PILOT INDUCED OSCILLATIONS DETECTION USING BOUNDARY AVOIDANCE TRACKING PROCEDURE

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Nowadays, most of the aircraft are man piloted, either from within the aircraft itself, or remotely. It is therefore crucial to understand the pilot-machine relationship, in order to prevent mishaps. In 2004, a new concept was developed, concerning the way aircraft are controlled by pilots. Boundary Avoidance Tracking (BAT) introduced the idea that pilots not always control the aircraft in order to follow a certain state, but to avoid certain boundaries (real or perceived). This approach helped explaining the pilot's reactions in certain cases and was used as a technique to artificially increase pilot workload, and expose poor handling qualities.

Keywords: boundary avoidance tracking, pilot induced oscillations, pilot workload, switching behavior, time to boundary.

1. Introduction

Since World War II there have been several attempts to develop a useful pilot model. Experiments and researches have evolved from early concepts to usable mathematical models, such as the Crossover model, the Structural-isomorphic model, and the Optimal Control model [1, 2]. All of them assume the same idea, i.e. the pilot generates commands by observing discrepancies between an actual vs. desired state of the aircraft. This is called point tracking [3].

Dr. William Gray from USAF TPS (United States Air Force Test Pilot School) assumed in [4] that a pilot often tends to avoid a certain condition, rather than maintaining another one. Illustrating this through the representation of a biker trying to follow a narrow line on the road, Dr. Gray then raised the problem of suspending that same line over the Grand Canyon. This way, he shows that the biker is more concentrated in not-reaching the edges of 2the line, in order to maintain the wheels within the line, avoiding thus the extremes.

Taking this same example to the flight operations area, a pilot is said that most likely, in an event of a cross wind, will try to avoid striking the runway with the wind rather than return to a wings-leveled situation. This is what it makes the difference, because trying to avoid striking with the wind will generate a strong action from the pilot, which will present the risk of hitting with the other wing. If

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several corrections are applied, with the purpose of avoiding striking with one wing at a time, this will lead the pilot-aircraft system into a classical Pilot Induced Oscillations (PIO) situation [5, 6]. The origins of PIO were actually the basis for the idea of BAT (Boundary Avoidance Tracking) [7, 8, 9].

BAT is based on the idea of moving away from something, and the actions required are less strong with the distancing of the boundaries. On the contrary, point tracking is the exact opposite, requiring a less and less significant force on the correction, as the target gets closer.

BAT has been developed as a supplement to the other pilot models, thus being a switching model, where pilots can switch as required between boundary tracking and point tracking. In the absence of any boundary, the BAT model is simplified to a classical pilot model. Statistically, the wide majority of time, the pilot will be tracking a point, and only in a small amount of time he will avoid a boundary.

The purpose of this paper is to introduce a different approach to boundary effect on the pilot. It is assumed that in flight, the pilot follows a certain given trajectory, but in some cases this state changes into an avoidance situation, where the goal is to not exceed a given restriction.

2. Boundary Avoidance Tracking Approach

The BAT concept is straightforward and intuitive, but in order to use it as a predictive tool, a model must be built describing exactly how pilots react to boundaries. Dr. Gray created a hypothetic model, based on switching behavior on the part of the pilot [10]. Fig. 1 graphically depicts this behavior:

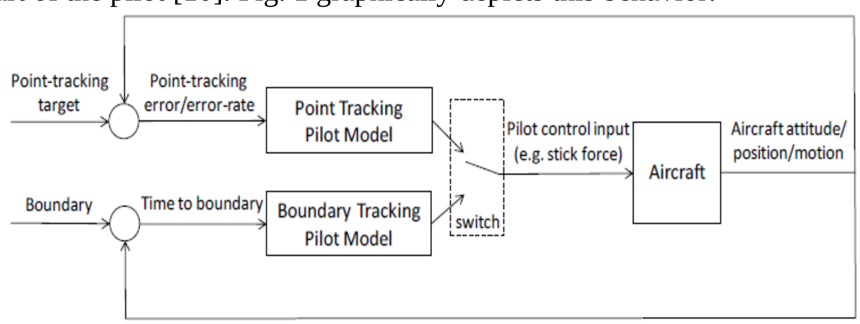

Fig.1. Block Diagram of the BAT model [10].

