Capturing the switch between point tracking and boundary avoiding pilot behaviour in a PIO event

Nico Brinkerink Delft University of Technology N_Brinkerink@hotmail.com Marilena D. Pavel Delft University of Technology M.D.Pavel@tudelft.nl

Summary

Pilot induced oscillations (PIO) are dangerous phenomena known to have been the cause for several aircraft and rotorcraft accidents. Usually, the primary method for PIO prevention focuses on fixing the aircraft. However, a key contributor to PIO's is incorrect pilot behaviour. Properly understanding and modelling the pilot characteristics in the moments immediately before and during a PIO is therefore of paramount importance. The present paper examines a new theory of pilot behaviour in PIOs, the so-called boundaryavoidance tracking (BAT) or more general boundary reactive control (BRC). The concept, defined initially for fixed wings, hypothesises that, in critical cases, pilots often engage in a boundary-avoidance tracking task where the goal is to avoid a hazardous parameter, such as ground impact, or a routine limit, such as an assigned minimum attitude. The BRC concept is applied to helicopters to predict a Cat I PIO event in the longitudinal axis induced by an excessive time delay between the pilot input and system response. The paper demonstrates that the pilot control aggressiveness is inversely proportional to the time it would take him to exceed a given boundary- the so-called time to boundary- and that this time threshold is proportional to the system delay. The paper proposes a hybrid pilot model for studying PIOs combining traditional pilot modelling with boundary reactive control. The hybrid pilot model is successful in reproducing the pilot behaviour observed during a PIO test in the simulator at the University of Liverpool.

Notations

- BF = boundary feedback (see eq. (2))
- BV_{osc}^{up} = upper boundary corresponding to a fully-oscillatory PIO with oscillatory BF
- BV_{in}^{up} = upper boundary where the first-instance reaction in the boundary feedback
- q = helicopter pitch rate [rad/sec]
- R = rotor radius [m]

 t_{min} , t_{max} = minimum and maximum time to the boundary

- θ = helicopter pitch attitude [deg]
- θ_{1s} = longitudinal cyclic [deg]
- τ = system time delay [sec]

Introduction

A Pilot Induced Oscillation (PIO) is generally defined as "an inadvertent, sustained aircraft oscillation which is the consequence of an abnormal joint enterprise between the aircraft and the pilot" (1). Pilot induced oscillations are dangerous, and known to have been the cause for several aircraft and rotorcraft incidents and accidents (F-22, JAS 39, V-22). Although PIO's cannot be ruled out altogether, PIOs should be detected and eliminated as soon as possible during the initial stages of the design process. In order to predict the susceptibility of an aircraft to PIO, three factors need to be taken into account: 1) the aircraft dynamics and 2) the pilot representation and 3) a trigger. A trigger can be anything that disturbs the pilot-vehicle control loop, be it shortly, a wind gust, a system malfunction, an object or a boundary.

The primary method for prevention of PIOs focuses usually on fixing the aircraft. This is true as it is difficult to find documented evidence of any PIO than that the aircraft/rotorcraft was deficient in some aspect of its design. Also, in the reconstruction of a PIO incident, triggers may be searched

Paper presented at the Rotorcraft Handling Qualities Conference, November, 4th-6th, 2008, University of Liverpool, Liverpool, UK

that have lead to the development of the PIO. Then, in new designs, such trigger will be taken into consideration to prevent the same incident from occurring again. However, a key contributor to PIOs is incorrect pilot behaviour. Understanding more about the characteristics of the pilot in the moments immediately before and during, a PIO, has been often undervalued. While pilot induced oscillations are not the fault of the pilot, being able to understand and model correctly the pilot during a PIO event would greatly enhance engineer's ability to predict and prevent PIOs.

Classically, there are two general formats of pilot behaviour: synchronous and compensatory. Synchronous control is the simplest possible form of pilot model in which the pilot, exposed to sinusoidal inputs (the initial stages of the PIO), will adapt continue the sinusoidal inputs with no special compensation or phase lag. It is said that only "input" information is available to the pilot. Synchronous pilot behaviour results in high level of control where the highly-skilled pilot has extensive knowledge on the vehicle dynamics to the point where he no longer relies on feedback signals. Compensatory control means that the pilot will adopt a feedback scheme, compensating continuously the perceived errors or aircraft motions. It is said that only error information is used by the pilot to generate control steering inputs in the vehicle system. In reality, of course, both error and input information is used by the pilot to command the aircraft/rotorcraft, this corresponding to a "pursuit" behaviour.

