Technical Note

Towards understanding effects of non-linear flight control system elements on inexperienced pilots

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ABSTRACT

This note presents the experimental method and results from a series of desktop simulation tests designed to investigate the manual control characteristics of relatively inexperienced civil pilots; with an average age and experience of 24 years and 66 hours respectively. Increased encroachment into non-linear command gearing was found to make aggressive subjects resort to high levels of crossover regression. The combined effects of rate-limiting and non-linear command gearing were observed only for demanding tasks during which over-control was a typical feature.

NOMENCLATURE

A_k	forcing function amplitude
e_θ	pitch attitude error
f_D	sum-of-sines forcing function
N_{zc}	commanded normal acceleration
Y_p	pilot frequency response function
δ_s	stick deflection
η	elevator deflection
η_c	commanded elevator deflection
θ	aircraft pitch attitude
θ_{FD}	flight director pitch command
σ_d	root-mean-square forcing function
ϕ_k	forcing function phase
ω_k	forcing function frequency

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1.0 INTRODUCTION

Single aisle aircraft make up most of the air traffic today and the increasing demand for air transport will most likely maintain this proportion. These aircraft tend to be crewed by a relatively young pilot population who have far less experience than those flying long haul wide-body types. The sheer number of such aircraft has also meant that they encounter upset incidents more frequently[1]. At the same time, the majority of studies done in the fields of flight simulation and aircraft handling qualities have involved experimental test pilots. In fact, the media for pilot feedback, such as the Cooper-Harper and pilot-induced oscillation (PIO) rating scales, requires the pilot to be trained in the use and interpretation of such subjective ratings scales. A need to develop an understanding of control techniques employed by relatively inexperienced pilots is therefore required. This study aims to investigate the control characteristics demonstrated by these pilots when faced with the activation of non-linear flight control system (FCS) components such as command gearing and actuator rate-limiting. This technical note presents the progress and insights made so far.

2.0 EXPERIMENTAL SETUP

2.1 Procedure

This study was undertaken in two experimental stages. The preliminary stage involved tests conducted with a mixture of young pilots and engineering students to achieve the following aims:

- Develop the man-machine interface and simulation capability necessary to capture relevant dynamics.
- Design and fine-tune tasks through direct testing of subjects.
- Develop analytical tools necessary to post-process and study experimental data.
- Study the effects of training.

Preliminary tests to investigate training effects were conducted for 14 subjects with an average age and experience of 25 years and 10 flying hours respectively. The subjects were presented with a sum-of-sines compensatory task (two minutes in duration) and root-mean-square (rms) error was taken as a performance indicator. It was found that the subjects stabilised their performance between five to seven runs. However, the tasks were found to require a considerable amount of concentration and therefore, fatigue became a major factor when deciding the number of training and experimental runs allowed per session.

The final experiment involved five trainee civil pilots with an average age and experience of 24 years and 66 hours respectively. They performed the following 11 tasks, each two minutes in duration:

- Five compensatory tasks for training.
- Three compensatory tasks with varying encroachments into command gearing non-linearity.
- Three tracking tasks with increasing rate limiting.

Fatigue effects were avoided by allowing a short break after each set of tasks.

Whether these tasks were sufficiently difficult to force the pilots into using a high gain control strategy remains a matter of debate. Although more so in simulation than during actual flight tests, it is very difficult to ensure pilots maintain a consistent level of aggressiveness or introduce high gains into the pilot-vehicle system. Here, two subjects performed the tests alongside each other

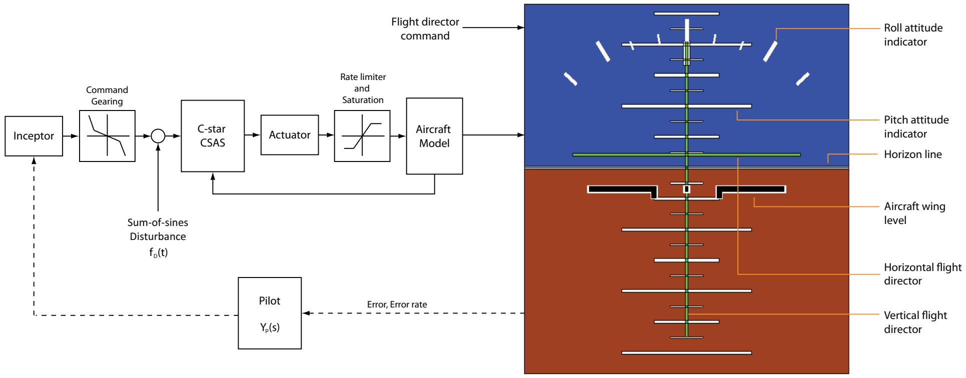

Figure 1. Experimental setup and display used for the experiments.

and both were informed of their and their counterpart's rms error at completion. It was hoped that this would introduce a competitive element and consequently induce the subjects to operate with higher gains. It should also be noted that the nature of the tasks were considerably different to that of manual control during normal flight. In this case, the pilots perceive and focus on only two variables at a given time. Therefore, the subject can apply control action based on only two feedback channels. Minimising the number of control variables in this manner limits attention allocation and allows the subject to develop a control structure with only error and error rate as inputs and stick deflection as the sole output.

