside world.
- Command Bar. This bar is independent of the aircraft body axis and is fixed with respect to the inertial or earth axis system.
- Adequate Performance Marker Bars. These bars are set at an angle of ±8° to the centre of the aircraft bar and would flash from between two and zero seconds prior to the next command bar angle change.

The pilot's task was to maintain alignment between the aircraft and command bars as far as practicable. The 'alignment' was judged satisfactory if the aircraft bar lay between the adequate performance marker bars. Prior to the adequate bars starting to flash, this level of alignment must be achieved. The command bar sequence is pre-determined, and four different sequences were used:

- 'R1' (initial roll to the left);
- 'R2' (roll angles opposite sign to 'R1');
- 'R1L' (as per 'R1' but duration between commanded angle changes doubled) and
- 'R2L' (roll angles opposite sign to 'R1L').

First, the experiment was conducted with no time delay between the pilot input and the command to the swashplate. Then the task was repeated for time delays of 100, 200 and 300 ms. Data was post processed using the ROVER algorithm.

4.3. Pilot rating of HQ and RPC

At each roll tracking task run the pilot's subjective opinion on the HQ level and RPC level was assessed. For the HQ rating the Cooper-Harper (CH) rating scale was used. A complete description of the scale can be found in ref. 3. Table 1 shows the HQ level corresponding to the CH rating as given by the pilot [2]. Level one HQ means that the helicopter has excellent response and the pilot finds no difficulty in controlling the rotorcraft. Level two HQ means that the helicopter has DHQ. The pilot may find some difficulties in controlling the rotorcraft. Level three HQ is an indication that the helicopter has poor HQ.

Table 1: Corresponding HQ level to CH rating scale

CH	*HQ*
1,2,3	Level 1
4,5,6	Level 2
7,8	Level 3

Also the pilot's opinion about the RPC tendency of the rotorcraft is asked using the pilot-induced oscillation rating (PIOR) scale (Figure 4). A complete description can be found in ref 4.

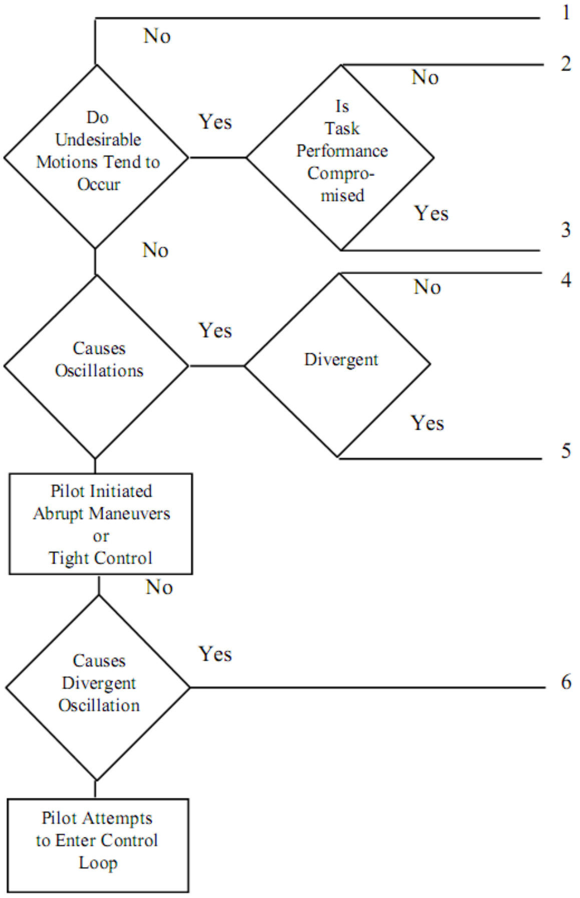

Figure 4: PIOR rating scale

5. RESULTS OF ROVER

5.1. Threshold values

From the offline simulation practices, it was observed that threshold values of peak selection method, as explained in section 3.1 , depend on:

- The order of the filter as well as the cut-off frequency.
- The system dynamic behaviour.

  When changing the time delay, to get a reliable peak picking, the thresholds need to be adjusted for each trial configuration. This also means that for a longitudinal task most likely the threshold values are different than a lateral task, depending on the vehicles response margin in longitudinal axis.

Thresholds for peak selection were chosen after inspection of the simulator trials for different time delays. The threshold values for the ROVER output have been determined by inspection of the output of the calculated amplitude, frequency and phase delay. The thresholds are presented in Table 2. This is one of the shortcomings of ROVER, i.e. the threshold values are dependent per flight task, helicopter and configuration.

Table 2: Threshold values for ROVER

Threshold name	*Value*	*Unit*
Stick amplitude	2.5	reg
Roll rate amplitude	18	reg/s
Frequency	1 to 8	rad/s
Phase delay	75	deg
Peak selecting threshold	*Value*	*Unit*
Δstick extreme	0.2	deg
Δtime stick extreme	0.3	sec
Δroll rate extreme	1.2	deg/s
Δtime roll rate extreme	0.3	sec

5.2. Frequency sweep results

To check the ROVER algorithm, some simple offline simulations were performed using a frequency sweep for stick from 1 to 8 rad/s at 60 knots for the lateral axis. The lateral stick and roll rate were fed to ROVER and the tests were repeated for the time delays of 100, 200 and 300 ms.