The majority of work in manual control theory has dealt up to date with compensatory control modelling. There have been built well-founded simplified tracking tasks pilot models, the most famous being McRuer's crossover model [ref (7)]. More elaborated models, such as Hess structural pilot model [ref (6)], include switching from synchronous to compensatory pilot behaviour. They have the merit and may explain certain characteristics of pilot behaviour. For a good overview on pilot modelling techniques and its state-of-the-art the reader is referred to refs. (12), (13), (14), (15). All conventional pilot models used up to date to describe the closed-loop pilot-vehicle interaction during a PIO have something in common, i.e. they make the assumption that a pilot tracking a task is controlling the aircraft by always attempting to maintain a certain flight parameter (such as pitch attitude, flight path, heading, etc.). This is the so-called "point tracking" assumption. All PIO criteria derived up to date are based on this assumption and explain PIO's due to an extraordinarily increase in the pilot gain controlling that point parameter. For example, the essence of the crossover model for PIO investigations is that the human operator adjusts the gain up to the border where he/she approaches the frequency where the aircraft responds out of phase to the input.

Recently, Gray (refs (2) and (4)) showed that during formation flying, pilots that are restricted to stay within tight altitude limits above and below the desired flight path, respond more aggressively to small excursions from the flight path than pilots following just a flight director. This increasing aggression can change pilot's normal behaviour and become a trigger for the vehicle that becomes PIO susceptible. From many discussions with the pilots, he concluded that "while pilots spend most of their time maintaining a variety of parameters" (thus, point tracking behaviour), "there are critical cases when the point tracking parameter is of secondary interest to the pilot". [see ref (2)]. Such a case can be a dangerous PIO where it seems that the pilot is tracking something more than a point parameter. In fact, in Gray's opinion pilots describe a PIO as a succession of opposing events wherein they continuously attempted to survive by alternatively attempting to track the opposing risks describing those events. In other words, in a PIO, rather than using a high gain tracking of a single parameter to control the situation, the pilots are tracking a hazard, expressible as a boundary. The concept of Boundary Avoidance Tracking (BAT), which was developed following the research by Grav, describes the behaviour of a pilot in the proximity of a boundary. Using simulations, Gray illustrated how BAT behaviour can result in severe oscillations. De Groot and Pavel (ref (3)) extended BAT into a new metric called "Specific boundary" characterizing a class of rotorcraft. This new metric, defined as the ratio between the boundary value at which the pilot would initially respond to the boundary and the boundary value at which a fully developed oscillation would appear could be used for design purposes.

The goal of the present paper is to understand the pilot behaviour in a PIO event in the case of a rotorcraft, more precisely to estimate whether the boundary avoidance concept can be applied to rotorcraft and, if yes, when and how is the pilot switching between BAT concept and point-tracking concept. The paper proposes to use, instead of BAT, the name "boundary reactive control" (BRC), for characterizing the pilot behaviour in the vicinity of a boundary. This is done in order to emphasize the fact that, in general, in a PIO the pilot is reacting to a boundary, either trying to avoid it or encounter it. The paper is organized as follows: Section II provides a brief background on BRC concept as initially defined by Gray. Section III applies BRC concept to rotorcraft for simulating a simple pitch manoeuvre. Section IV discusses on the signification of the parameters used for the BRC analysis. Section V proposes a new hypothesis in building the BRC model in the case of PIOs analysis. Section VI describes a hybrid point tracking/BRC pilot model for studying a PIO event. Finally, conclusions complete the paper.

II Background on Boundary Avoidance Concept

In Gray's first paper on BAT concept (ref (4)), a sequence of events is sketched in an incident where an aircraft pilot is approaching a boundary (e.g. the ground) up to and at the moment where the pilot is in danger of hitting the boundary. Assuming that the pilot is aware of the imminent danger, he will, at some point, start to respond to the boundary. However, not before he has crossed an imaginary limit, the so-called 'minimum time to boundary', denoted t_{min} . Gray defines the 'time to boundary', t_b as the ratio between the distance from/to the boundary, x_b , and the speed towards the boundary, dx_b/dt , i.e.:

$$t_b = x_b \left(dx_b / dt \right)^{-1} \tag{1}$$

The minimum time to boundary t_{min} is then defined as the threshold of t_b at which the pilot will start to respond to the boundary. Each pilot has a different threshold at which he will start to respond to boundaries. One pilot can even respond differently in different situations. The level of danger associated with the boundary plays an important role. The higher the level of danger, the sooner the pilot would respond.

