A Cybernetic Approach To Assess Flight Simulator Fidelity

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This paper presents the results of an experiment in which a cybernetic approach has been used to investigate the effect of motion filter setting changes and display type on simulator fidelity. Pilot control behavior, pilot remnant, open loop behavior, open loop performance and subjective evaluations in a real jet-aircraft were compared with that in a high-fidelity motion base simulator. The task studied was a pitch-tracking following task. Peripheral information was omitted from the experiment. The results from the flight tests, in the first phase of the experiment, were used to tune and validate simulator models and settings for the simulator tests in the second phase of the experiment. These flight test results are also used as a base-line condition to which the results from the simulator tests are compared. Two types of displays were used in the experiment, a compensatory and pursuit display, and in the simulator, a set of nine different motion filter settings. Results show only slight differences in pilot control behavior and open loop behavior between the aircraft and the simulator, between the different motion filter settings in the simulator, and between the two display types used. A more significant effect is found on the pilot injected noise level and consequently on the open loop performance. Analytical biases and variances are calculated for the estimated open loop describing functions. The applied cybernetic approach has provided objective and accurate results, which makes this technique suitable for more extensive research on simulator fidelity in the future.

I. Introduction

Pilot training heavily relies on the use of flight simulators, by which expensive flying time is saved. In the future, simulator training will become even more important. In the ab-initio training of pilots, where low-level piloting skills are trained, the realism of the pilot’s perception of the environment is of great influence and thus training time in the real aircraft, with a perfect realism, is still of importance. For type-rating of pilots, however, where more rule-based and knowledge-based behavior is trained, a zero-flight time condition is already common practice.

In both types of training, high-fidelity simulators are required for good transfer of training. However, a lot of unclarity continues to exist about how to measure simulator fidelity and about how much fidelity is required to guarantee a certain level of transfer of training. Standard fidelity levels are usually based on technical simulator requirements, where more high-tech simulators generally have a higher fidelity. However, these criteria are not concerned with minimum motion response, which greatly influences the required amount of motion space of the simulator, and consequently its complexity and cost. In addition, partly due to a lack of detailed knowledge of human use of motion cues, controversy still exists about the role of motion on simulator fidelity, for which a lot of research still has to be done. The results of this type of research can considerably affect the design and operation of future aircraft simulators and its motion cueing systems. In this context, scientific data on the relationship between e.g. platform motion and its effect on the transfer of pilot performance and behavior to and from the airplane are becoming very important.

In this paper an experiment is described which has been performed with the objective of comparing human pilot control behavior in real flight with that in the simulator. The first part of the experiment was flown on a Cessna Citation II (Fig. 1(a)), a twin-jet aircraft. The second part was flown in the SIMONA Research Simulator (SRS) (Fig. 1(b)), a high-fidelity motion base simulator. This set-up

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is reflected in the structure of this paper. First, a background on the subject is given, followed by a description of the design of the experiment. After that, the flight tests and the simulator tests are described. This paper concludes with the results and conclusions.

![Facilities used in the experiment](image)

(a) The Cessna Citation II laboratory aircraft  
(b) The SIMONA high-fidelity motion base simulator

Figure 1. Facilities used in the experiment

II. Background and previous research

Simulator fidelity is a widely used term for which several definitions exist, which may cause confusion and discussion. For many years the prevailing idea in the simulator community was that by employing more advanced hardware (e.g., better visual scene quality, better motion system performances, etc.), simulator fidelity could be increased. This resulted in technically advanced, but at the same time complex and expensive simulators. The definition of simulator fidelity which is used here is: "the degree to which characteristics of perceivable states induce adequate pilot psychomotor and cognitive behavior for a given task and environment". It is the authors' claim that simulator fidelity is not only determined by the technical capabilities of a simulator but also by our understanding of the human physical and psychological capabilities, and, that it is not the technical differences between the nominal and simulated vehicle which should be focused on, but their effect on the pilot's perceptual array and especially the resulting effect on the pilot's control behavior and pilot/vehicle performance. This idea is supported by the fact that human pilots, as a reaction to a changed environment, adapt their behavior and their use of the available information sources (central visual, peripheral, vestibular) to achieve the same level of performance. In some cases e.g., a pilot can visually compensate for motion information when the latter is not present. Simulator fidelity should therefore address the changes of the pilot's perceptual array (perception) when going from aircraft to simulator, as well as the effect of these changes on the pilot's control behavior (action) and aircraft/vehicle performance. This perception-action philosophy underlies the experiment described in this paper.

Literature on this subject can be divided into two groups.

A. Analytical approach

Because of the lack of available comparable flight test data in simulator research, an analytical methodology to predict simulator fidelity was developed by Hess et al. Instead of comparing real measured human pilot describing functions, analytical human pilot models are compared. The hypothesis is that many major fidelity problems stem from simulator limitations that adversely affect the primary control loop in a control task. These limitations are modeled and used to tune the pilot model. As an example, this approach has been applied to available rotorcraft flight and simulator data and extended with a handling quality prediction. The analytical model for human use of motion cues in tracking and regulation tasks is an extension of the structural model of a human pilot, which incorporates the dynamics of the human central nervous system and neuromuscular system. An additional loop closure involving motion feedback has been added. This model was able to match experimental results from manned simulation with different motion conditions without model parameter changes.

