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Evaluation of Perceived Motion During a Simulated Takeoff Run

Eric L. Groen*
TNO Human Factors, 3769 ZG Soesterberg, The Netherlands
Mario S. V. Valenti Clari†
National Aerospace Laboratory, 1006 BM Amsterdam, The Netherlands
and
Ruud J. A. W. Hosman‡
AMS Consult, 2625 LK Delft, The Netherlands

The range of motion stimuli that produce realistic sensations of longitudinal acceleration during a simulated takeoff run in a research simulator are presented. In all conditions, the visually simulated motion profile consisted of a step acceleration of 0.35 g. The gain of the translational (surge) and tilt-coordination channel (pitch) were systematically varied. The linear travel of the motion platform was kept constant by covarying the bandwidth with the gain of the high-pass surge filter. Rate and acceleration limit of tilt coordination were fixed at 0.052 rad/s and 0.052 rad/s^2, respectively. Using a two-alternative-forced-choice paradigm, seven experienced pilots judged their motion perception as pilots non-flying. Based on their subjective response, psychometric curves were constructed. Pilots' judgments were negatively influenced by any perceived discontinuity between the initial surge stimulus and the sustained pitch stimulus. The range of realistic motion parameters was centered around a gain of 0.2 and natural frequency of 0.73 rad/s for the surge filter and a gain of 0.6 for the low-pass pitch filter. Remarkably, unity gains were rejected as too powerful. Therefore it is concluded that, for the typical hexapod platform, the takeoff maneuver can be more effectively simulated by providing less than the full mathematical model acceleration.

Nomenclature

a_x	=	aircraft surge acceleration, m/s^2
g	=	gravitational acceleration, m/s^2
k_x, k_θ	=	motion filter gain surge, pitch channel, respectively
n	=	number of data points in mean
x	=	simulator surge travel, m
μ, σ	=	mean and slope of psychometric curve, m/s^2
ω_{HP}, ω_{LP}	=	natural frequency of high-pass, low-pass motion filter, respectively, rad/s
θ	=	simulator pitch angle, deg
ξ	=	damping coefficient motion filter

Introduction

FOR self-motion perception, humans rely on a combination of motion sensors with physiological ranges that are complementary to an extent. Visual motion sensors are tuned to velocity rather than acceleration, and the frequency response of visual motion perception approximates a first-order low-pass filter.[1] As a consequence, the visual system of a flight simulator is particularly effective in simulating motion patterns that are relatively constant.[2] Changing motion patterns, however, are best perceived by means of the vestibular system in the inner ear and other proprioceptors in the body (seat-of-the-pants).[3] These motion sensors are specifically tuned to acceleration, and have high-pass filter characteristics.[4] Therefore, a simulator motion base should essentially generate acceleration cues to support realistic motion perception. When simulated accelerations are of short duration, such as with high-frequency motion, a six-degrees-of-freedom motion platform can reproduce these cues quite accurately. Low-frequency or sustained accelerations, however, tend to drive the simulator into its mechanical limits. A good example is the longitudinal acceleration during takeoff. Normally, low-frequency longitudinal and lateral accelerations are removed from the motion input by a high-pass filter in the motion base driving software. A common trick is to cross feed these components into the rotational channel of the washout algorithm. In this way, sustained accelerations are mimicked by orienting the simulator relative to the direction of Earth's gravity.[5] This technique is known as tilt coordination.

For tilt coordination to be effective, it is important that the pilot does not perceive the angular motion. As an empirical rule, the rate of tilt should not exceed 2–3 deg/s (0.03–0.05 rad/s) (Refs. 6 and 7). This value was recently verified in a psychophysical experiment.[8] Compared with this rate limit criterion, the criteria for the amplitude of tilt, that is, the gain, are much less clear. To obtain a realistic percept of linear self-motion, the specific force simulated by the tilt stimulus should at least exceed the detection threshold. However, knowledge of detection thresholds alone is not sufficient because these thresholds are considerably influenced by the visual stimulus.[9] Furthermore, it may not be necessary to reproduce exactly the specific forces in real flight because the perceptual system may not be able to distinguish between a range of motion stimuli. Although this point has been stated in the literature before, we could not find many papers describing the quantitative boundaries of this perceptual range.[5] Flight simulation literature on motion fidelity usually focuses on handling qualities or tracking performance.[9–15] As regards literature on self-motion perception, one still depends on studies performed in the vestibular laboratory.[16–18] Recently, some psychophysical studies in The Netherlands looked into the quantitative range of visual and vestibular motion cues that produce realistic self-motion percepts in a flight simulator.[19,20] Another study on a linear track suggested that the optimal motion range does not necessarily include the veridical motion stimulus.[21] In this study, subjects observed longitudinal motion through a virtual corridor, while simultaneously being translated along the track. Not only was perceived self-motion most realistic when the seat motion was only one-third of the visually simulated motion, but also was seat