The reaction of a pilot to a boundary is inversely proportional to the time to boundary t_b . The pilot starts applying boundary reactive control at the threshold $t_{min.}$ Depending on the time to the boundary t_b , the pilot will apply a feedback gain, the so-called boundary feedback BF, before reaching the upper/lower boundary. The equation that determines the feedback gain BF is according to Gray:

$$BF = \frac{t_{\min} - t_b}{t_{\max} - t_b} K_{bm} \quad if \quad t_{\min} < t < t_{\max}$$
⁽²⁾

where t_{max} is the value of t_b where the largest boundary reaction is applied, t_{min} is the value of t_b where the pilot starts to respond to the boundary, and K_{bm} the maximum boundary gain the pilot can apply in order to avoid reaching the boundary. t_{max} in the present paper is considered to be zero, because there is no evidence that the pilot has a level of saturation when reacting to boundaries. Figure 1 presents the variation of the boundary feedback as a function of t_b as described by equation (2). One can see that in BAT model the pilot gain changes continuously as the pilot is moving within the upper/lower boundaries.



Figure 1 Boundary feedback increase as the pilot approaches the t_{max}

The crucial parameters to be estimated when applying BAT concept are K_{bm} and t_{min} . While in Gray's research, t_{min} was set constant, the present paper will demonstrate that the value of t_{min} cannot be held constant, at least when investigating a PIO event. In fact, it will appear that pilot alertness plays a decisive role in setting the value of t_{min} . If a pilot is more tired, he is likely to respond at a later moment (i.e. maintain a lower value of minimum time to boundary) than he would respond when he would have been fit.

III A Simple Example on the Application of Boundary Reactive Control to Rotorcraft

The rotorcraft selected for study is the Bölkov Bo-105 helicopter. For this helicopter an eleven state-space model corresponding to an eight degree-of-freedom body-disc-tilt model has been built based on a model developed at Delft University. Detail on the vehicle model is given in the Appendix. Assume that the pilot is tracking a sinusoidal doublet input in the pitch axis of about 0.7 seconds, the amplitude is 15-20% of the total control range. After the doublet control input the pilot holds the stick in the same position as before the manoeuvre (trim value) regardless of the pitch movement of the helicopter. Consider now the BRC concept applied to study a helicopter PIO problem in longitudinal axis. Figure 2 presents the close-loop pilot/vehicle. For stabilization of the helicopter in the roll and yaw axis PID controllers have been introduced, for pitch axis the BRC concept was implemented as seen in Figure 2.



Figure 2 Boundary avoidance tracking for controlling pitch attitude

Looking at this figure one can see that the helicopter pitch attitude and rate are fed back and used by the pilot to determine how much time is needed to reach the boundary, i.e. the time to boundary t_b . The time to boundary t_b is in fact the source in provoking a PIO. For the pitch manoeuvre t_b can be calculated as:

$$if q < 0 \quad t_b = \frac{BV^{low} - \theta_{rel}}{q}$$

$$if q > 0 \quad t_b = \frac{BV^{up} - \theta_{rel}}{q}$$
(3)

Equation (3) depends whether the pilot is approaching a lower BV^{low} or an upper pitch attitude boundary BV^{up}. The notations in eq. (3) refer to imposed values in :1) an upper BV^{up} and a lower

boundary value BV^{low} for the relative pitch attitude $\theta_{rel}=\theta-\theta_{trim}$ that show the boundaries between which the pilot can move without threat; 2) a maximum t_{max} and a minimum t_{min} time with the signification that when the $t_b \le t_{max}$ the pilot is moving towards the boundary and there is maximum threat for "hitting" the boundary, when $t_{max} < t_b < t_{min}$ then the pilot is not threatened by the boundary but he is aware of it in his actions and finally when $t_b \ge t_{min}$ then the pilot is not threatened by the boundary.

Figure 3 presents the fuselage attitude response when no lower and upper boundaries are implemented in the Bo-105 model ($t_b \ge t_{min}$). One can read that the boundary feedback is 0 deg.



Figure 3 Helicopter pitch attitude with no boundary feedback

Figure 4 shows the helicopter pitch response when upper $BV^{up} = 14$ deg and lower boundaries $BV^{low} = -14$ deg are imposed to the relative pitch attitude. Looking at Figure 4 it appears that, by imposing these boundaries at a certain value and allowing the pilot to move inside these boundaries, there will be an initial upper/lower boundary value where the boundary feedback start to react to the pilot motion as the pilot moves towards the boundary. This first-instance boundary feedback reaction is achieved in the point where the helicopter reaches its maximum pitch attitude as seen in Figure 4.



