Motion Cueing in Flight Simulators: A Psychophysical Approach

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Washout filters

In flight simulation, actual aircraft motions are transformed to simulator motions by applying a motion cueing algorithm or washout filter. The goal of the washout filter is to provide the required motion stimulation to the pilot while keeping the simulator motion system within its limits. Obviously, the motion space of a simulator differs from that of the actual aircraft, although the simulator's roll and pitch capabilities often match the maximum pitch and roll angles of transport aircraft in normal operation. In contrast, the motion freedom in surge, sway, and heave of motion systems falls short of the linear aircraft translations in, respectively, X, Y, and Z direction. In this respect it is advantageous that the human vestibular system is sensitive just to accelerations, not displacements. Thus the washout filter should drive the simulator motion system to represent the angular and linear acceleration cues. In general, this is done by linear transformations that apply to the whole flight envelope. However, for some maneuvers these "average" parameter settings may not be optimal, and adequate simulation may be difficult without understanding of the required motion cues. On this point, knowledge of human motion perception may help to decide on the cues that are essential to the pilot.

Psychophysical studies on tilt co-ordination

Since a few years, the vestibular research group of TNO Human Factors collaborates with AMS Consult and the National Aerospace Laboratory (NLR) in psychophysical studies on motion perception in flight simulators. The results should improve our insight in the visual-vestibular interactions in a synthetic environment, which may differ from what one may intuitively expect based on the real environment. The results also serve to validate the TNO Spatial Orientation Model in a simulator setting, which eventually should be used to objectify the choice of washout filter settings (Bos et al. 2001). The present paper summarizes three studies focusing on the simulation of linear accelerations, which is interesting with respect to motion perception since the sensors in the inner ear (the "otoliths") cannot distinguish between translational accelerations and gravity. With respect to the washout algorithm, linear accelerations are interesting because the accompanying displacements easily exceed the stroke length of the simulator's actuators. This is especially true for low-frequency accelerations, which is the reason that motion inputs to a simulator are high-pass filtered. Usually, low-frequency components of linear acceleration are simulated by tilting the simulator relative to gravity, a procedure known as "tilt co-ordination" (Schmidt & Conrad 1970).

For tilt co-ordination to be effective, the gravity's component along the simulated motion axis (i.e. $g.\sin\theta$) should be perceptible to the pilot. At the same time, however, the simulator angular rate should stay below the perceptual threshold for rotation. Here, thresholds of the peripheral senses for self-motion do not necessarily apply, since the wide-field visual display of the simulator also elicits strong sensations of self-motion, which interacts with the motion cues provided by the motion system. This was the reason to investigate the perceptual thresholds related to tilt co-ordination in more detail. We concentrated on the simulation of linear accelerations along a longitudinal axis, because in aircraft these are more common than lateral accelerations (other than cars, airplanes make co-ordinated turns where the specific force remains in the vehicle's X-Z plane).

Experiment I: Thresholds of tilt co-ordination in frequency domain

The first experiment concerned a laboratory study in which the perception of longitudinal self-motion was investigated as a function of stimulus frequency (Groen & Bles 1999). Sinusoidal self-motion through a virtual corridor was simulated by an ESIG 2000 Image Generator in a head-mounted-display (FOV 65 deg x 55 deg). The physical motion stimulus was provided by a servo-controlled tilting seat, tilting back- and forward synchronized with the visually simulated motion. The visual acceleration amplitude was held constant, while the amplitude of seat tilt was varied in fixed steps. This was done at four different stimulus frequencies (0.04, 0.08, 0.16, and 0.33Hz). Fifteen naive subjects judged their motion percept in a forced-choice-two-alternative paradigm; i.e. the perceived motion was either judged realistic or unrealistic. From the answers the ratio of realistic trials was calculated, yielding two psychometric curves: one indicating the probability that the physical motion amplitude perceptually matched the visual stimulus, and another indicating the seat tilt amplitude at which rotation was detected. Using a ratio of 0.5 as a measure for the perceptual threshold, the shaded area in Fig. 1 depicts the range of tilt co-ordination gains that produced realistic linear self-motion as function of stimulus frequency.

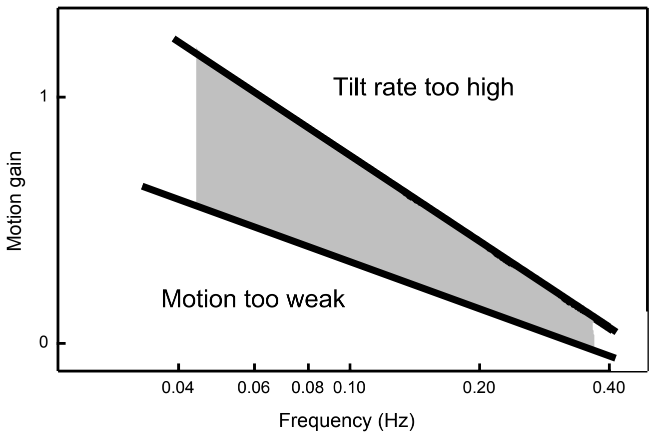


Figure 1. Left: *Tilt co-ordination in the laboratory.* ***Right:*** *Lower and upper thresholds in frequency domain.*

Realistic linear self-motion was already achieved with a gain smaller than one (lower solid line). This was most pronounced at higher frequencies. The threshold at which seat rotation was detected (upper solid line) was found to depend on the seat's angular velocity, and varied between 2-4 deg.s^{-1}. This is on the order of the rate limit of 3 deg.s^{-1} that is normally used in flight simulator washout algorithms (e.g. Nahon & Reid 1988).