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*Researcher, TNO Equilibrium and Orientation Group, P.O. Box 23; groen@tm.tno.nl. Member AIAA.

†Research Engineer, Flight Simulation Department, P.O. Box 90502; valenti@nlr.nl.

‡Aerospace Engineer/Pilot, Wielengahof 46; r.hosman@amsconsult.demon.nl. Member AIAA.

motion rejected as too powerful when it exactly equaled the visual stimulus. The question remains how useful this result is for flight simulation practice because the visual display used in the study was rather primitive and the presented stimuli were neither in (acceleration) amplitude nor in character related to flight simulation practice. Moreover, none of the subjects used in the study were pilots.

The present study investigates the range of motion cues that result in realistic perception of longitudinal acceleration in a high-fidelity research simulator. Seven experienced civil pilots were asked to judge their self-motion percept during a simulated takeoff run. This maneuver suits our purpose for two reasons. First, during takeoff, there is little or no interference with other flight tasks. In fact, the subject pilots in our study were not actually controlling the aircraft, but experienced the simulation as the pilot nonflying. Hence, this paper explicitly deals with motion perception, not with pilot's control behavior or handling qualities. Second, a stepwise acceleration profile was used to simulate a so-called static takeoff, which is particularly interesting because it presses for concerted high-frequency linear motion and low-frequency tilt coordination.

Experimental Setup

Test Facility

The study was performed in the National Simulation Facility (NSF) of the National Aerospace Laboratory in Amsterdam. The NSF consists of a six-degrees-of-freedom Stewart platform system with fully hydrostatic actuators (Hydraudyne, The Netherlands). An F-16 cockpit (General Dynamics) is mounted on the motion system, surrounded by a 6-m-diam wide-visual dome display (Evans and Sutherland). The present study only employed surge (longitudinal translation) and pitch (longitudinal rotation). The NSF characteristics in these motion axes are listed in Table 1.

Visual Stimuli

The projected visual scene was generated by an ESIG-3000 visual system and projected inside the dome with a refresh rate of 60 Hz (Fig. 1). The projected (full color) visual scene consisted of an elliptic background with a field of view of 142-deg horizontal and 110-deg vertical, with a high-resolution inset extending 50-deg horizontal and 36-deg vertical. The lower midpart of the scene was occluded by the cockpit front. The projection system usually operates in a head-slaved mode, which allows for a field of regard of nearly 360 deg. However, because in the present study pilots were requested to look straight ahead, this option was disabled. When looking straight ahead, pilots observed the visual scene through a head-up display (HUD). The light absorption from this HUD can be neglected. The resolution of the visual scene is 21.2 arcmin per optical line pair (OLP), and the average luminance 4.24 ft · L. The high-resolution inset has a resolution of 7.1 arcmin per OLP and a luminance of 6.83 ft · L.

A visual database was used of the Edwards Air Force Base in California. Each trial started at the begin position of runway 22, which has a length of almost 4600 m and is textured with the usual markings and lines. The vicinity of the runway is clear of trees and large objects, with exception of some buildings in the background of the airport. Consequently, the visual motion stimulus primarily consisted of movement with respect to the runway markings.