In Figure 5 an example of the ROVER output is presented for the frequency sweep with a 300 ms time delay. The first (upper) subfigure shows the stick and body motion after application of the Butterworth filter.

The second subfigure (middle) shows when the threshold value for stick amplitude, roll amplitude phase delay or frequency is met. If they are met, a flag is issued. The last subfigure (down) indicates the total ROVER score which is the total number of flags at each time. A score of four indicates a RPC detected (RO4) and a score of 3.5 indicates danger of RPC about to happen (RO3.5).

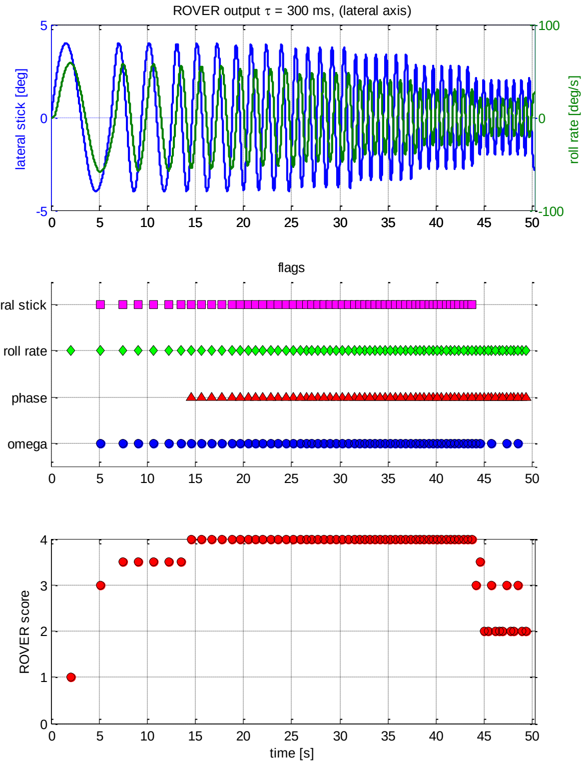

Figure 5: ROVER output for roll tracking at 60 knots with 300 ms time delay

Table 3 shows the output of the ROVER at 60 kts for the frequency sweep. It can be concluded that indeed, when degrading the HQ of the rotorcraft by introducing a time delay, the number of RPC detected warnings increases with increasing time delay. In general the number of warnings for RPC danger reduces with degrading HQ. Therefore, for DHQ level a dangerous oscillation of the rotorcraft develops faster into a RPC event than for a helicopter with better HQ.

Table 3: number of ROVER warnings for 50 seconds duration frequency sweep for 1 to 8 rad/s for roll axis at 60 kts

τ [ms]	*RO4*	*RO3.5*
0	0	54
100	26	28
200	43	11
300	48	6

5.3. Simulator results

Examples of the simulator results for two different pilots for the 300 ms time delay case are found in Figure 6 and Figure 7. The first two columns of Table 4 and Table 5 display the complete results for all roll tracking trials for two pilots.

As in the frequency sweep cases the number of RPC detections increase with increasing time delay.

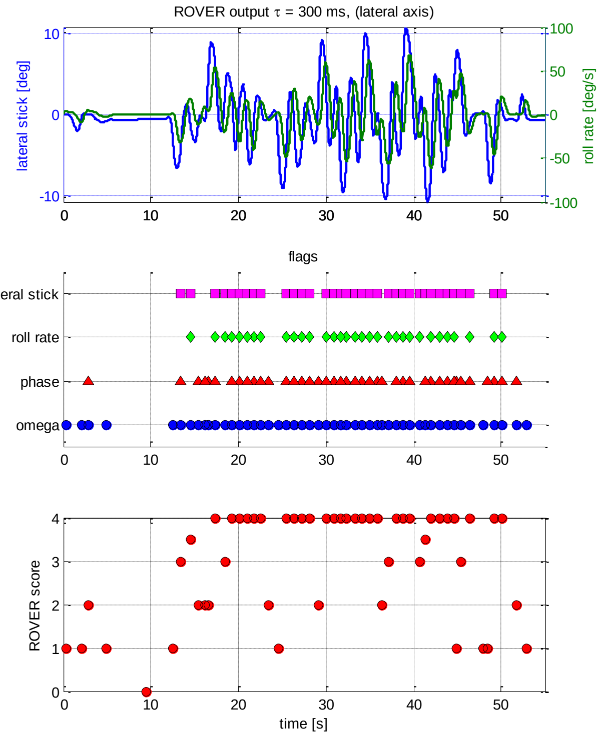

Figure 6: ROVER output for roll tracking at 60 knots with 300 ms time delay in simulator for Pilot 1

Table 4: Pilot 1 number of ROVER alerts, Handling Qualities Rating (HQR) and Pilot-Induced Oscillation Rating (PIOR)

τ [ms]	*RO4*	*RO3.5*	*HQR*	*PIOR*
0	0	10	4	1
100	1	9	7	1
200	10	8	7	4
300	28	2	7	3

Table 4 and Table 5 also the HQR and PIOR awarded by the pilots are presented. It is interesting to note that Pilot 2 did not report any noticeable RPC during the roll tracking simulator experiments. By close inspection to the stick input and roll rate output temporal behaviour (Figure 6 and Figure 7) it is noted that there are less oscillations in the traces of Pilot 2 with large time delay configurations.