When this model is incorporated in a computer simulation of the primary control loop of a pilot
controlling an aircraft/simulator, in which a mathematical model for the aircraft or simulator (with its limitations) is included, the parameters of this model can be predicted by the use of a set of adaptation rules. The resulting differences in pilot/vehicle dynamics reflect the simulator fidelity for the primary control loop. This methodology has later been extended to multi-axis tasks including visual cue quality.

The accuracy of its results primarily depends on the accuracy of the available models of the aircraft and the simulator with its hardware and software limitations and the applicability of the assumed pilot model for the task tested.

B. Experimental approach

Pilot’s perception and control of aircraft motion have been studied by Hosman and Van der Vaart. From a literature survey it appeared that experiments in which pilot behavior and performance are extracted from aircraft flight test data and simulator test data are rarely done.

Kuehnel performed an experiment in a two-place jet trainer with modified control system and in a fixed-base simulator. A single-loop compensatory pitch-tracking disturbance task was flown with a forcing function consisting of a sum of 12 sinusoids. Pitch-attitude indicator in the simulator and natural horizon in the aircraft were used. Differences were found in the shape of the human pilot describing function in flight and the fixed-base simulator. In the aircraft the pilot’s frequency response looked the same as a lead network and in the simulator it looked like a lag-lead network. Preliminary indications were found that pilot’s control behavior depends primarily on pitch response, and is not influenced by normal accelerations. Newell and Smith performed an experiment in a variable stability T-33 airplane and a fixed-base general-purpose simulator. A single-loop compensatory roll-tracking disturbance and following task was flown with an augmented rectangular forcing function consisting of a sum of 10 sinusoids. Similar pilot behavior was found in flight as compared to the ground simulator, but differences were found between the VFR and IFR flight condition.

Van Gool and Mooij performed an experiment with a Beechcraft Queen Air aircraft with selectable dynamic characteristics and a moving base simulator of the TU Delft. A single-loop pitch-tracking task was flown with an augmented rectangular forcing function consisting of a sum of 10 sinusoids. Results from this research showed that pilot remnant was dependent on the amount of low-frequency lead generated by the pilot. Indications were found that motion cues are used by the pilots to increase the stability of the total system in ‘difficult’ control tasks, where high lead is required. Error scores in flight were significantly lower than in the simulator and relatively unaffected by the simulator motion.

However, care should be taken in interpreting these results, as all experiments in this area are characterized by the many differences in task, display, controlled system dynamics, input signal, motion system etc. It is therefore hard to explain, generalize or extrapolate the conclusions from these experiments.

New research at the Delft University of Technology aims to provide more insight into these issues. Having access to both a laboratory aircraft and a high-performance moving-base simulator, the university is in a unique position to investigate the effects of motion parameters on the pilot’s control behavior. In the experiments described in this paper, only a lumped pilot describing function is identified, from which possible changes in pilot control technique might not be detected when lumped pilot behavior remains constant. In this light, a parallel experiment program has been conducted with the aim of clarifying the different contributions of visual and motion feedback to the pilot response in manual control tasks.

III. Experiment design

A. Research objectives

The main objective of the research described in this paper was to compare human pilot control behavior, pilot remnant, open loop behavior and open loop performance for a pitch-tracking target following task, in real flight with that in the simulator. The differences in pilot control behavior are assumed to be a measure of the fidelity of the simulator, for that specific task. That is, when the differences are small, fidelity is high, and vice versa.

A secondary objective was to investigate the relative importance of angular rate information \( (q) \), as compared to vertical acceleration information \( (a_z) \) in the simulator motion cueing for a pilot controlling the pitch dynamics of an aircraft. In 6-dof synergetic motion systems heave motion is limited, therefore knowledge of the relative importance of heave motion compared to pitch motion for control tasks is valuable for simulator design.
B. Integrated approach

The experiment was divided in two phases. In phase I, the flight tests with the Cessna Citation II laboratory aircraft were conducted, and afterwards, in phase II, the simulator tests in the SRS. The results of the flight tests were used to tune and simulator parameters and models, and to design an appropriate set of motion filter settings for the simulator tests.

The results of the flight tests were used as a base-line condition to which the results of the simulator experiments were compared.

Figure 2. The longitudinal control of the aircraft as a nested system of 3 control loops. In this representation the control system of the aircraft is treated as a separate system. The aircraft model only represents the longitudinal dynamics of the aircraft with the elevator as input. Only the innermost loop was exited during the experiment.

C. Task definition

The experiment focused on the control of the longitudinal axis of the aircraft, which can be modeled by a system of three nested control loops (Fig.2). The inner loop provides attitude control, the middle loop provides flight-path angle control and the outer loop provides height control. Only one control loop could be identified in the aircraft, because only at the display position a test signal could be inserted. The inner loop (pitch-attitude control) was chosen to be excited as is it this loop which has the highest band-width. Performance in this loop forms the basis for outer loop control.

A pitch-tracking following task was flown, in which the pilot was provided with central visual (display) and vestibular (motion) cues. Peripheral cues were omitted from the experiment by the use of a hood in the aircraft and by turning off the visual system in the simulator.

A following task differs considerably from a disturbance task, as can be seen in Fig. 3. In a disturbance task, the human controller has to compensate for an input signal \( i \) inserted in the loop at the input of the controlled system (Fig. 3(a)). This is representative for e.g. flying through atmospheric turbulence. In a target following task, the human controller has to follow a signal \( i \) inserted at the display (Fig. 3(b)). This is representative for e.g. chasing other aircraft.