Figure 4: Boundary-avoidance feedback with imposed upper/lower boundaries

The value BV_{in}^{up} corresponds to the value of the upper boundary where the first-instance reaction in boundary feedback appears. As the boundaries are moving closer to each other as shown in Figure 5 corresponding to ±10 deg, the helicopter response in attitude "excites" the boundaryavoidance feedback and causes 3-instance oscillations of this feedback. This is because the 1st instance of the boundary-avoidance feedback adds to the longitudinal cyclic doublet and results in larger fuselage attitudes that damp out slowly in time. This situation is as a "bobble" felt by the pilot during flight.



Figure 5 Tightening the Upper/lower Boundaries results in 3-instance oscillation in boundaryavoidance feedback

Figure 6 shows the case of ±8 deg boundaries. One can see that when the boundaries are close enough an oscillation is initiated. Note the wave nature of the feedback signal typical of PIO's. The value BV_{osc}^{up} corresponds to the value of upper boundary where the boundary feedback is oscillatory as seen in Figure 6.



Figure 6 Tightening further the Upper/Lower Boundaries to oscillatory boundary feedback

In Figure 7 the boundaries are moved even closer at ± 5 deg where the boundary-avoidance feedback "hits" the maximum K_{bm.} The oscillation of the fuselage is at its boundaries. If the boundary feedback wouldn't have been limited, the fuselage oscillation would have grown unstable passing the imposed boundaries. The boundary feedback remains at its maximum value K_{bm} as long as the system is at the limit or above the boundaries (t_b<t_{max}).



Figure 7 Tightening even further the Upper/Lower Boundaries with boundary feedback limited by its maximum value

This example showed that, by using boundary-avoidance tracking model, the resulting model seems to coincide well with actual pilot tracking especially when the pilots are manoeuvring within tight boundaries.

IV Understanding Boundary Reactive Control Concept

The boundary reactive control concept is different from the more usual approaches to model pilot behaviour such as the crossover model. To allow for a comparison with more conventional models, an inquiry is made into the changes in pilot behaviour that are caused by the proximity of boundaries. Looking at the time to boundary concept, it is apparent that the end result of a decreasing time to boundary is equivalent to a classical interpretation of an increase of the pilot's gain, as a function of the distance to the boundary and the speed towards the boundary.

The pilot gain can thus be modelled as a variable depending on proportional (position) feedback and differential (speed) feedback.

$$K_{bm} = K_{x_b} x_b + K_{v_b} v_b \tag{4}$$

Both proportional and differential feedbacks are introduced by the pilot's visual field. In the proposed analysis, the switch from point tracking behaviour to boundary reactive control boils down to a change of aggressiveness of the pilot in response to visual input. In fact, in simulations such as performed by Gray, the to-be-followed tracking marker can be used to model boundary reactive control, because a deviation from the tracking marker correlates directly to the approach of a boundary, and vice versa.

A controlled system has a range of gains that allow for smooth, exact control. In this paper, a system is under consideration with a tracking task that requires proportional and differential control from the pilot. If the proportional gain is too high, especially with an additional high differential gain, the closed loop pilot vehicle system becomes unstable and any deviation from the intended flight path leads to a diverging oscillation.

Coming back to the point tracking model and introducing the maximum gain of boundary reactions as a PD controller, one can discriminate between regions of stability or instability as a function of gain values. In Figure 8, a map is presented where these regions are indicated as a function of proportional and differential gain. Three regions have been assigned to discriminate between levels of stability; precise control, marginally stable control and diverging, instable control. Within the precise control region, the error between the wanted- and the true flight path angle stays within a tight margin around the amplitude of the input signal. In the marginally stable

region the error exceeds this margin, but the flight path is not divergent. In the instable region the flight path is divergent.

The pilot 'equalization capability', explained by McRuer (ref. (7)), allows for a continuous adaptation of the gains, such that optimal control is possible, i.e. to stay within the precise control region in Figure 8. If however, due to external influences such as an approaching boundary the pilot is forced to abandon this 'optimal region', and instantaneously enter the instability region, momentarily the pilot finds him in a PIO-sensitive situation. Only after the peril has disappeared, the pilot will return to the stable region.

In helicopters that have no excessive time delay, such as the system used in Figure 8, the precise control region is sufficiently large to make sure that after having engaged in boundary reactive control, the pilot is able to retain normal control. The frequency response diagram associated with the controlled system is presented in Figure 9. Clearly, the stability margins (gain margin and phase margin) are large.



Figure 8 Combinations of P,D gain and their corresponding stability on Bo105 with no time delay



Figure 9 Bode diagram of longitudinal cyclic to pitch angle of the Bo105 with no time delay

Assume now that an excessive time delay is introduced between the control input and the helicopter response. In such a case, controlling the system becomes more difficult. The pilot has less 'playground', i.e. the precise control region is smaller. A stability diagram of the system with

0.2sec time delay is presented in Figure 10. The associated bode diagrams of the systems with 0.2s delay is presented in Figure 11. Clearly, the stability margins have decreased significantly after introducing a time delay.