Experiment II: Simulation of a takeoff run

The next psychophysical study was performed in the National Research Facility of the NLR (Groen et al. 2001) with a six-degrees-of-freedom Stewart platform. Using a similar forced-choice-two-alternative paradigm, professional airline pilots judged various combinations of simulator's surge motion and tilt co-ordination in the simulation of the longitudinal acceleration during the first 10s of a takeoff of a transport aircraft. As in the laboratory experiment, the pilots did not have a control task and participated as observer subjects. Visually, a static takeoff was simulated, involving a stepwise build-up of longitudinal aircraft acceleration up to

0.3g. In a series of trials, the gain and bandwidth of the high-pass surge filter in the washout algorithm was varied in fixed steps, and presented in combination with similarly varied gain settings of tilt co-ordination. In all trials, the rate limit was set at 3 deg.s^{-1}, and the maximum stroke length of 1.3m was used.

The best simulation of the stepwise aircraft acceleration was achieved with a gain K_x=0.2 (and bandwidth=0.73 rad.s^{-1}) for surge motion, combined with K_θ=0.6 for tilt co-ordination (Fig. 2, right plot). Thus, analogous to the first study, realistic longitudinal self-motion was achieved with motion gains smaller than one. A problem with translational simulator motion is that an increasing gain is automatically coupled with a larger stroke. In this experiment this was compensated by choosing a higher bandwidth of the high-pass surge filter. This way, a high surge gain resulted in a larger acceleration cue, but was followed by a large deceleration, which had a strong negative effect on the pilot's opinion and may explain why surge gains larger then 0.2 were rejected. Thus, temporal aspects of platform motion cannot be ignored.

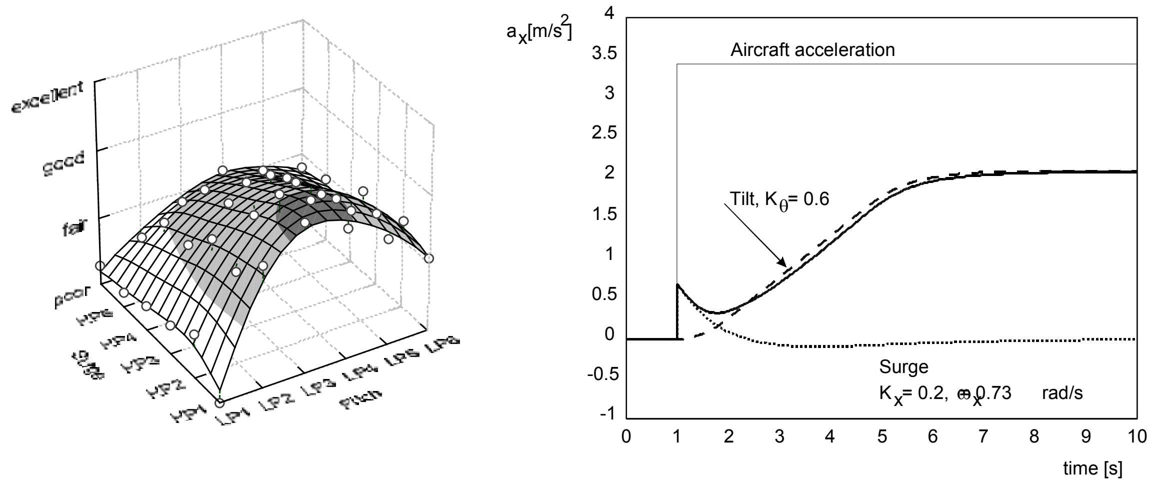


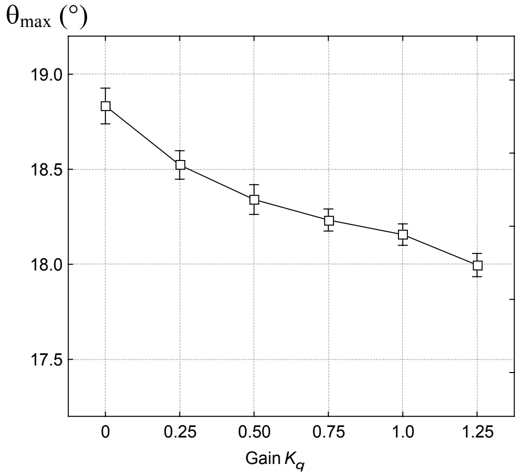
Figure 2 ***Left:*** *Psychophysical judgements as function of surge and tilt-coordination (pitch) gain.* ***Right:*** *Optimal motion profile for the simulation of stepwise acceleration during takeoff.*