The differences in pilot control behavior for these two types of tasks are important, because of the different role of motion. In a disturbance task, the motion is the result of the combined, lumped, pilot’s
actions $\delta_c$ and the inserted signal $i$ (representative for external turbulence), while in a target following task, the motion is the result of the pilot’s actions $\delta_c$ only.

As the Cessna Citation II laboratory aircraft is not equipped with a fly-by-wire system, it was technically not possible to fly disturbance tasks. This was the reason to select a target following task.

The duration of an experimental run was 90s, of which the first 10s were used as run-in time for transitional effects to fade out and for the subject to adjust himself to the task. The remaining 80s were used for data analysis. Data was recorded with a sample frequency of 25 Hz.

1. Subjects and instructions to subjects

Four pilots participated in the experiment (Table 1). All pilots had considerable experience with tracking tasks. They were asked to minimize the pitch-attitude-error, while limiting bank-angle deflections to an absolute minimum.

D. Identification

Fig. 3(b) is a representation of the pitch-tracking following task flown, in which the following signals are found:

- $i(t)$ forcing function
- $e(t)$ pitch-attitude error ($= i(t) - \theta(t)$)
- $n(t)$ pilot remnant
- $\delta_c(t)$ aircraft control column position
- $\delta_e(t)$ aircraft elevator position
- $\theta(t)$ aircraft pitch-attitude

The following transfer function estimations are defined:

$$
\begin{align*}
\hat{H}_p(\omega) &= \hat{H}_c^\delta(\omega) &= \hat{S}_{\delta_p}(\omega)/\hat{S}_\omega(\omega) \\
\hat{H}_c^e(\omega) &= \hat{H}_c^\delta(\omega) &= \hat{S}_{\delta_e}(\omega)/\hat{S}_{\delta_p}(\omega) \\
\hat{H}_c^{\text{dyn}}(\omega) &= \hat{H}_c^\theta(\omega) &= \hat{S}_\theta(\omega)/\hat{S}_{\delta_p}(\omega) \\
\hat{H}_OL(\omega) &= \hat{H}_c^\theta(\omega) &= \hat{S}_\theta(\omega)/\hat{S}_{\delta_e}(\omega)
\end{align*}
$$

(1)

The averaged power spectra are calculated as:

$$
\hat{S}_{xy}(\omega) = \frac{1}{n} \sum_{n=1}^{7} X_n^*(\omega) \cdot Y_n(\omega),
$$

(2)

where $X_n^*(\omega)$ is the conjugate of the fourier transform of $x_n(t)$ and $Y_n(\omega)$ the fourier transform of $y_n(t)$. The subscript n stands for the number of the sample in the set of available data for one condition. The estimations of the transfer functions are biased because of the pilot’s remnant $n$ and because of the uncertainties in the measurements and the non-linearities of the system dynamics (Fig. 3(b)). The spectra are averaged over the set of 7 measurements per condition in order to decrease the relative noise content, i.e. to increase the signal-to-noise ratio and consequently to improve the accuracy of the estimates.

The test signal $i$ is a sum of 10 sinusoids and identification is done at these set of frequencies (Table 3).
E. Dependent measures

The following variables were calculated:

1. \( \hat{H}_p \)  
   pilot control behavior

2. \( \hat{H}_{OL} \)  
   open loop system behavior

3. \( P_{x_n} \)  
   power in signal \( x(t) \) due to the noise \( n(t) \)

4. Score  
   score, performance index

A lumped pilot model \( \hat{H}_p \) has been identified, which is the transfer-function between the error of the system \( e \) and the pilot’s control actions \( \delta_c \) (Fig.3(b)). This is the so-called visual equivalent of \( H_{lp}^{in} \) (Fig.2). Normally, a pilot has multiple information sources available (central visual, peripheral, vestibular, etc.), which should be modeled by a multi-dimensional model accordingly. A visual equivalent describing function assumes that all information has been obtained from the central visual channel (here \( e \)).

Parallel to the described experiment, another experiment was conducted in which a multi-dimensional pilot model was identified, from which the influence of all these different information sources could be distinguished.

According to the theory of McRuer, the human pilot will adapt his behavior \( (H_p) \) to the dynamics of the controlled system \( (H_{cs} \cdot H_c) \) to yield integrator-like open loop dynamics in the crossover region.\(^{11}\)

The following performance measurement was presented to the pilot after each run:

\[
Score = 1 - \frac{\sigma_e^2}{\sigma_i^2}.
\]

(3)

In the ideal case that the error would be reduced completely \( (e = 0) \), the score would be 1. In the case that the pilot would not do anything \( (e = i) \) the score would be 0. In the case the pilot would aggravate the error, the score could become negative. During this experiment, scores were found between 0.2 and 0.7. Because a score less than 0.5 is sometimes associated with ‘failure’, it was chosen to multiply the score, before presenting to the pilot, by a (randomly chosen) factor 7.

F. Independent variables

The following variables were varied and used as different experiment conditions:

1. Aircraft/simulator
2. Display type
3. Motion filters

1. Aircraft/simulator

The laboratory aircraft is a Cessna Citation II (Fig.1(a)). It is a twin-jet with a ceiling of 42650 ft and a maximum cruising speed of 383 kts. It has been equipped with test instruments.