When tracking a point, the inputs of the pilot follow the upper loop in the figure, acting on the aircraft's rate, position, etc and can be modeled by any pilot model. At the same time, when boundaries come into play, the lower loop in the figure is adequate. The main factor in this case becomes the time to the boundary, which determines the time and intensity of the pilot's reaction with respect to the boundaries.

It is not a new approach, the pilot switching his behavior. The Dual-mode Controller model has been used to explain, until now, pilot response to step inputs, thus describing the pilot's different reactions to different phases of compensation [11]. The proposed BAT model applies the switching behavior, for the first time, to something else rather than simple point tracking.

There are four parameters that describe pilot characteristics, in the hypothesized model:

t_{min} = time to boundary, when the pilot begins to react to boundaries. A larger value implies that the pilot reacts sooner.

t_{max} = time to boundary when the pilot uses maximum gain to avoid boundaries. A larger value means the pilot applies maximum gain sooner.

K_{bm} = maximum gain used by the pilot to avoid boundaries

τ_b = pilot time-delay during boundary avoidance.

The time to boundary (t_b) is the critical parameter for boundary avoidance tracking, computed using the displacement (x_b) from, and rate ($\dot{x}_b$) toward, the boundary [12, 13, 14]:

$$t_b = \frac{x_b}{\dot{x}_b} \tag{1}$$

To compute t_b, the following conditions must be taken into consideration:

$$if \;\; q < 0 \quad t_b = \frac{BV^{low} - \theta_{rel}}{q} \tag{2}$$

$$if \; q < 0 \quad t_b = \frac{BV^{up} - \theta_{rel}}{q} \tag{3}$$

Equations (2) and (3) depend upon whether the pilot is approaching a lower BV^{low} or an upper pitch attitude boundary BV^{up}. Depending on the time to the boundary, the pilot will feed back the helicopter response with a boundary feedback BF value before reaching the upper/lower boundary.

The input of the pilot is expected to increase from zero at t_{min}, to K_{bm} at t_{max}, linearly:

$$BTF = \frac{t_{min} - (t_b + \tau_b)}{t_{min} - t_{max}} K_{bm} \tag{4}$$

It is important to note that the minimum input occurs at a greater time to boundary that the maximum input (i.e. $t_{min} > t_{max}$). In case the boundaries are exceeded (if it is possible without catastrophic results), then K_{bm} is held until the position is again within the boundaries.

The BAT theory also describes, in addition to pilot behavior, the change in his behavior over time, as the boundaries are decreased. The effect of the boundaries on the pilot can be seen by studying the control stick movement: pilot duty cycle and pilot aggressiveness, that are called pilot inceptor workload [15]. The duty cycle describes how often the pilot inputs on the controls, while the aggressiveness is the speed at which he does so. These two concepts sum up pilot inceptor workload, because they describe how often and how fast he acts on the controls.

Before introducing the BAT, Dr. Gray had developed a theory concerning the link between the required and the achieved performance during a piloting task. This means that as performance tolerances become tighter, pilots will respond with increased performance, until the tolerances become so tight that the pilot is unable to perform as required, thus leading to a PIO occurrence scenario.

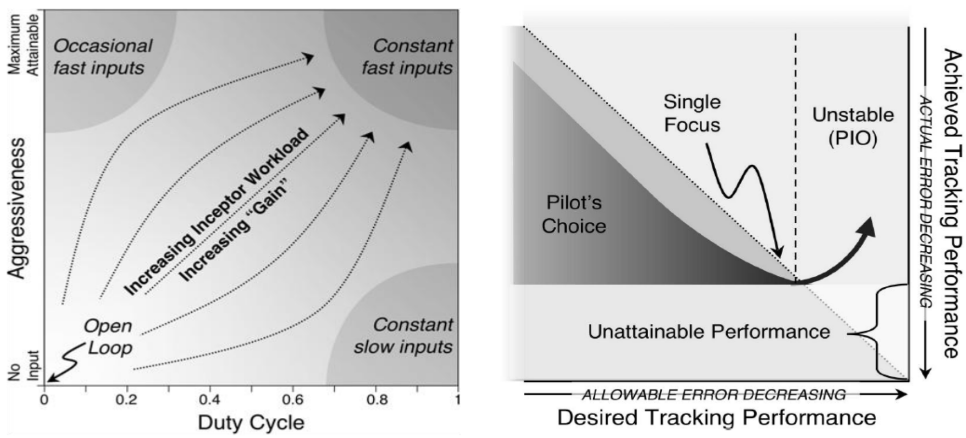

Fig. 2. Pilot Duty Cycle and Aggressiveness Theory / Achieved & Desired Performance Theory [3].