Table 1 Surge and pitch system limits (amplitude) of the NSF motion system

Characteristic	Surge x	Pitch θ
Excursion	± 1.53 m	± 28.6 deg
Velocity	± 0.80 m/s	± 29.8 deg/s
Acceleration	± 8.00 m/s^2	± 200 deg/s^2

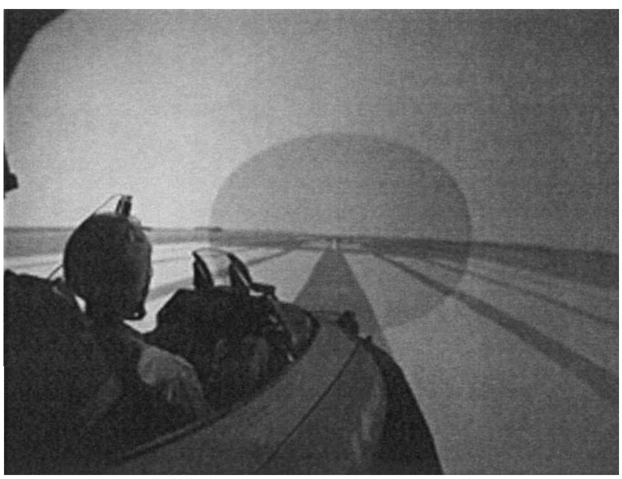

Fig. 1 Out-the-window scene used in the experiment at the begin position of the runway.

Table 2 Motion filter configurations for surge and pitch motion

Surge high-pass filter			Pitch low-pass filter		
Configuration	k_x	ω_{HP}	Configuration	k_θ	ω_{LP}
HP1	0.0	0.0	LP1	0.0	2.0
HP2	0.2	0.76	LP2	0.2	2.0
HP3	0.4	1.03	LP3	0.4	2.0
HP4	0.6	1.26	LP4	0.6	2.0
HP5	0.8	1.45	LP5	0.8	2.0
HP6	1.0	1.62	LP6	1.0	2.0

Motion Stimuli

During each condition, the first 12 s of the same takeoff run were simulated. The stepwise acceleration profile corresponded to a static takeoff where the pilot gives takeoff thrust before releasing the brakes. The magnitude of the visual acceleration was constant at 3.43 m/s^2 (0.35 g) representative for a medium-sized civil aircraft. The relevant components of the motion drive algorithm involved a second-order high-pass filter (varying ω_{HP}, see subsequent discussion) in the translational surge channel and a second-order low-pass filter ($\omega_{LP} = 2$ rad/s) in the tilt-coordination pitch channel (Fig. 2). Tilt rate and acceleration were limited to 0.052 rad/s and 0.052 rad/s^2, respectively. Between conditions, the gains of surge motion k_x and of pitch motion k_θ were varied systematically from 0 to 1, using increments of 0.2 (Table 2). This resulted in 36 different motion conditions.

As an example, Fig. 3 shows the acceleration profile produced by the configuration where both surge and pitch motion have unity gain. The motion base responded to the stepwise increase in aircraft acceleration with a transient forward acceleration, directly followed by a deceleration. Simultaneously, the simulator pitched backward up to a maximum angle of 20.8 deg, so that the gravity's component acting along the longitudinal axis equaled the visual acceleration of 3.43 m/s^2. With a rate limit of 0.052 rad/s, this maximum pitch angle was reached after about 8 s. We decided to keep the linear travel fixed at 1.30 m in all conditions (except in the $k_x = 0$ condition). (Note that although maximum surge travel of the NSF is 1.53 m, a maximum displacement of 1.30 m was chosen to remain within the constant dynamic characteristics of the actuators). This was achieved by coupling the filter's bandwidth to the gain:

$$\omega_{HP} = \sqrt{(k_x * a_x)/x_{max}} \tag{1}$$

The six configurations (HP1–HP6) of surge gain and natural frequency are given in Table 2. Independent variation of ω_{HP} was considered, but would have increased the number of experimental conditions from 36 to 216. By keeping the maximum displacement constant rather than the filters bandwidth, we made better use of the

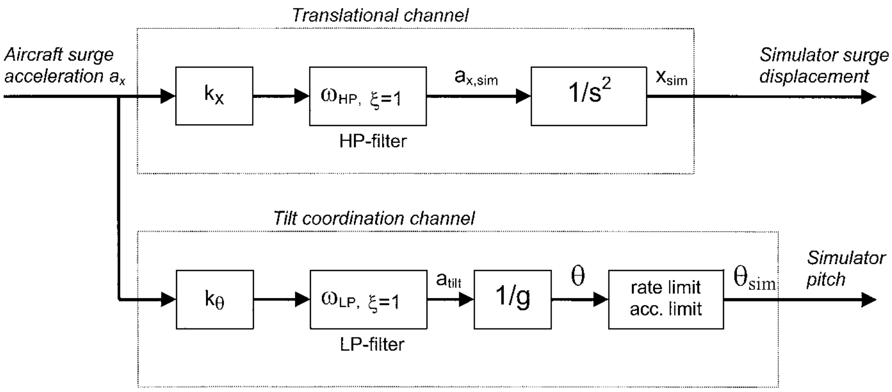

Fig. 2 Washout filter layout for the present experiment.