This could be an indication that Pilot 2 is more able to control a helicopter with degrading HQ and that he possibly unintentionally changed his control strategy to keep the rotorcraft within its performance envelope. Though, he might not be aware of the degradation of the HQ because of the excessive time delay. This could lead to a dangerous situation as RPC events are likely to occur at DHQ levels.

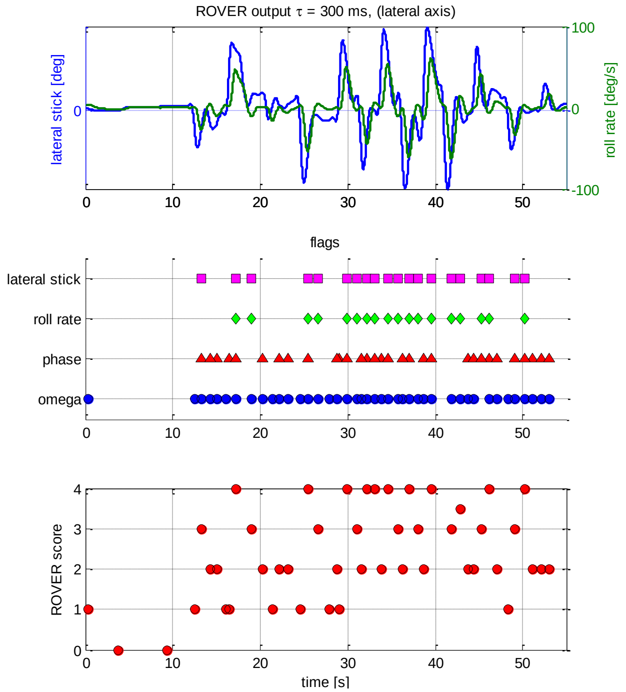

Figure 7: ROVER output for roll tracking at 60 knots with 300 ms time delay in simulator for pilot 1

Table 5: Pilot 2 ROVER alerts, HQR and PIOR

τ [ms]	*RO4*	*RO3.5*	*HQR*	*PIOR*
0	-	-	-	-
100	2	8	3	2
200	8	1	4	2
300	10	1	4	2

6. HQ ASSESMENT

In ADS-33E the requirements for helicopters is given for the levels of HQs. An example of the HQ for roll tracking at flying speed higher than 45 knots is presented in Figure 8. This figure presents the HQ requirement for roll tracking task with forward speed higher than 45 kts and was used for determine the HQ levels of the experimental configurations. However, requirements of Figure 8 apply to small roll angles only. It is assumed that the roll angles during the experiment were small enough and therefore the HQ chart of Figure 8 can still be applied to the simulator trial data to determine the HQ levels.

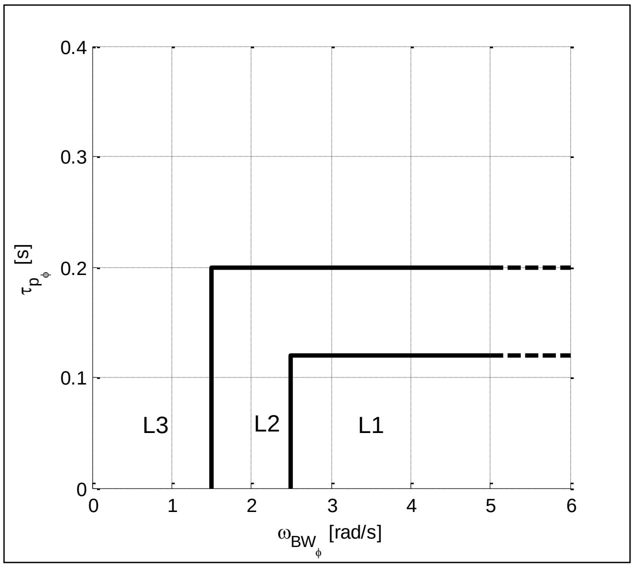

Figure 8: ADS-33E HQ requirements for roll axis at forward speed larger than 45 kts

RPC events are likely to occur at Level 2 and Level 3HQ's. This statement was also observed from the simulator results (see subsection 5.3).

The HQs are given as a function of the bandwidth frequency (ω_{BW}) (horizontal axis) and the phase delay (τ_p) (vertical axis), Therefore, to determine the HQ, the bandwidth and phase delay of the simulation model (Figure 2) needs to be determined for the time delay values under consideration.

6.1. Determination of bandwidth

The procedure for determining the bandwidth is also given in the ADS-33E document (Figure 9).