The SIMONA Research Simulator (SRS) (Fig.1(b)) is a light-weight, high-performance, 6 degree-of-freedom, high-fidelity flight simulator, characterized by its very small motion lags (20-30 ms) due to its light weight and special motion control algorithms, and small computation delays.\(^{24}\)

2. Display type

Two types of displays were used in the experiment, based on a classical primary flight display: a compensatory display and a pursuit display (Fig. 4). In both displays, the aircraft symbol can be found in the center of the display. The display gain is chosen such that the displays cover a vertical field of view of 10 deg pitch. This value is chosen during a first test-flight and was a balance between a high gain for perceptual accuracy and a low gain for a better overview and for the pilot not to have to ‘chase’ the signal.

The compensatory display (Fig. 4(a)) only shows the error between the forcing function and the actual measured pitch-attitude of the aircraft. The large horizontal line in Fig. 4(a), does not represent the true horizon. The pilot has to pitch up in order to bring the aircraft-symbol towards the large horizontal line, and thus minimize the error. The information on this display is not congruent with the motion felt by the pilot, as the motion provides information about the attitude, while the display shows the difference between the attitude and the unknown and unpredictable reference signal. The pursuit display (Fig. 4(b)) presents the real attitude, which is congruent with the motions felt by the pilot. The
Figure 4. The two types of displays which are used in the experiment. The difference between the two displays is the information which is presented. In the compensatory display only error information is presented. On the pursuit display also state information is presented.

large horizontal line represents the true horizon and the second, smaller, horizontal line represents the forcing function, which is the reference pitch angle to be tracked. The error is the difference between the aircraft symbol in the center of the display and the smaller horizontal line. The pilot has to pitch up in order to bring the aircraft-symbol towards the smaller horizontal line.

3. Motion filters

In the aircraft, perfect motion cues were available, but in the simulator, however, because of space limitation, motion filters had to be used. For the longitudinal axis, two motion filter channels were of importance: the pitch channel (rotational motion) and the heave channel (vertical motion). Different motion filter settings for these two channels were chosen with data from experiment phase I. The resulting set of settings were used as experiment condition in the simulator, by which the influence of changes of motion cues on pilot control behavior could be investigated (the second research objective).

4. Summary: experiment matrix

In the aircraft two conditions were flown. The first condition was with a compensatory display, the second condition was with a pursuit display. Ten consecutive runs were flown per condition, 3 training runs and 7 measurement runs.

In the simulator the same two displays were flown, but with each display a set of different motion filters was used, 9 motion filters in case of the compensatory display and 4 motion filter in the case of the pursuit display. 8 sets of runs were flown, 1 set of training runs and 7 sets of measurement runs. In one such a set of runs every motion filter was used once, in a randomized order.

Table 2 presents an overview.

Table 2. Overview of all the dependent variables which are varied in the experiment. With the compensatory display 9 motion filter combinations were used, with the pursuit display 4.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Subject</th>
<th>Display</th>
<th>Pitch</th>
<th>Heave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td>A,B,C,D</td>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Simulator</td>
<td>A,B,C,D</td>
<td>C</td>
<td>00,05,10</td>
<td>N,L,H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P</td>
<td>00,10</td>
<td>N,H</td>
</tr>
</tbody>
</table>

C=Compensatory, P=Pursuit display
00=no pitch, 05=half pitch, 10=full pitch
N=no heave, L=low heave-level, H=high heave-level
Table 3. Definition of forcing function signal $i$.

<table>
<thead>
<tr>
<th>$j$</th>
<th>$k_j$</th>
<th>$f_j$ (Hz)</th>
<th>$\omega_j$ (rad/s)</th>
<th>$\phi_j$ (deg)</th>
<th>$A_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0.0375</td>
<td>0.2356</td>
<td>1.1421</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0.0625</td>
<td>0.3927</td>
<td>1.0921</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>0.0875</td>
<td>0.5498</td>
<td>1.0282</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>0.1625</td>
<td>1.0210</td>
<td>0.8210</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>0.2375</td>
<td>1.4923</td>
<td>0.6532</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>31</td>
<td>0.3875</td>
<td>2.4347</td>
<td>0.4458</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>47</td>
<td>0.5875</td>
<td>3.6914</td>
<td>0.3068</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>79</td>
<td>0.9875</td>
<td>6.2046</td>
<td>0.1867</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>131</td>
<td>1.6375</td>
<td>10.289</td>
<td>0.1135</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>223</td>
<td>2.7875</td>
<td>17.514</td>
<td>0.0669</td>
<td>10</td>
</tr>
</tbody>
</table>

G. Fixed variables

The forcing function $i$ (Fig.3(b)) consists of a sum of 10 sinusoids and is defined as:

$$i(t) = \mu_i + \sum_{j=1}^{10} A_j \cdot \sin(\omega_j \cdot t + \phi_j), \quad (4)$$

in which $\mu_i$ represents the average of the input signal $i$, $\omega_j$ the set of frequencies and $\phi_j$ the set of beginning phases. This type of test signal has the advantage of being quasi-random (random appearing) and having all energy concentrated at a set of discrete frequencies. The power $P_i$, of the forcing function $i$ can be calculated as

$$P_i = 2 \sum_{j=1}^{10} A_j^2. \quad (5)$$

This $P_i$ reflects the intensity of the signal. A balance is needed between a high $P_i$ of the signal for good identification purpose, and a limited $P_i$ for the pilot workload not to get too high. The $P_i$ was determined during a first flight test and was set to 2.5 deg$^2$. All sinusoids in the test signal had a frequency being an integer number of the base frequency $2\pi/80$ rad/s and none of the frequencies are a multiple of any other frequency. A first-order filter has been chosen to limit the bandwidth of the test signal. The break-frequency of this filter was set to 1 rad/s. This was chosen such that cross-over regression was avoided and still enough energy was put in the cross-over region. The values of $A_j$ and $\omega_j$ can be found in Table 3. Ten different sets of $\phi_j$’s are chosen randomly. This results in 10 different forcing functions with the same spectrum. Every run, one of these sets was used. By doing this pilot adapting effects were avoided.