Figure 10 Combinations of P,D gain and their corresponding stability on Bo105 with 0.2s time delay



Figure 11 Bode diagram of longitudinal cyclic to pitch angle of the Bo105 with 200 msec time delay

The theory is now, that if a pilot is controlling a system such as depicted by Figure 10, and he is confronted with two opposing boundaries, he will move into the instability region to avoid the first boundary. Before being able to return into the stability region, he is forced to respond to the opposing boundary with control action that is still in the instability region. Effectively, the pilot becomes 'trapped' in the instability region, creating a sustained instable situation. Whether or not this situation should be defined as PIO or not is a matter of discussion.

V A New Hypothesis on Boundary Reactive Control for PIO studies

Gray demonstrated that the presence of boundaries influences the behaviour of the pilot, and as a consequence the characteristics of the closed aircraft-pilot control loop. During further research,

de Groot and Pavel (ref. (3)) showed that PIO's are more easily triggered when boundaries are present. This is an interesting observation, because it shows that a relation exists between the stability of the aircraft-pilot control loop and the change in pilot behaviour when approaching a boundary (such as the ground, with as familiar and frequently occurring examples low terrain flight, hover and landing). However, up to the present the minimum time to boundary tmin was assumed to be constant for every controlled element. The present research proposes a new assumption in order to apply the boundary reactive control to a PIO problem: the minimum time to boundary t_{min} is proportional to the effective time delay τ between the pilot input and system response. The reasoning for this assumption is as follows: The pilot is assumed to passively perceive time delay of the system he is controlling. The result is that the pilot knows, or feels, that the response of the vehicle effectuates at a certain amount of time after he has ordered the action. If he is approaching a boundary, he will have to take this amount of time delay into account in order to be able to safely avoid the boundary. The safety margin the pilot has to maintain (i.e. the time between control input and foreseen boundary violation) is at least equal to the effective time delay of the pilot-vehicle system. This margin is in fact the threshold for boundary reactive control, t_{min} . Therefore, the minimum time to boundary t_{min} is now proposed to be proportional to the effective time delay of the controlled system $\tau,$ i.e. $t_{min} \propto \tau.$

This means that if a pilot is controlling a hypothetical system with <u>no time delay at all</u>, he would not have to maintain a margin. Effectively, the pilot is then able to instantaneously change the controlled parameter. This means that the pilot does not have to anticipate on upcoming boundaries and will <u>not apply boundary reactive control</u>, because the minimum time to boundary is zero. On the other hand, if a system has an excessive amount of time delay, the pilot may be forced to anticipate very early the boundary. Effective time delays of more than 200 msec are characteristics to rotorcraft (50-70 msec inherent rotor response delays, some 30 msec actuator delay and additional delas due to digital computing, sensor signa shaping and filtering). For a pilot avoiding the boundaries it becomes important to have quick response for a stable rotorcraft controllability. In the proximity of boundaries, a too large time delay leads to a too early response to the boundary. As it will be demonstrated next, in specific situations this too early response can lead to instability.

To check the validity of this hypothesis, simulator tests on BRC concept were performed under the umbrella of GARTEUR AG-HC16 working group in a 6-dof motion base flight simulator at the University of Liverpool (see refs. (9), (10), (11), (12)). Within these tests, more knowledge was built up upon the change in pilot behaviour in proximity of approaching boundaries. Figure 12 presents the head-up display (HUD) used in the BRC experiment.



Figure 12 Designing the head-up display for a BRC experiment in the pitch axis [ref. (10)]

The pilot was asked to follow a flight path representing a pre-determined sum-of-sines by following the oscillation director staying within the limits of the boundary markers which, again, became increasingly narrow at a pre-determined rate. The helicopter flight dynamics model had

all axes fixed except the pitch. The hypothesis was that as the boundaries closed in, the pilot would at some point start to respond to them. From the observation at what moment the pilot starts to respond to the boundaries, the minimum time to boundary t_b could be extracted. The test runs were performed with different amounts of additional system time delay τ , to artificially increase the PIO-susceptibility of the helicopter. In the flight-path configuration to be flown the pilot had to stay within two boundaries: one above and one below the pilot. This is an experimental representation to simulate situations in which the pilot is forced to stay within tight attitude- or altitude limits. It is essentially an identical configuration as was used in the HAVE BAT (ref. (5)) experiments. The fact that there were two boundaries present instead of one was paramount to the outcome of the test runs. Avoiding control action from one boundary could drive the pilot directly into the proximity of the other boundary, especially when the boundaries were close to each other. Once near the opposing boundary, the pilot would respond and once again approach the first boundary.