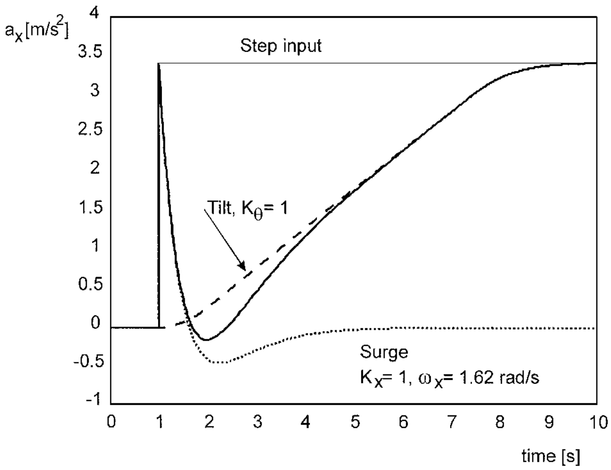

Fig. 3 Separate and combined acceleration profiles of surge and pitch motion.

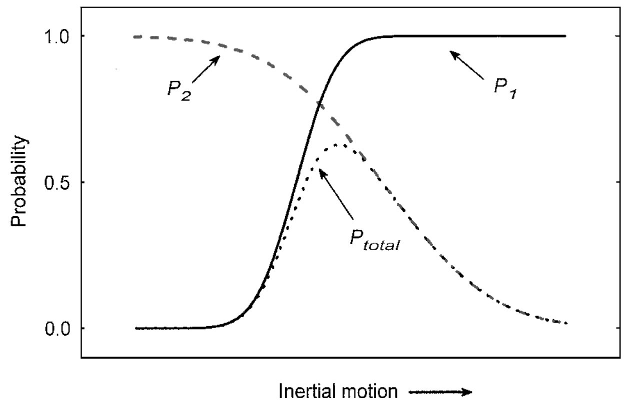

Fig. 4 Theoretical psychometric curves as a function of inertial motion gain.

simulator's linear travel and smoothed the transition between the initial surge and successive pitch motion as much as possible. To accomplish maximum tilt in combination with this large displacement, the simulator was prepositioned 1.30 m backward before each trial, so that the surge stimulus would return it to the neutral position, where it would remain for the rest of the condition.

Each takeoff run was initiated by the simulator operator after a pilot's signal of being ready. After 12 s of acceleration, a light flashed on in the cockpit, prompting the pilot to report the sensations of self-motion during the first 12 s. While the pilot gave the report, the run continued for another 18 s. During the last 10 s, the visual acceleration was gradually reduced to zero, together with the simulator tilt. In this way, feelings of discomfort arising from repositioning cues were avoided. Vibrations due to runway roughness were not simulated, but the pilot wore headphones through which engine sound, airflow hiss, and runway rumble was presented. These additional sound cues were also used to mask possible sounds of the motion system actuators.

Task

Seven experienced civil pilots participated in two sessions of 45 min, separated by 1 h. In each session, one complete set of 36 different motion conditions was presented in random order. Thus each pilot experienced all conditions twice, yielding 14 observations per condition. Pilots were to judge their percept of acceleration in relation to the visual simulation. Using a two-alternative-forced-choice (2AFC) paradigm they indicated whether this percept was realistic or not. In case of a negative judgement, it was further specified whether motion cuing was either too weak or too powerful. In their judgements, pilots were asked to differentiate between the initial and sustained acceleration phase. In another 2AFC task, pilots indicated whether platform motion felt continuous or not (in consideration of the transition between surge and tilt motion). Finally, pilots gave an overall judgement of each condition on a four-point rating scale: 0 = poor, 1 = fair, 2 = good, and 3 = excellent.