As the pilot adapts its behavior to the dynamics of the aircraft, which was also identified during flight, the aircraft dynamics had to be kept constant. Therefore speed, and also altitude had to be kept stationary. In order to fly, on the average, a horizontal path (finishing a run on more or less the same height as at the start of the run), the mean value $\mu_i$ of the forcing function $i$ had to be set at the $\theta$-value of the aircraft in its horizontal, stable and trimmed condition before the start of the run. Some off-line simulations with an accurate non-linear aircraft model of the Cessna Citation I predicted that speed and height variations would stay limited.\(^\text{(25)}\)

H. Experiment hypothesis

The experiment hypothesis was that pilot control behavior in the simulator would be similar to pilot control behavior in the aircraft when the motion system workspace of the simulator would be used to its limits.

Another hypothesis was that when decreasing the motion cues in the simulator by selecting motion filters with a smaller gain or break frequency, pilot control behavior would start to deviate from pilot control behavior in the aircraft. This would provide an indication of how much of the motion workspace would be required for good simulator fidelity for this task.
IV. Experiment phase I: flight tests

A. Flight information

Three flight tests with the Cessna Citation II were held in November 2003 (Table 4). The first flight was a test flight in which the equipment was tested, the procedure checked and some parameters tuned (input power and maximum display gain). The two other flights were production flights, in which the necessary data were gathered. Per flight two pilots conducted the experiment. The flights consisted of quasi-horizontal flights (during which the runs were flown) and 180°-turns. The altitude was chosen such that little or no atmospheric turbulence was encountered. The speed was chosen in the middle of the aircraft speed envelope and was kept constant for constant aircraft dynamics throughout the experiment.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>IAS</th>
<th>Altitude</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A,B</td>
<td>160 kt</td>
<td>FL 120</td>
</tr>
<tr>
<td>2</td>
<td>A,B</td>
<td>160 kt</td>
<td>FL 55</td>
</tr>
<tr>
<td>3</td>
<td>C,D</td>
<td>160 kt</td>
<td>FL 60</td>
</tr>
</tbody>
</table>

B. Set-up

1. Conditions

Per flight 40 runs of 90s were flown. This was 10 runs per subject/per condition (compensatory/pursuit). Between his two sets of 10 runs, the test pilot was given some time to rest. During the runs the auto-throttle was switched off and direct control was used for aircraft control. Landing gear was retracted and no flaps were used. The test pilot used a hood to block out outside visual (peripheral) information. The display was presented to the test pilot by an LCD-screen in front of him.

2. Cockpit Procedure

The right pilot was the test pilot and flew the tracking task. The left pilot was the captain and also safety pilot. The responsibility of the safety pilot was to see if the aircraft did not get into a dangerous situation during the experiment, and to intervene if it did. One pilot change was performed per flight.

Before the start of each run, the captain brought the aircraft to the desired speed and altitude. When the aircraft was stable and trimmed, the experiment controller made the necessary computer settings. When this was done, the test pilot was asked to prepare, and when he was ready the run could begin. After the end of the run, the test pilot stabilized the aircraft and passed control back to the captain, who brought the aircraft back to its desired speed and altitude.

During the complete set of 10 runs of one condition, the throttle settings were left unaltered and the auto-pilot was kept switched off. Because of this constant throttle setting, the total energy state of the aircraft was kept constant and the desired speed and altitude could be reached simultaneously by elevator control only.

C. Data acquisition and processing

1. Apparatus

Two laptops were installed in the aircraft. One laptop controlled the LCD-screen in front of the test pilot, received the data from the data-acquisition system and performed the necessary calculations. The second laptop was used by the experiment controller to control the experiment and perform the data-logging. The measured aircraft data were received through a network connection from the FTIS (Flight Testing Instrumentation System)-computer.

The FTIS-system gathered data from different systems (air-data, inertia measurements, GPS, FMS, etc.), filtered it, and put it on channels which could be read from extern software modules. This system was designed at the Faculty of Aerospace Engineering and is used for educational flight test programs and several research purposes.
2. Data-flow

Fig. 5 gives a schematic overview of the data-flow in the aircraft. The pilot \((H_p)\) controls the aircraft \((H_c)\) by a control stick which is a part of a larger control system \((H_{cs})\). The analogue data is measured by different systems with different filter characteristics and sent to the FTIS system. The FTIS system has a time delay of about \(0.1\) s. Then this data is logged on a laptop. A second laptop calculates the error \(e (=i - \theta)\) and sends this information (together with \(\theta\) in case of a pursuit display) to the LCD screen. It is important to note that, compared to the other parameters, the error \(e\) does not have a time-delay of \(0.1\) s. This can be understood by looking at Fig. 5. If one traces back these data from where they are logged (Logging) to where they appear in the control loop, then it is clear that \(e\) has not passed the FTIS-system and therefore has not been delayed by \(0.1\) s. Or in other words, \(e\) is a calculated parameter and the others are measured ones.