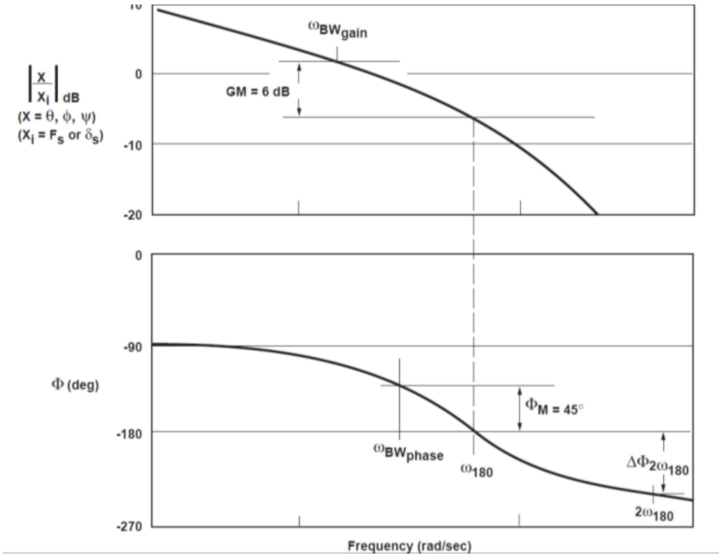

Figure 9: Bandwidth definition from ADS-33E [1]

The following steps illustrate how the bandwidth is determined:

- The Bode plot of the model is made after which the phase crossover frequency (ω_{180}) is determined. This is the pilot input frequency where the stick and the body motion get out of phase.
- Based on the crossover frequency a phase bandwidth frequency (ω_{BW_p}) is determined as the input frequency at which there is still a 45 degree lead of the stick with respect to the body rate.
- Also a bandwidth frequency gain (ω_{BW_g}) is determined which is defined as the input frequency at which there is still a gain margin of 6 dB with respect to the gain at the crossover frequency.
- Finally, the phase delay is describing the steepness of phase roll-off. It is defined as:

(5)
$$\tau_p = \frac{\pi}{180} \frac{\Delta\varphi_{2\omega_{180}}}{2\omega_{180}} \text{ [s]}$$

The bandwidth frequency is the smallest of the ω_{BW_p} and the ω_{BW_g} . Further, a guideline for RPC proneness is given in ADS-33E whenever the ω_{BW_g} is smaller than the ω_{BW_p} .

Figure 16 of Appendix A presents the bandwidth calculation for the simulation model (Figure 2) for the roll tracking task manoeuvre at 60 knots. Note that the bandwidth frequency decreases with increasing time delay. The only difference is the reaction time of the rotorcraft with respect to the pilot stick input which results in a time lag and therefore a phase lag between the pilot input and the body rate response.

6.2. HQ rating from ADS-33E

Figure 10 shows the ADS-33E HQR based on the bandwidth frequency and phase delay for the roll tracking task at 60 kts. It was found that for the roll tracking task, the degradation was from Level 1 at 0ms time delay down to Level 3 at 300 ms. From this figure it is proven that the HQ are degraded by introducing a time delay.

Further, it is noted that although the HQ are degraded, there is no indication of RPC proneness based on the ADS-33E guideline.

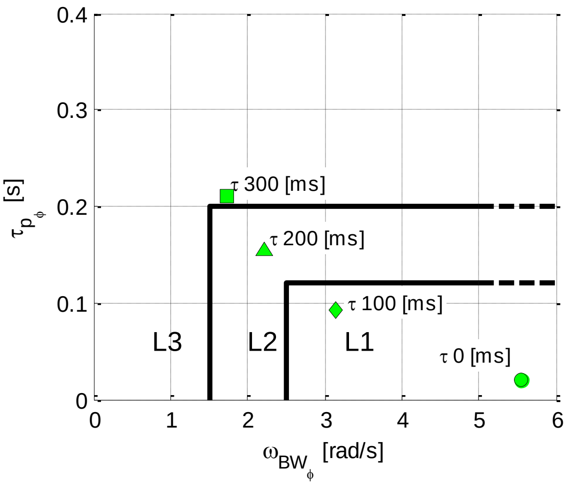

Figure 10: ADS-33E HQ levels for simulation model

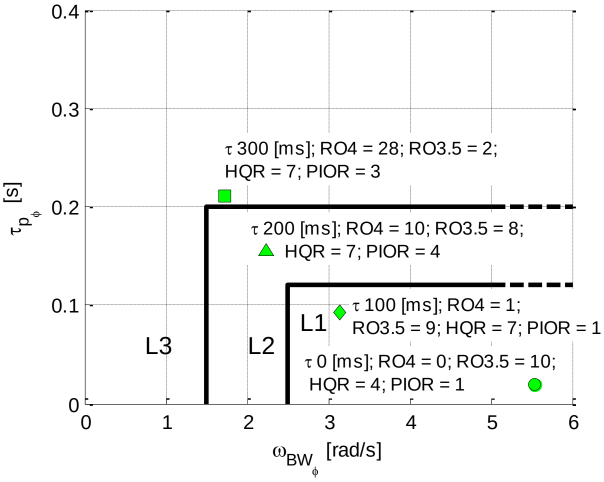

Figure 11: ADS-33E HQ levels for simulation run of pilot 1; number of 4 flags issued by ROVER and number of 3.5 flags issued by ROVER; HQR and PIOR;