Experiment III: Simulation of a complete takeoff

In a recent study in the NLR's four-degrees-of-freedom Research Flight Simulator, a complete takeoff of a passenger aircraft was simulated (Groen et al. 2003). In this maneuver three distinct phases with specific motion cues can be distinguished:

1. Takeoff run on the runway (aircraft longitudinal acceleration)
2. Rotation (aircraft longitudinal acceleration and pitch rotation)
3. First segment climb (aircraft attitude at 17 deg)

Platform motion consisted of pitch only, providing the tilt co-ordination for the simulation of longitudinal acceleration, and pitch rotation for the simulation of attitude changes in the plane of symmetry. Thus the same motion degree-of-freedom was used to simulate different perceptual entities, which may cause a priority conflict. The goal of the experiment was to determine the perceptual entity that determines the required motion cues most. For example, in the extreme situation where the washout gains for both longitudinal acceleration and rotation are set at one, the simulator would tilt over 17 deg during the rotation phase, *on top of* the 15 deg pitch tilt resulting from tilt co-ordination during the preceding takeoff run. This would lead to a maximum simulator pitch of about 30 deg, where the aircraft's pitch amounts to 17 deg.



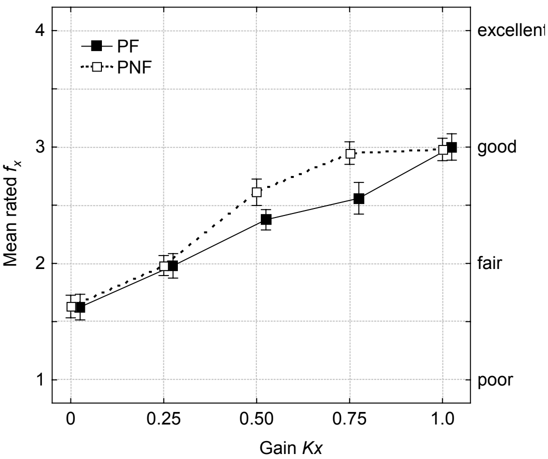


***Figure 3. Left:** Self-motion judged by PF and PNF in take off run as function of tilt co-ordination gain.* ***Right:** Mean pitch overshoot as function of rotation gain (intended attitude was 17.2 deg).*

Professional airline pilots flew all conditions twice: once as pilot-flying (PF) and controlling the aircraft from the left-hand seat, and once as pilot non-flying (PNF) on the right-hand seat. Interestingly, the perception of the longitudinal acceleration during the takeoff run depended on the task. As shown in the left diagram of Fig. 3, as PNF pilots were satisfied with a lower gain (Kx=0.75) than PF (Kx=1). Other than expected, no interaction was found between longitudinal acceleration cues and rotation cues in the rotation phase. Rather, in this phase of flight, the pilots' response was determined primarily by the rotation cue, not by the longitudinal acceleration cue. Moreover, all pilots preferred high rotation gains, close to unity. In addition to the subjective responses, the logged simulator data were analyzed, showing that pilots had difficulties in stabilizing the aircraft at the end of rotation, and generally produced an overshoot in pitch attitude. Clearly, pilot's performance improved with platform rotation (right diagram in Fig. 3). On average, this overshoot amounted to 1.5 deg without platform rotation (Kq=0), and linearly decreased to about 0.5 deg with full rotation cue (Kq=1).

Conclusions

Psychophysical methods prove to be useful in characterizing the motion cues required to optimize pilot's motion perception in a simulator. Clearly, there may be a whole range of motion cues that result in realistic perception of self-motion. The general picture is that, for linear accelerations, pilots prefer motion gains smaller than one. However, the last experiment showed that linear motion perception is task-dependent; pilots-in-the-loop required higher gains than pilots undergoing the simulation in a more passive way did. Moreover, temporal aspects of platform motion, as determined by the bandwidth of the washout filter, may affect pilots' judgements even more than the motion gain. In a synergistic motion system, these motion filter parameters are difficult to separate. The analysis of performance data showed that the pilots' ability to control the pitch attitude profited from a high gain of platform pitch motion. This is in accordance with the motion fidelity criteria defined by Sinacori (1977), and may be typical for cues that play a role in the inner control loop (Hosman 1999). In aircraft, this inner control loop primarily concerns attitude control by means of rotations. In contrast, linear accelerations are less required for the pilot's control task, and play a role on a higher level (outer control loop) to create a realistic self-motion percept. This self-motion percept will certainly affect the pilot's acceptance. In this respect, simulation of linear accelerations in a driving simulator may obey different rules, when they are necessary for the driving task.

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