![Figure 5. Set-up of citation experiment. Full lines are analogue data and not delayed, dotted lines are digital data and delayed.](image)

3. Filters

In Table 5, the characteristics of the filters can be found of all important data gathered during the flight tests.

As explained before, the error signal had to be delayed with \(0.1\) s, in order to match in absolute time with the other signals in the loop, which all passed the FTIS system before being recorded.

Before identifying the systems \(H_p, H_{cs}, H_c\) and \(H_{OL}\), \(\delta_c\) had been post-filtered for the 4\(^{th}\)-order filter which was implemented in the FTIS-system (Table 5).

Table 5. Characteristics of the data acquisition equipment. Signal types are (A)nalogue, (D)igital and (S)ynchro. Filter characteristics are given as (order of filter/break-frequency).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Data</th>
<th>Equipment</th>
<th>Type</th>
<th>Filter</th>
<th>Signal</th>
<th>Filter</th>
<th>Converter</th>
<th>Sample time</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_e)</td>
<td>elevator force</td>
<td>force sensor</td>
<td>strain gauge</td>
<td>3(^{rd})/2Hz</td>
<td>A</td>
<td>4(^{th})/6Hz</td>
<td>A/D</td>
<td>30ms</td>
</tr>
<tr>
<td>(s_e)</td>
<td>column position</td>
<td>transducer</td>
<td>potentiometer</td>
<td>-</td>
<td>A</td>
<td>4(^{th})/6Hz</td>
<td>A/D</td>
<td>30ms</td>
</tr>
<tr>
<td>(\delta_c)</td>
<td>elevator position</td>
<td>transducer</td>
<td>synchro</td>
<td>-</td>
<td>S</td>
<td>-</td>
<td>S/D</td>
<td>30ms</td>
</tr>
<tr>
<td>(\theta)</td>
<td>pitch attitude</td>
<td>vertical gyro</td>
<td>synchro</td>
<td>-</td>
<td>S</td>
<td>-</td>
<td>S/D</td>
<td>30ms</td>
</tr>
<tr>
<td>(q)</td>
<td>pitch rate</td>
<td>rate gyro</td>
<td>laser</td>
<td>-</td>
<td>D</td>
<td>-</td>
<td>RS485</td>
<td>1ms</td>
</tr>
<tr>
<td>(a_z)</td>
<td>vertical acc.</td>
<td>accelerometer</td>
<td>force/balance</td>
<td>1(^{st})/10Hz</td>
<td>A</td>
<td>-</td>
<td>A/D</td>
<td>1ms</td>
</tr>
</tbody>
</table>

D. Time-histories

In Fig. 6 some measured time-histories are given for a representative run in the Cessna Citation II. Height and speed variations stayed limited. The pilot followed the commanded pitch-signal fairly well, except for higher frequency components, and with a slight time-delay. The vertical accelerations stayed
limited, with peaks of more or less ±0.4g, as predicted in earlier made off-line simulations.25 This range was determined by the choice of the $P_i$ of the forcing function.

V. Experiment phase II: simulator tests

A. Model tuning and validation

In Fig. 7, a schematic overview of the different stages in the data-flow in both parts of the experiment is given. In order to repeat the flight tests as realistically as possible in the simulator, all the different elements found in the lower ‘SRS’ data-chain of this figure were modeled and validated properly in the simulator. The use of the same software, displays and forcing function in both parts provided good task similarity.

The control column of the SRS is equipped with a control loading system, a software-controlled hydraulic system which can simulate the forces and dynamics a pilot feels when controlling an aircraft. For the tuning of this system, the results of the analysis of the flight test data were used. The dynamics of the aircraft control system were modeled as a gain, without any dynamics. As can be seen in Fig.8, this resulted in a good match between the dynamics of the control system in the aircraft with that in the simulator. $\delta_e/\delta_c$ (both in rad) was set to 1.15 and $F_c \delta_c/\delta_e$ was set to 2150 Nm/rad.

The aircraft model which was used in the simulator is a non-linear Cessna Citation I model, implemented in Simulink. After the flight tests, the gathered flight test data was used to fine-tune this simulink model to match the identified pitch dynamics of the Cessna Citation II. This process is illustrated in Fig. 9. The original model has first been corrected for its inertia. The Citation II, which is used in the experiment, is a slightly heavier airplane. By multiplying the matrix in which the inverses of the inertia factors are used by a factor of 0.7, a good match of the linearized non-linear model dynamics with the identified pitch dynamics have been obtained, for what concerns the magnitude. This corresponded with a small downward shift of the short period frequency.

However, as can be seen in the phase-plot of Fig. 9, differences are still present. These differences can be modeled by a time-delay of 0.1 s, which gives good results, at least for the lowest 8 frequencies.
<table>
<thead>
<tr>
<th>Input</th>
<th>Controls</th>
<th>Dynamics</th>
<th>Measuring</th>
<th>Processing</th>
<th>Cueing</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Aircraft Motors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>common</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Display on LCD-Screen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Central Visual Information</td>
</tr>
<tr>
<td>SRS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Simulator Motors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7. Overview of the elements to be matched. In the upper part the elements in the aircraft are given and in the lower part the (corresponding) elements in the simulator. In the middle part the common elements are given. This figure illustrates the modularity of the experiment set-up and shows which topics have to be addressed for good repeatability of the task in the simulator.