I. Numerical results

Simulations were made for the Airbus A300-600 aircraft mathematical model, generated from the stability matrices with given nominal conditions. The boundary-avoidance situations were simulated with the BAT model, by controlling a moderately-damped 4-th order longitudinal plant model (resulting in Level 1 handling qualities along the pitch axis).

Considering the following approximation of the longitudinal dynamics,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{5}$$

with the human operator transfer function:

$$Y_p = K_p \cdot e^{-\tau s} \cdot \frac{T_L s + 1}{T_I s + 1} \tag{6}$$

where Y_p, K_p, T_L, T_I and τ represent the pilot transfer function, pilot gain, lead time constant, lag time constant and effective time delay respectively. The longitudinal transfer function is shown in equation (7):

$$\frac{q(s)}{\delta_e(s)} = \frac{-4.794\,s^3 - 6.263\,s^2 - 0.4773\,s - 2.998e-015}{s^4 + 3.776\,s^3 + 20.9\,s^2 + 0.9119\,s + 0.8304} \tag{7}$$

where q is the pitch rate and δ_e is the elevator deflection (degrees).

In the case when the boundaries were distant enough, such that the time-to-boundary was never less than $t_{\min}$ it was not necessary to make any boundary avoidance inputs, and the system response damped naturally.

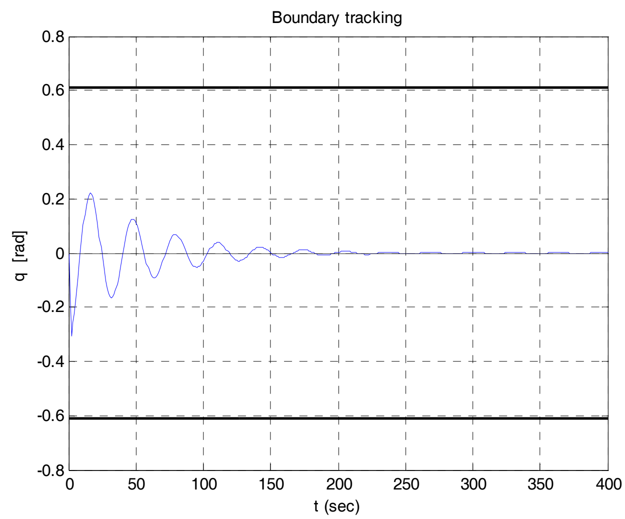

Fig.3. A damped system with no boundary tracking
($K_{bm} = 0.7$, $\tau_b = 0.3$, $t_{\min} = 2.1$, $t_{\max} = 0.1$)

In Fig. 4 a) the boundaries are closer, such that only one avoidance is to be made, and $t_{\min}$ was greater than the time to boundary. Even in this case, the system response damped naturally. For even closer boundaries (Fig. 4 b)), an input-overshoot-opposite input pattern developed, that later led to a typical PIO system.