2.2 Aircraft model and hardware

The experimental setup used for both tracking and compensatory tasks is shown in Fig. 1. A linear time invariant (LTI) model, representative of a large four-engined transport aircraft during climb/approach was used. This was obtained by linearising a full non-linear model at Mach 0·6 and 12,000ft altitude. A C-star command and stability augmentation system (CSAS) was designed to present the subjects with dynamics representative of modern large transports. The FCS gains were selected such that aircraft response lay well within the C-star boundaries defined for optimum response at this flight phase.

Aircraft pitch rate and attitude were presented to the pilot via a 110mm × 115mm display shown in Fig. 1. The attitude indicator scales were spaced such that 5 degrees pitch attitude equalled a 10mm separation. All tests were conducted on laptops in a MATLAB/Simulink® environment with a nominal computational time delay of 13ms. The subjects performed tasks by manipulating Microsoft Sidewinder® joysticks. The inactive nature of such an inceptor allows the relationship between pilot command and stick deflection to be kept relatively simple. Significant contributions to attenuation and phase lag was found only well above the manual control frequency range. At 5Hz, the joystick introduced negligible attenuation along with only 7 degrees of phase lag.

2.3 Experimental tasks

All experiments involved the subjects performing either compensatory (disturbance rejection) tasks or tracking tasks in the aircraft longitudinal axis. When performing compensatory tasks, the flight director was switched off and the subjects tried to align the aircraft attitude indicator with the

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horizon line. Disturbance was injected, as shown in Fig. 1, in the form of the following forcing function:

$$f_D(t) = \sum_{k=1}^{15} A_k \,\mathrm{Sin}\,(\omega_k t + \phi_k) \qquad \ldots(1)$$

Whilst being a relatively simple task, such a forcing function effectively excites the pilot's control action at selected frequencies over the desired frequency range. The phase for each sinusoid was randomised such that the subject could not perceive any internal coherence and thus adopt high level behaviour. A detailed discussion on the design of forcing functions can be found in work done by McRuer *et al*[2].

Such a forcing function along with its corresponding pilot dynamics are well suited for the derivation of pilot's frequency response[3]. The raw time domain data was converted to frequency domain via the discrete fast Fourier transform (denoted here using the $\mathcal{F}$ operator). Pilot frequency response to a perceived variable was then derived as follows:

$$|Y_p(s)| = \frac{|\mathcal{F}(\delta_s(t))|}{|\mathcal{F}(e_\theta(t))|} \quad , \quad \angle Y_p(s) = \arg\mathcal{F}(\delta_s(t)) - \arg\mathcal{F}(e_\theta(t)) \qquad \ldots(2)$$

The pilot-aircraft system was analysed in the frequency domain via the superposition of the pilot and LTI model frequency responses. Crossover frequency was obtained by noting where the frequency at which the gain for the open-loop pilot-vehicle system was unity.

The tracking task required the pilot to follow the pitch attitude commands provided by the flight director. This demand comprised of a series of steps and ramps and is a modified version of the task used by Mitchell *et al*[4] in their investigation of rate-limiting effects.

The forcing functions and the tracking tasks were kept relatively small in magnitude such that the LTI model remained valid. Limiting the study in this way meant that the inability to provide acceleration cues was made inconsequential.

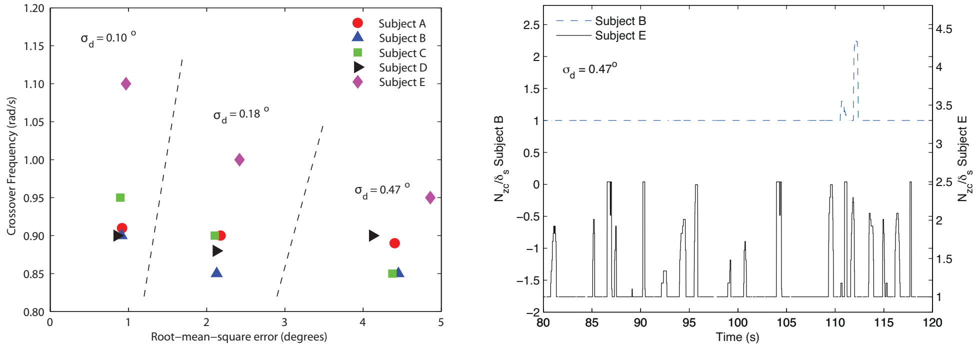
3.0 RESULTS

3.1 Command gearing

The effects of command gearing were investigated by presenting the subjects with a series of compensatory tasks. The following command gearing, similar to that used in modern civil aircraft, was used to convert the stick deflection to load factor demand:

$$\frac{N_{zc}}{\delta_s} = \begin{cases} -4, & -1{\cdot}0 \le \delta_s \le -0{\cdot}5 \\ -1, & -0{\cdot}5 < \delta_s < 0{\cdot}9 \\ -16, & 0{\cdot}9 \le \delta_s \le 1{\cdot}0 \end{cases} \qquad \ldots(3)$$