From the experiments it appeared that the amount of time delay partly determined the aggressiveness of the test pilot in response to approaching boundaries. As the pilot commented himself, he was not really threatened by the boundaries as long as the gross manoeuvrability was sufficient, i.e. the time delay was zero. However, as more time delay was added to the controlled element, the pilot started to respond to the boundaries earlier. This confirmed the hypothesis made initially in this study. Concluding, the simulator test configurations with an excessive time delay resulted in PIO's, and these PIO's occurred sooner when boundaries were imposed. This means that the PIO tendency that was already present in the pilot vehicle system was exposed by the boundaries. This demonstrated that the most important role the boundaries played in the development of the PIO's was that they were **triggers** evoking a PIO that was already waiting to strike.

VI Hybrid Pilot model for PIO investigations

From the test simulations two conclusions were drawn: 1) the time delay influenced the response to the imposed boundaries 2) when the pilot is far away from the boundaries his behaviour is not influenced by these boundaries The second conclusion suggests that the best approach to model the human operator in a PIO is to use a <u>hybrid pilot model</u> including both the point-tracking and boundary tracking concepts. The present paragraph develops and tests such a hybrid model for PIO analysis. Figure 13 presents schematically the combined point/boundary switching model developed in the pitch axis; the roll and yaw axis are stabilized by a conventional PD controller. The idea is that if the pilot is far away from the boundaries he will use the point-tracking pilot model; if he is approaching the boundaries a boundary reactive model takes over the control.



Figure 13 Pilot model featuring point tracking behaviour and boundary reactive control behaviour

The model has two elements: the boundary reactive control element and the point tracking element. The larger of the two is passed on by the decision block. The point tracking element creates an output that is proportional to the difference between the required flight path and the true flight path, $\theta_{err} = \theta_{track} - \theta_{heli}$, and the speed at which this difference is developing, $\theta_{track} - \theta_{heli}$. The boundary reactive control element creates an output only if a boundary approaches. The control output is inversely proportional to the 'time to boundary'. The time to boundary t_b is defined by the ratio between $\theta_{bound} - \theta_{heli}$ and $\dot{\theta}_{heli} - \dot{\theta}_{bound}$. If the time to boundary t_b reaches a value below the minimum time to boundary t_{min}, the element is activated. Note that it does not necessarily need to be the dominant control signal, because in most cases the sense of the boundary reactive model and the point tracking model is the same. The purpose of the difference between the two different control elements is to simulate what in reality is happening when a pilot switches from a normal tracking task to boundary reactive control. The crucial question to be answered when building this new model is when does the pilot switch between one concept and the other. During test runs in the Liverpool simulator, the test pilot testified that he started to respond to boundaries when the pitch attitude was between halfway and 2/3 of the distance between the point tracker and the closest boundary. This information is used to determine when the model has to switch from the point tracking to the boundary reactive control (see Figure 14 and Figure 15).



Consider now that the pilot has to track the boundaries imposed during the simulator tests as presented in Figure 16 representing a sum-of-sines of form $\sin \frac{\pi t}{2} + \sin \frac{\pi t}{4} + \sin \frac{\pi t}{8} + \sin \frac{\pi t}{16}$ while staying within boundaries at all times. The boundaries were closing in as the manoeuvre was evolving from 14deg to 8deg, 5deg and finally 3 deg.



Figure 16 Tracking task with discretely decreasing boundaries

Figure 17 and Figure 18 present the simulation results in the interval 20 to 40 seconds (where the imposed boundaries are far away from the track to be followed, i.e. 14 deg) and 70 to 100 seconds (where the boundaries have closed in from 5deg to 3deg). Two cases are analysed:

1) no time delay is added to the system (Figure 17) and

2) a 0.2 sec time delay in pilot input is added to the model (Figure 18).

One can see that in the interval 20 to 40 seconds, which corresponds to the case of boundaries far away of each other, the time to boundary is always above the minimum time to boundary t_{min} = 2.2sec (left hand side of the figures). This means that the boundary reactive control element is not active, so the control output is dominated by the point tracking element. The result is a smooth control pattern and a reasonably accurate flight path. When the boundary reactive model output is hardly reacting and the pilot action is dominated by point tracking strategy (Figure 17 right-handside, plot of boundary feedback output). This behaviour can be translated into that of a pilot who, seeing that the boundaries are approaching, is not "frightened" by them and does not

make strong corrections in controlling the helicopter. However, when the boundaries close in at the interval 70 to 90 seconds and there is a time delay of 0.2 seconds added to the system, the time to boundary parameter drops far below the minimum time to boundary. In this case the resulting boundary reactive control output becomes more and more important. (Figure 18 right-handside, plot of boundary feedback output). The pilot action is dominated by boundary reactive control. In such a case the pilot is actually driven by the boundaries and overcorrects the track he has to fly, evading from one boundary to the other.