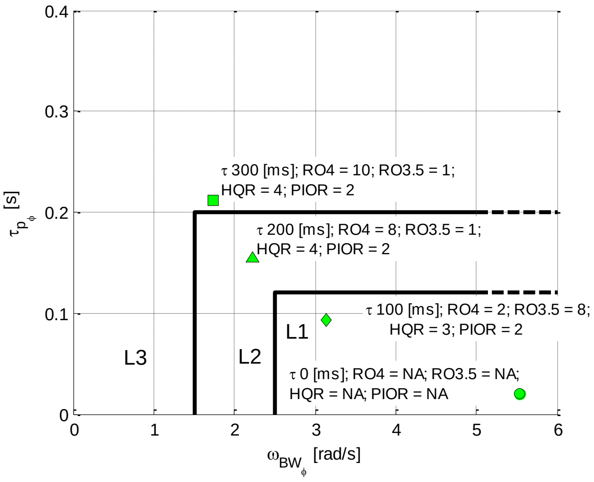

Figure 12: ADS-33E HQ levels for simulation run of pilot 2; number of 4 flags issued by ROVER and number of 3.5 flags issued by ROVER; HQR and PIOR; (green = no RPC prone; red = RPC prone)

7. PROPOSED IMPROVEMENT OF ROVER

To improve the ROVER algorithm with HQ degradation detection, the following method is applied. Alongside ROVER's classical output, the ROVER algorithm is extended to generate the stick frequency using equation (2).The ROVER score at each instant together with the phase delay are sorted with corresponding stick frequency.

Using these data scatter points from the output of the ROVER can be superimposed on the phase diagram of the Bode plot from the simulation model. If the scatter points deviate from the original Bode plot, the HQ may been degraded or improved. This occurs for example when introducing a time delay. The ROVER scatter superimposed on the Bode plot is presented for both pilots in Figure 17 and Figure 18 of Appendix A. Zoomed versions of the graphs are presented below. Also the RPC detected events are indicated on the Bode plot in yellow color.

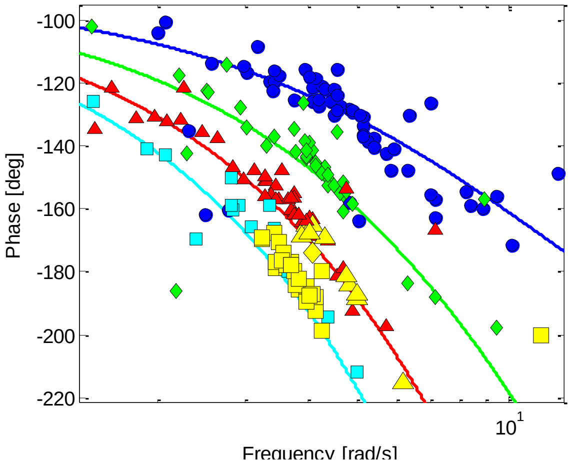

Figure 13: Zoomed phase Bode plot with superimposed ROVER output for pilot 1. Simulation model phase plot: blue = no time delay; green = 100 ms time delay; red = 200 ms time delay, turquoise = 300 ms time delay. Coloured points are corresponding ROVER output. Yellow markers are corresponding RPC detected points by ROVER.

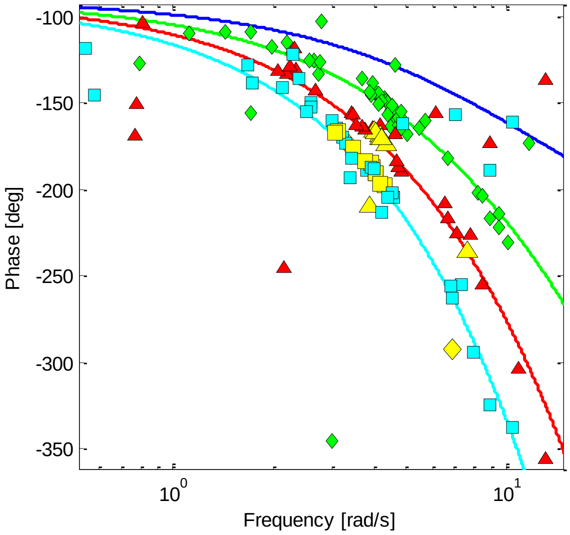

Figure 14: Zoomed phase Bode plot with superimposed ROVER output for pilot 2. . Simulation model phase plot: blue = no time delay; green = 100 ms time delay; red = 200 ms time delay, turquoise = 300 ms time delay. Coloured points are corresponding ROVER output. Yellow markers are corresponding RPC detected points by ROVER.