The subjects' control actions were forced to span over the non-linear region by increasing the forcing function rms (σ_d). The effects are succinctly summarised in Fig. 2(a). Increasing the number of incursions into the non-linear region was found to make the task more difficult as evident by larger rms error. Most subjects maintained a crossover frequency of around 0·9rad/s, where as Subjects C and E resorted to different degrees of crossover regression. Adoption of greater crossover frequencies by Subject E indicates increased



(a) Subject crossover frequency and rms error (b) Stick activity for Subjects B and E

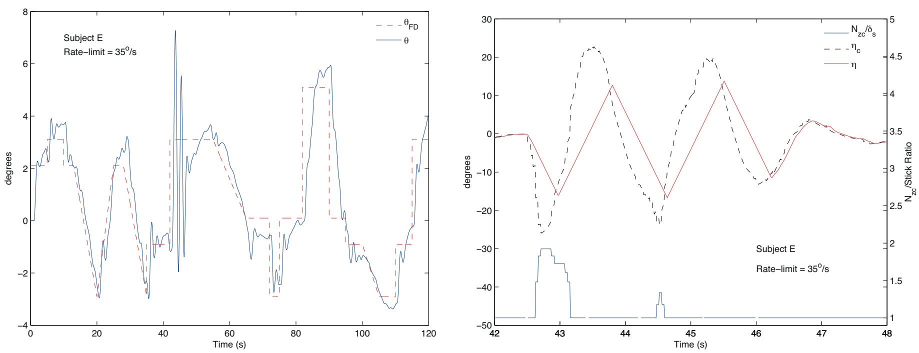
Figure 2. Effects of command gearing on performance and stick activity.

aggressiveness leading to degraded performance. Some insight can be gained by comparing Subject E's stick activity with that of Subject B in Fig. 2(b). It shows the frequency with which the subjects encroach the non-linear regions. Subject E's aggressive control strategy leads to a cycle where every encroachment into a non-linear region causes over-control which in turn, demands an equally aggressive recovery action. Therefore, the subject perceives high frequency oscillations in attitude and so maintains the greater crossover frequency. Thus, reinforcing the cycle.

3.2 Actuator rate-limiting

Actuator rate-limiting is known to introduce phase delay and amplitude attenuation into a closed-loop system[5]. A series of tracking tasks were used to investigate its effect on manual control. The reference attitude used for the tracking task is shown in Fig. 3(a). Tests were conducted with 25deg/s, 35deg/s and 45deg/s actuator rate-limits. The command gearing described earlier was retained.

Upon hitting a rate-limit, subjects were found to compensate by increasing their gain (leading to larger stick deflections) to get the desired response. However, the introduced phase delay led to larger overshoots and longer recovery times. This can be seen around 43 seconds in Subject E's data, shown in Fig. 3(a). The more demanding commands occurring



(a) Tracking task and subject performance (b) Actuator performance and command gearing

Figure 3. Compounded effect of rate-limiting and command gearing.

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at 42, 82 and 115 seconds led to the triggering of non-linear command shaping causing actuator rate-limiting. This can be seen clearly in Fig. 3(b).

Although this subject was found to be the most aggressive, the dynamics after the first minute is representative of the remaining subjects. They were found to apply gentle stick movements to track the flight director. Post-experiment feedback found that this characteristic was encouraged at the flight school.

4.0 CONCLUSIONS AND FUTURE WORK

The experimental method and results from a series of desktop simulation tests designed to investigate the manual control characteristics of young and relatively inexperienced pilots has been presented. Five subjects with an average age of 24 years and 66 hours average flight experience were asked to perform a series of simple tasks. Compensatory and tracking tasks were used to study the effects of non-linear command gearing and actuator rate-limiting respectively. Increased encroachment into the non-linear command gearing was found to make aggressive subjects resort to a high degree of crossover regression. The combined effects of rate-limiting and non-linear command gearing were observed only for demanding tasks during which over-control was a typical feature.

Future work consists of expanding the experimental database by testing more subjects. It is also hoped that a comparison with older and more experienced pilots can be made. However, at the time of writing, identification processes are being developed to obtain pilot model parameters that will allow pilot-in-the-loop stability analysis.

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