In the interval t=75sec to t=78 sec, the reaction to the boundaries is not yet strong enough to drive the system into a sustained oscillation. Nevertheless, after t=80sec when the boundaries have closed in to 3 degrees, the pilot gets "trapped" in a boundary reactive control pattern. This leads to a fast alternating, cliff like control behaviour where the pilot applies such a strong control, that the overshooting reaction drives the system directly into the opposing boundary resulting in a sustained oscillation in the flight path. The pilot recognizes this as a PIO. The only method to recapture the desired tracking task is a significant reduction of gain or momentary release of control altogether and back out from the control loop.



Figure 17 Simulation of the pitch manoeuvre, 65 kts forward flight, 0 sec time delay





Conclusions

The goal of the present paper was to understand pilot behaviour during a PIO. The paper examined a Cat. I PIO event in the pitch axis on a Bolkov BO-105 helicopter introduced by excessive time delays between the pilot response and system response (τ =0.1 sec and τ =0.2 sec). For modelling the pilot during the PIO a new pilot tracking model was applied, the so-called boundary avoidance tracking (BAT) or more general boundary reactive control (BRC). This concept, introduced by Gray for fixed wings, assumes that, in critical situations, pilots do not focus upon maintaining a specific parameter as assumed up to date in the so-called pointtracking behaviour. Instead of this, in a PIO, pilots engage in avoiding a hazard which can be expressed as a boundary parameter, such as ground impact, or a routine limit, such as an assigned minimum attitude, resulting in the BAT / BRC behaviour. The paper applies the BRC concept to the rotorcraft and demonstrates that, expressing the pilot gain as a function of the time to exceeding a given boundary -the so-called time to boundary- one is able to identify the characteristics of the pilot just before and during the PIO. In addition to Gray's theory, it is demonstrated the time to boundary is not a constant value, but in fact depends on the responsiveness of the controlled element, in this case the time delay. It is shown that pilots may adopt either point-tracking or BRC behaviour depending on the distance and velocity to the boundary. The paper develops a hybrid point-tracking/boundary reactive pilot model and uses it to reproduce the pilot behaviour observed in motion-based simulator tests at Liverpool.

References

(1) McRuer, D.T., et al., (1997), "AVIATION SAFETY AND PILOT CONTROL. Understanding and Preventing Unfavorable Pilot-Vehicle Interactions", ASEB National Research Council, National Academy Press, Washington D.C., 1997

- (2) Gray, W., 2005. "Boundary-Avoidance Tracking: A New Pilot Tracking Model " AIAA 2005-5810, AIAA Atmospheric flight mechanics conference and exhibit, San Francisco, CA, August 15-18.
- (3) de Groot, S., Pavel, M., 2006. "New Insights into Pilot Behaviour during Hazardous Rotorcraft Pilot induced Oscillations" 62nd American Helicopter Society Annual Forum May 9-11 2006
- (4) Gray, W., 2007. "Boundary-Avoidance Tracking and Its Use in Handling Qualities Evaluations" 18th SFTE (EC) Symposium, 11-13 June 2007, Madrid, Spain
- (5) Warren, R, et el., "A limited investigation of boundary avoidance tracking" USAF TPS Technical memorandum AFFTC-TIM-06-04, June 2006
- (6) Hess, R.A., 1997. "Unified theory for aircraft handling qualities and adverse aircraft-pilot coupling." AIAA97-0389, Aerospace Sciences Meeting and Exhibit, 35th, Reno, NV, Jan. 6-9 1997
- (7) McRuer, D., Jex, H. R., "*A review of quasi-linear pilot models*" IEEE Transactions on Human Factors in Electronics, Vol. HFE-8, No. 3, September 1967
- (8) Mitchel, D.G., Klyde, D.H. "*Identifying a PIO signature new techniques applied to an old problem*" AIAA 2006-6495, August 2006
- (9) Dieterich, Oliver, et. al., "Adverse Rotorcraft-Pilot Coupling: Recent Research Activities in Europe", 34th European Rotorcraft Forum, September16-19, 2008, Liverpool, UK
- (10) Jump, Michael, et. al., "Adverse Rotorcraft-Pilot Coupling: Test Campaign Development at the University of Liverpool", 34th European Rotorcraft Forum, September16-19, 2008, Liverpool, UK
- (11) Pavel, M.D., et. Al, "Adverse Rotorcraft-Pilot Couplings Prediction and Suppression of Rigid Body RPC", 34th European Rotorcraft Forum, September16-19, 2008, Liverpool, UK
- (12) Zaychik, Kirill, B., Cardullo, Frank M., George Gary, "A Conspectus on Operator Modelling: Past, Present and Future", AIAA Modelling and Simulation Technologies Conference and Exhibit, 21-24 Aug. 2006, Keystone, Colorado, AIAA 2006-6625
- (13) Hess, Ronald A., "Simplified Technique for Modelling Piloted Rotor Operations Near Ships", J. of Guidance, Control and Dynamics, Vol.29, No.6, Nov-Dec. 2006
- (14) Hess, Ronald A., "Feedback Control Models- Manual Control and Tracking", Handbook of Human Factors and Ergonomics, Edited by Gavriel Salvendy, A Willey-Interscience Publication, Second Edition 1987, 1250-1294
- (15) Åström, K.J., Hägglund, T., "The future of PID control", Control Engineering Practice, 9(2001), 1163-1175
- (16) Mitchell, David G., "Identifying the Pilot in Pilot-Induced Oscillations", AIAA Flight Mechanics Conference, 14-17 Aug. 2000, Denver, Co, AIAA-2000-3985