From Figure 13 and Figure 14 it is observed that in general, when the time delay is increased or decreased the ROVER scatter points are mainly matching the corresponding phase graph on the Bode plot. Therefore, degradation in HQ can be detected in quasi real-time if the algorithm is applied on streaming data.

Another observation is majority of the RPC detected (4 flags, yellow markers) frequencies are more or less around the crossover frequencies of the pilot (180 degrees) for the controlled vehicle dynamics. Hence, considering a same amount of pilot control input, possible RPC zone will be around crossover frequencies, not the high frequency pilot activity, nor the likelihood of low frequency pilot compensation. This observation also agrees with results of Ref.16.

Pilot 2 gives only a PIOR of 2 at level 3 HQ. Further, he does not experience the degradation of HQ to level 3 [Figure 12]. Contrary, Pilot 1 gives high rating for RPC which matches the output in Figure 13.

To alert Pilot 2 to the fact that the HQ have degraded when flying with a time delay of 300 ms, improved ROVER could inform the pilot about this HQ degradation. Thus, even if the pilot experiences that the rotorcraft behaves as Level 1 or Level 2 HQ, the improved ROVER would warn him that actual HQ level has degraded and that the chance of a RPC event has increased. Thus, they could prepare themselves for a possible upcoming RPC, or a loss of control scenario (often caused by DHQ).

Improved ROVER is proposed to be able to simultaneously check for altering HQ levels. The combination of ROVER with the HQ degradation detection indicates the severity of RPC in quasi real-time process. This level of severity has only recently been applied in RPC analysis for rotorcraft real-time analysis [8].

- *No RPC*: If ROVER score is other than four and HQ level is not degraded, the pilot is in a safe situation of no RPC event to occur.
- *RPC danger*: If ROVER score is other than four but the HQ has degraded, the pilot is still in a safe situation of no RPC event, but he/she needs to be alert because the rotorcraft has degraded its HQ. Since RPC are likely to occur at DHQ levels the pilot needs to be alert of this.
- *Moderate RPC*: If ROVER score is 4 and the HQ remains unchanged, then the pilot knows that the helicopter has not DHQ but that the RPC is due to the pilot control strategy.
- *Severe RPC*: If ROVER score is 4 and the HQ has degraded, the pilot knows that he enters a dangerous situation in which the rotorcraft has degraded and entered a RPC. The control strategy of the pilot must be changed in order to avoid a fully developed RPC event.

Since the pilot is alerted about the possible DHQ, the RPC detection accuracy is believed to be improved. This is because the source of the RPC in combination with classical ROVER will indicate a level of severity of the warnings given.

7.1. Tentative HQ Flag Determination for ROVER

In addition to detection of HQ level change as shown in previous sections, next step would be how to present this warning to the pilot during the simulation run. A tentative method is proposed in this section to illustrate a way of determination of the resultant HQ deviation and an attempt to describe a new flag to represent this HQ deviation.

As being theoretical at the moment, no absolute values are given on any variable or parameter. To keep the consistency, the ADS-33E roll bandwidth-phase delay criterion chart is used for illustrative purposes.

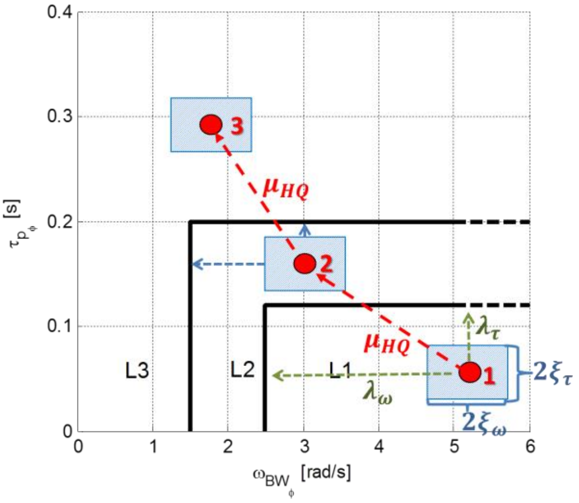

Figure 15: Tentative HQ flag determination of ROVER, for the roll bandwidth-phase delay criterion of ADS-33E.

Figure 16 describes the proposed HQ determination metrics: the filled circles indicate the mean of neighbour handling quality points within the vicinity of epsilon $\pm\xi_\tau(\mathrm{s})$ for phase delay, $\pm\xi_\omega(\mathrm{rad/s})$ for the frequency (hence, these epsilons form a rectangle of vicinity due to the fact that determined HQ data will be scattered, and it is not aimed to detect the HQ change for every single determined point (see Figure 13 and Figure 14), instead, the significant change is desired to be detected). When the mean of the scattered data from ROVER are gathered, the mean HQ point will be determined for the content within the epsilon rectangle. Depending on this mean, the differences to the boundaries of the next HQ quality level are determined; λ_τ to the phase delay border, λ_ω to the frequency border. Therefore, the mean and it's orientation in the HQ chart will be clarified (point 1 in Figure 15). If the new HQ data is found to be out of the epsilon vicinity rectangle, they start to be stored in a new data set, namely the new epsilon vicinity rectangle, and they start to form a new mean for the new offset of data (point 2 in Figure 15). Then, the HQ change from one HQ point to the new HQ point (μ_{HQ}) is determined (as shown in Figure 15, from point 1 to point 2). Depending on the λ_τ and λ_ω of the new HQ point, this HQ deviation and its time derivative $(\frac{\Delta\mu_{HQ}}{\Delta t})$ will be used to produce the new HQ flag. The sub-rules are not defined yet, since the scattered data, data point HQ border onset, and unsymmetrical HQ border may lead further modifications. Nevertheless, this tentative method will be checked with desktop simulations with artificial noise in the simulated data. Then, a set of simulator tests will be used to check the validity of the new flag with real measurement data.