![Bode plot of identified control system dynamics](image)

Figure 8. Bode plot of identified control system dynamics ($\hat{H}_{cs}$) in the aircraft and in the simulator. The control system is treated as a pure gain in the simulator without any dynamics.
of interest. The solid line in Fig. 9 is a linearisation of the obtained adapted non-linear model which is
used in the simulation experiment. Both the identified dynamics of the aircraft and simulator aircraft
model coincide very well, especially for the most important frequencies (the first 7).

![Bode plot of linear and identified aircraft/simulator pitch dynamics](image)

Figure 9. Bode plot of linear and identified aircraft/simulator pitch dynamics ($H_c$ vs. $\hat{H}_c$). The aircraft
identified pitch dynamics ($\hat{x}$) coincide very well with the simulator identified pitch dynamics ($\hat{o}$).

When looking at Fig. 5, one can see that the $\theta$-values used to calculate the error which is presented
to the pilot by the means of a central display, had passed a synchro-filter and the FTIS-system. This
makes that the signal has undergone a time-delay of about 0.1 s, before having been presented to the
pilot. The aircraft dynamics presented on the central display to the pilot are therefore not the real
dynamics felt by the pilot through motion cues, but delayed with 0.1s with respect to the motion cues.
This extra time-delay of 0.1s has also been implemented in the simulator display. The motion system on
the contrary was not delayed, as it was not either in the aircraft.

B. Motion system

For the design and implementation of the motion filters for experiment phase II, the approach from
Gouverneur has been used. This approach is based on checking whether simulator limitations are
reached for different motion filter settings. A first important limitation is the actual space of the simulator
motion-system. E.g. the SRS actuators have a maximum operational length of 1.15 m each. Aside from
this, the speed at which the actuators can work also has a maximum value. Finally, the pressure on the
actuators has a maximum as well. In different frequency regions, different hardware limitations (length,
speed, acceleration) limit the maximum reachable accelerations of the simulator motion system. As the
vertical accelerations found during this experiment, see Fig. 6, are relatively low-frequent, the main
limiting factor in this experiment is the stroke of the actuators.

During this experiment, the asymmetrical axis of control was of minor importance as it was almost
not excited. Therefore, standard motion filter settings for this axis were chosen. For the symmetrical
axis, the motions can be divided in pitch-motions and heave-motions (vertical accelerations).

As pitch motions stayed limited during the flight test, as can be seen in Fig. 6, a direct pitch-channel
could be used, having a gain 1. However, three different filter-gains were chosen as three experiment
conditions to investigate the effect of pitch motion on pilot control behavior (Table 6).

For the heave motions, motions had to be limited by the choice of appropriate high-pass filter char-
acteristics, again by the use of the technique from Gouverneur. Three filters have been selected, one
filter with gain 0 -(N)o heave-, one characterized by a (L)ow break-off frequency and a (L)ow gain, and
the other by a (H)igh break-frequency and a relative (H)igh gain (Table 6).

For the other channels, the filter settings which are used are the same as used in past experiments. They are designed such that not much motion space is used, but have enough fidelity for tasks in these
An validation of the simulated motion by the motion system of SRS has been done to check if the commanded accelerations are being simulated accurately.

Table 6. High-pass filter settings. \( k = \text{gain}, \omega_n = \text{break-frequency} \) and \( \zeta_n = \text{damping ratio} \).

<table>
<thead>
<tr>
<th>Pitch-channel</th>
<th>Name</th>
<th>Order</th>
<th>( k )</th>
<th>( \omega_n ) (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>00</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>1</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heave-channel</th>
<th>Name</th>
<th>Order</th>
<th>( k )</th>
<th>( \omega_n ) (rad/s)</th>
<th>( \zeta_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>2</td>
<td>0.1</td>
<td>0.75</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>2</td>
<td>0.5</td>
<td>2.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 7. 'Off-Axes' filter settings

<table>
<thead>
<tr>
<th>Dof</th>
<th>Order</th>
<th>( k )</th>
<th>( \omega_n ) (rad/s)</th>
<th>( \zeta_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>2</td>
<td>0.7</td>
<td>2.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Sway</td>
<td>2</td>
<td>0.5</td>
<td>2.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Roll</td>
<td>1</td>
<td>0.4</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Yaw</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

1. Conditions
Two independent variables are used in the simulator experiment. The first one is the pitch-motion-filter-setting and the second one is the heave-motion-filter-setting (Table 6). 3 filters for each variable results in an experiment matrix of 9 conditions. Two displays (C)ompensatory and (P)ursuit can be used with each combination of motion filter settings. This results in 18 experiment conditions. However, it has been chosen, in the case with the pursuit display, to only use the 4 extreme motion-filter-settings, as can be seen in Table 8. This finally results in 13 experiment conditions in the simulator.

Table 8. Experiment matrix

<table>
<thead>
<tr>
<th>N</th>
<th>L</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>CP</td>
<td>C</td>
</tr>
<tr>
<td>05</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>10</td>
<td>CP</td>
<td>C</td>
</tr>
</tbody>
</table>

VI. Results and discussion
A. Pilot describing function
In Fig. 10 and Fig. 11, the results of the identification of the pilot control behavior in the aircraft and in the simulator with different motion filter settings and display type respectively are plotted.

For all motion filter settings, in the mid- and high-frequency range a lower gain is used in the simulator as compared to the aircraft. The effect of pitch motion filter changes is limited, as can be seen in Fig. 10(a), while slight differences can be noticed in the mid- and high frequency gain for the different heave motion filter settings (Fig. 10(b)). Phase characteristics do not show to be influenced noticeably by the motion filter settings.
For both the aircraft and the simulator, the high-frequency gain is lower for the pursuit display as compared to the compensatory display (Fig. 11). In Fig. 11(b), this is illustrated for a constant, no-motion condition in the simulator. This same effect is observed for all other motion filter settings. In the phase characteristic, no apparent differences are noticed.