Appendix

The vehicle dynamics in an 8 degree-of-freedom linear model are:

$$\underline{\dot{x}} = A\underline{x} + B\underline{u}$$

(5)

with $\underline{x} = (u \ v \ w \ p \ q \ r \ \phi \ \theta \ \psi \ a_1 \ b_1)^T$ the state vector corresponding to helicopter translational velocities u,v,w (in m/sec), rotational velocities p,q,r (in rad) in x-,y- and z-axis; ϕ , θ , ψ the Euler angles (rad) and a_1 and b_1 longitudinal and respectively lateral disc-tilt angles (in rad); $\underline{u} = (\delta_{1c} \ \delta_{1s} \ \delta_0 \ \delta_{0r})^T$ the control vector corresponding respectively to lateral, longitudinal, collective and pedal pilot controls (in rad); *A* and *B* the matrices of state derivatives and control derivatives. The signs of the pilot controls are as: longitudinal control -100% pushed and +100% pulled; Lateral control -100% left,+100% right; Collective control 0% pushed down, +100% pulled up; Pedal control: -100% pushed left, +100% pushed right. Matrices A and B are calculated with a linearized 8 degree-of-freedom model developed at Delft University [see ref. (3)]. For example, matrices A and B in hover condition correspond to:

	u	v	w	р	q	r	Ψ	θ	ϕ	a_1	b_1
u	-0.0103	0.0007	-0.0142	0.0046	0.0751	-0.0154	0	-9.798	0	-14.62	0.189
v	0.0007	-0.0575	0.0000	-0.1553	0.0015	0.3024	0	0.00768	9.796	0.1845	14.62
W	0.0550	-0.0253	-0.9225	-0.1999	-0.3907	0.6653	0	-0.4136	0.1821	-0.466	-0.441
р	-0.0004	-0.0822	0.0032	-0.2753	0.0117	0.3490	0	0	0	-3.638	60.99
q	0.0048	0.0005	0.0419	0.0041	-0.0353	-0.0135	0	0	0	17.14	-0.108
r	-0.0045	0.1428	0.0066	0.2332	0.0124	-0.9641	0	0	0	-8.809	3.43
ψ	0	0	0	0	-0.0186	1.001	0	0	0	0	0
θ	0	0	0	0	0.9998	0.01858	0	0	0	0	0
ϕ	0	0	0	1	-0.00078	0.04221	0	0	0	0	0
a_1	0.00074	0	0	0	-1.005	0.0014	0	0	0	-0.629	6.64
b_1	0	-0.00073	0	-1.005	0	0.0007	0	0	0	-6.643	-0.629

A=

	Lat	Long	Coll	Pedal
u	-0.156	14.77	1.775	0
v	14.77	0.1605	-2.335	7.007
w	-0.4479	0.4599	-134	0
р	64.55	0.5969	3.59	8.61
q	0.118	-17.23	3.58	0
r	10.47	0.5042	19.31	-21.48
ψ	0	0	0	0
θ	0	0	0	0
ϕ	0	0	0	0
a_1	0.006743	-0.5471	0	0
b_1	0.5471	0.006743	0	0

B=