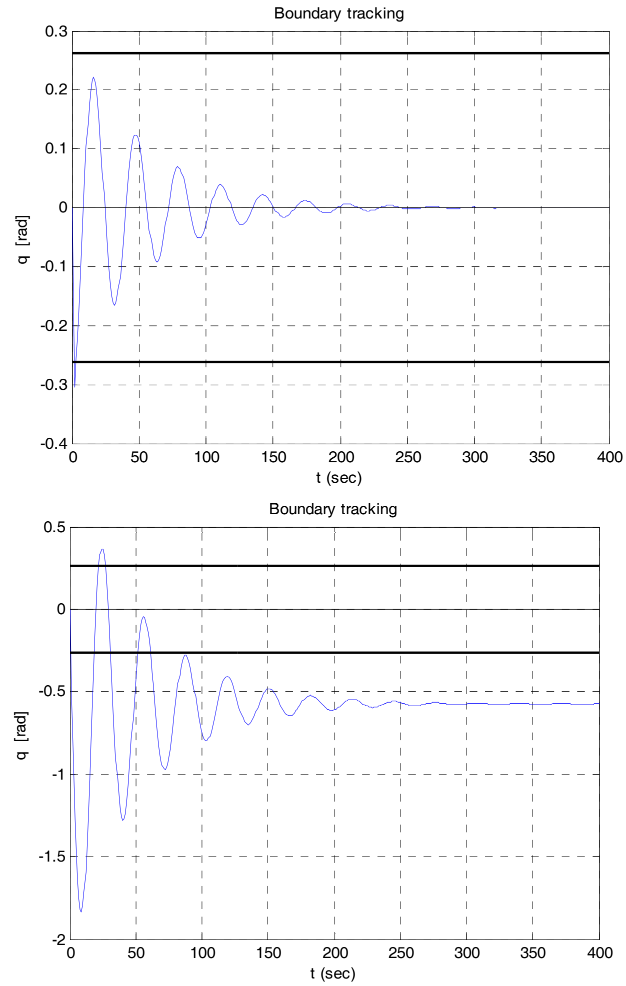

Fig. 4. a) A single instance of boundary tracking b) Two instances of boundary tracking ($K_{bm} = 0.7$, $\tau_b = 0.1$, $t_{\min} = 2.1$, $t_{\max} = 0.1$).

The Boundary Tracking method was compared with the Neal-Smith Criterion (that is similar with the Point Tracking method) that is based on pilot-aircraft closed loop analysis of the pitch attitude response, and the results were are displayed the following figures:

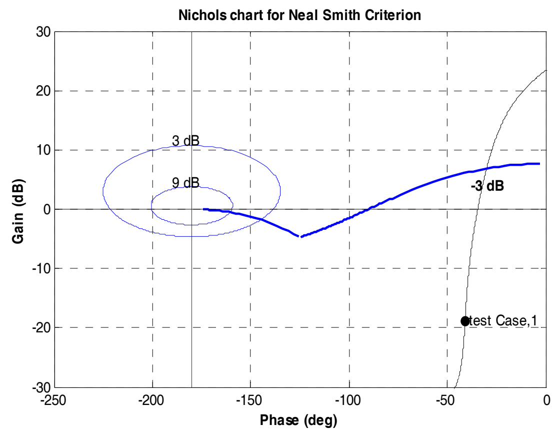

Fig.5. Neal-Smith criterion for $K_p = K_{bm}$.

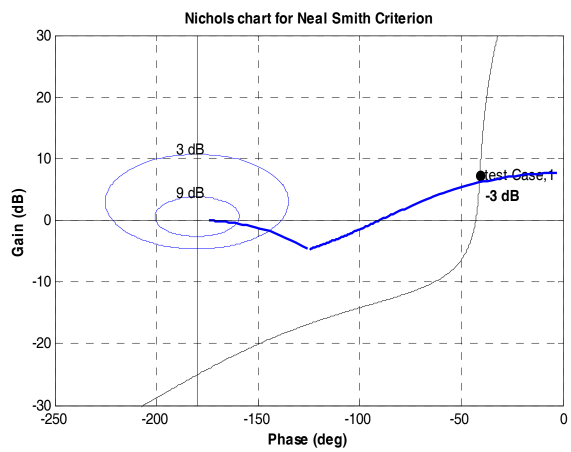

Fig.6. Neal-Smith criterion for K_p varied.

Both figures analyze the system stability response for the given configuration, using the precise trajectory tracking method [15]. In Fig. 5 the gain pilot parameter was kept constant, and in Fig. 6 only the lead and lag were varied, resulting in an instability response.

2. Conclusions

The optimization of the BAT model not only guarantees the closest match to the input data, but also has the capability to suggest a switch to the boundary tracking stick force equation, thus providing better matches with the input.

In average, decreasing boundaries improve pilot performance up to the point where he is performing at maximum capacity, as revealed by the data so far gathered. The pilot has the tendency to accept a small amount of error, when the performance demands are not too stringent, but also will tend to tighten the control when errors could exceed boundaries fatally.

The more pilot performance improves, and simultaneously workload decreases, the pilot tended to assign better PIO scale [7].

3. Future research

Ongoing studies will possibly refer to the relationship between time-to-boundary and other parameters, to better characterize the switching from tracking to avoidance. While a theory has been developed to identify the point of transition, adding more cueing parameters to the analysis will improve the accuracy of determining this point.

Acknowledgement

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