Hereby, it should be noted that like the thresholds of the classical ROVER, a tuning is required to obtain the significantly effective parameter boundaries. Small limits may end up with over sensitive detection of HQ due to scattered data, whereas high limits may result in under predicted HQ changes and lumped RPC detection. Hence, the settings will be checked for the next desktop and simulator trial data analyses with pilot in the loop tasks.

8. CONCLUSION

In this paper the ROVER algorithm was applied to a rotorcraft simulation exercise. It has been demonstrated that in the classical ROVER, with DHQ, the number of RPC detections increase.

In this paper the idea is presented of improving ROVER by inclusion of real-time detection of DHQ. This is achieved by superimposing the calculated phase and stick frequency of ROVER to the Bandwidth Phase Delay criterion of ADS-33E.

During simulator trials where the pilots were asked to perform a roll tracking task, it was shown that ROVER output and the bandwidth Bode phase plot matched for varying time delay values. As a result the bandwidth levels as given in ADS-33E (for example Figure 8) can be determined in a using ROVER output. Therefore it has been demonstrated that DHQ can be determined by improved ROVER and it showed its opportunity to be used in quasi real-time.

From the DHQ, a warning to the pilot can be provided. This will trigger the pilot to change his/her control strategy to keep the helicopter under control at the degraded HQ level and hopefully prevent a RPC event. The improvement of the ROVER lies in this regard. In this example classical ROVER does not detect a RPC, but with improved ROVER, the pilot knows that the HQ has degraded. Therefore, he/she already knows that if the control strategy is not adapted to this DHQ, the rotorcraft is more likely to enter RPC event.

By additional HQ information, it is believed that the onset of RPC is detected in an earlier phase such that RPC detection accuracy can be improved.

Finally there are some limitations of the improved ROVER:

- Only single axis detection is possible. For the analysis, only one axis control input and one axis helicopter response is used. No cross control information is used in the algorithm. Further investigation is required to determine if multi-axes application is possible.
- The improved ROVER is only applicable for velocity around trim conditions, because of linear model analysis used in the bandwidth criterion. Operation not around trim values does not indicate reliable HQ levels according to ADS-33, and therefore the outcome of ROVER may become unreliable.
- The improved ROVER algorithm only uses time delay as trigger (Category I A/RPC). No rate limiting is applied in the current analysis (category II A/RPC). Further research is required to investigate the applicability to rate limiting, CAT II PIOs.
- Only small deflections of helicopter response are allowed for the ADS-33E HQ figures to be applicable. Hence the amplitude of roll angle deviations assumed to be within this small deflection interval.
- Due to the averaged data usage, it is only possible to alert the pilot in quasi-real-time. There is no way to determine the current value of any variable as a peak or not, without experiencing the further data alteration in timeline. Hence, theoretically any ROVER originated algorithm can not function in perfect real time, but in quasi real-time.