![Figure 10. Pilot describing functions for different motion filters as compared to the baseline-condition in the aircraft.](image)

![Figure 11. Pilot describing functions for the two display types for the aircraft and for the no-motion condition in the simulator.](image)

B. Noise power in error

In Fig. 12, the Power Spectral Density of the part of the error signal $e(t)$ (Fig. 3(b)) due to the noise $n(t)$ is plotted for different motion filter settings in the simulator as compared to the baseline condition in the aircraft. The spectrum is smoothed over 20 frequencies. In the high-frequency range a higher power due to noise is observed in the aircraft as compared to all condition in the simulator. In the absence of pitch motion (heave motion), adding heave motion (pitch motion) results in a lower low- and mid-frequent error-noise. The peak in PSD is due to the total, closed loop frequency response in that frequency range.

In Fig. 13, an error-bar representation is given of the effect of motion filter setting changes in the
simulator as compared to the baseline condition in the aircraft, on the total power due to noise in the error signal $e(t)$. Adding pitch motion has a considerable effect on the noise level in the error signal, especially for the no-heave condition. This is related to the trend observed in Fig. 16(a), where adding pitch motion resulted in a higher average score.

**C. Total open loop describing function**

In Fig. 15, the total open loop describing function for different motion filter settings in the simulator as compared to the baseline condition in the aircraft are plotted, for the compensatory display condition. Differences in total system behavior are limited. A slight decrease in phase margin in the simulator as compared to the aircraft can be found for all motion filter settings.

**D. Score**

In Fig. 16, an error-bar representation of the Scores is presented in which the influence of motion filter setting changes and the display type is illustrated. For nearly all conditions in the simulator, the Scores obtained in the aircraft are lower than those obtained in the simulator. When the N or L motion filter setting is used, the effect of adding pitch motion on the score become apparent (Fig. 16(a)). The Scores obtained with the pursuit display are generally lower than those obtained with the compensatory display.
Figure 15. Open loop describing function for different motion filter settings in the simulator as compared to the baseline condition in the aircraft. Compensatory display. Vertical lines show the analytically calculated $2\sigma$-interval around the aircraft measurements, based on the signal-to-noise-ratio.

Figure 16. Error-bar representation of Scores for different motion filter settings and display types.
for all motion filter settings, except for the no-motion condition, where no differences in Score are found. Pilots reported that a pursuit display provides more information (sometimes conflicting) and therefore requires more mental effort. Nevertheless, pilots generally preferred the pursuit display compared to the compensatory display.

E. Subjective evaluations

Fig. 14 presents the results from a subjective evaluation of the realism of the motion cues during the experiment. This figure illustrates that pitch and heave motion is sometimes difficult to distinguish for pilots. This can be illustrated by the increase in experienced realism when adding heave motion, with a constant pitch motion filter setting.

F. Discussion

The effect of motion filter setting changes appeared to be relatively limited, especially on the total open loop behavior. However, the validity of these results is limited to pitch-tracking following tasks with similar controlled system dynamics. As reported in literature, the effect of motion cues become more important in disturbance tasks and in more difficult tasks (higher order dynamics). The main purpose of the experiments described, however, was to compare pilot control behavior in the aircraft with that in the simulator. This limited the scope of possible experiment conditions to following tasks with the pitch-dynamics of the Citation II.

In the frequency range around the crossover frequency, these dynamics are more or less integrator like. According to the theory of McRuer, human controllers do not show lead compensation for this type of system dynamics, which is confirmed by the results of the experiment. When vestibular cues are treated as a source of higher order state information in the context of a human pilot modeled as a information processing system, the results of the experiment can be understood. However, the theory of McRuer is a linear theory and does not explain the dependence of the pilot’s remnant on the motion filter settings.

Another important consideration is that by looking at the lumped pilot behavior, only overall changes in pilot control behavior can be detected. Visual compensation for the lack of motion cues e.g. can result in the same lumped response and performance, and may not be detected, while such compensation can be considered as fundamental pilot control behavior change.

With the knowledge gained from this research and a parallel research on finding the separate contribution of different information channels on the human pilot control behavior, further research in this area will be conducted in the near future.

VII. Conclusions

The present paper shows how a cybernetic approach to simulator fidelity can be applied. An experiment with both a laboratory aircraft and a high-fidelity motion-base simulator has been conducted. Care was taken that every part of the simulation (control system, aircraft model, display, motion etc.) showed the best possible similarity with the aircraft. For the motion a set of 9 motion filter settings has been chosen as experiment conditions. Two types of displays were used and four subjects participated in the experiment. Pilot control behavior and open loop behavior showed little influence of motion filter setting changes and display type. Pilot remnant, error scores and subjective experience showed to be more influenced. As a final conclusion it is stated that the applied technique has proven to provide objective and accurate results and can therefore be considered as being very suitable for this type of research.

The current paper is only based on the results of subject A, as subjects B, C and D still have to perform the simulator part of the experiment.

References


“Proposed Study of Simulation Validation/Fidelity for NASA Simulators,” Nov. 1979, Ad Hoc Advisory Subcommittee Avionics, Controls and Human Factors, List of Definitions, Committee Tasks, and Study Scope.