Acknowledgements

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APPENDIX A

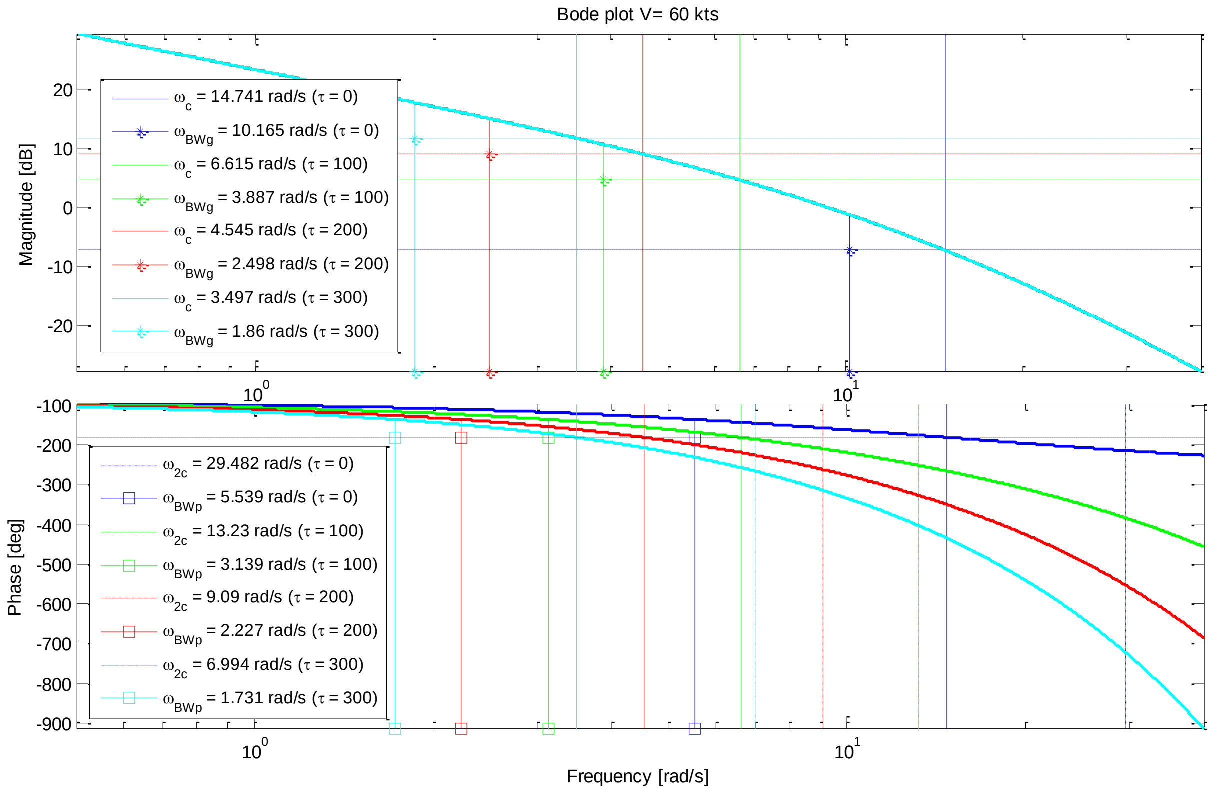

Figure 16: Bandwidth calculation for simulation model at 60 kts for lateral axis with varying time delay

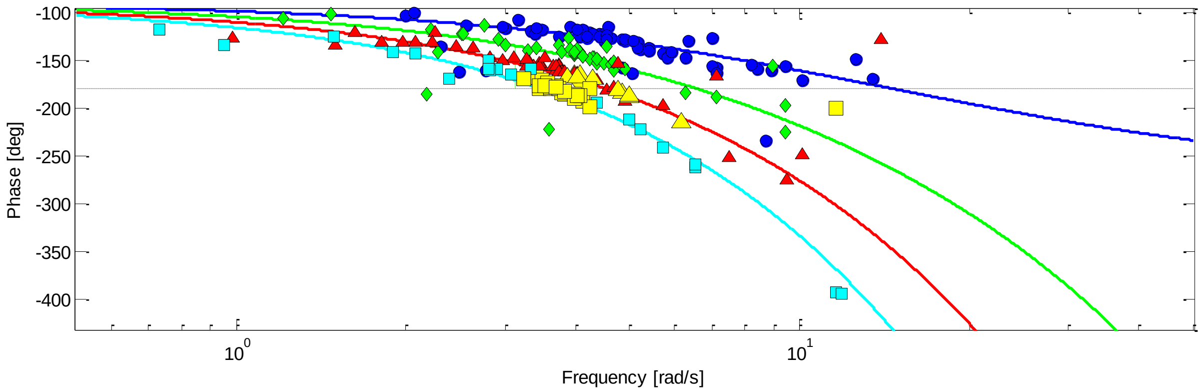

Figure 17: Scatter points superimposed in phase diagram for pilot 1

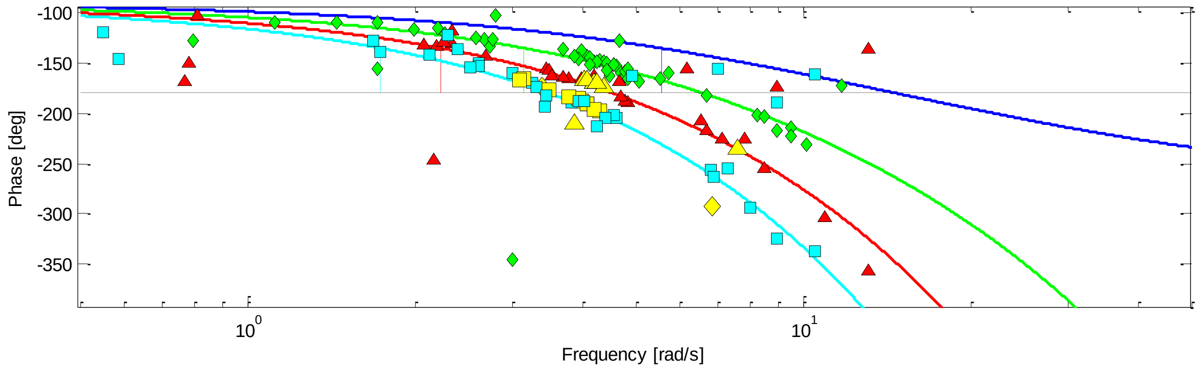

Figure 18: Scatter points superimposed in phase diagram for pilot 2