Data Analysis

The data analysis is based on the idea that the range of realistic motion stimuli is confined by a lower threshold, at which a motion cue is perceived as insufficient, and an upper threshold, at which a motion cue becomes too strong in comparison to the visual stimulus.[8,19,21] We will define a threshold as the motion stimulus that results in a realistic motion percept in at least 50% of the presentations. When interpreting this as a probability of 0.50, the lower and upper threshold can be estimated by fitting a so-called psychometric curve to the ratio $P(I)$ of one type of the pilots' response to the binary judgement (realistic or not). Analogous to logistic regression, this ratio can be described by a cumulative normal distribution, where the mean μ corresponds to the threshold $P_{0.5}$:

$$P(I) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{I} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \mathrm{d}x \qquad (2)$$

As shown in Fig. 4, the probability that motion is realistic depends on two psychometric curves, related to the lower and upper threshold, respectively. On one hand, motion cuing should be strong enough to be sufficient. This is unlikely (probability close to zero) in the absence of motion, but becomes more likely (probability approaching to one) when motion becomes stronger, as shown by the $P1$ curve in Fig. 4. On the other hand, motion should not become too strong. The probability that this is the case, that is, motion being not too strong, shows the inverse behavior, starting with a probability close to one in the absence of motion cuing and approaching to zero when motion cuing increases, as shown by the $P2$ curve in Fig. 4. According to this model, the product of $P1$ and $P2$ ($= P$ total) describes the probability that pilots accept the platform motion. When motion fidelity would depend exclusively on the motion filter gain, this model would be complete. However, because we varied the gain and bandwidth of the surge filter at the same time, motion judgements were expected to be confounded by effects of the surge filter bandwidth. We anticipated that the interdependence of both surge parameters would result in a high correlation between the probability that surge motion became too strong and the probability that platform motion became discontinuous.

Results

Psychometric Curves

Judgements of the initial and sustained acceleration were analyzed separately. The summarized responses of all seven pilots are shown in Fig. 5. Data points correspond to the ratio of trials ($n = 14$) in which motion cuing was considered realistic. For visual presentation purposes only, a two-dimensional polynomial fit was applied to the data. The labels along the horizontal axes refer to the motion filter configurations, as explained in Table 2, where the arrows denote increasing gain. Both upper Figs. 5a and 5d show the probability P total. Analogous to Fig. 4, this probability was decomposed in $P1$ (Figs. 5b and 5e) and $P2$ (Figs. 5c and 5f). Because the gain of two motion stimuli were varied separately, Fig. 5 should be interpreted as a three-dimensional version of the theoretical plots in Fig. 4. Hence, the response to the initial acceleration is plotted as function of surge motion with simulator pitch as covariable. Likewise, the response to the sustained acceleration is plotted against simulator pitch, with surge motion covarying along the secondary abscissa.

The shaded area in Fig. 5 marks the range where the probability exceeded threshold value 0.5. The corresponding motion gains were quantified by fitting psychometric curves to the data. The estimated parameters (threshold μ and slope σ) are listed in Table 3. The left part of Table 3 corresponds to judgements of initial acceleration, where for each pitch gain k_θ a $P1$ and a $P2$ curve were fitted as a function of the surge gain k_x. Conversely, the right part of Table 3 corresponds to judgements of sustained acceleration, where for each surge configuration a $P1$ and a $P2$ curves were fitted as a function of the pitch gain. The explained variance R^2 indicates the goodness of fit.

The negative μ values of the $P1$ curve for initial acceleration indicate that this curve already reached the lower threshold in the absence of any transient surge motion, $k_x = 0$. This was due to an interaction with pitch motion because the only case where $P1$ did not exceed 0.5 at $k_x = 0$ was in the absence of pitch, $k_\theta = 0$. In other words, the minimally required surge stimulus was influenced by the sensation of sustained acceleration. This explains the twisted plane in Figs. 5a and 5b. Note that in conditions where $k_x = 0$ and $k_\theta > 0$, pilots often reported that the simulation no longer felt as a static takeoff, but as a rolling takeoff instead, where takeoff thrust is gradually increased during the run.

Despite the strong effect of consecutive pitch on judgements of initial acceleration, surge motion did improve motion sensations to some extent (Fig. 5b). However, when k_x and ω_{HP} increased, the initial motion sensation soon became exaggerated, as shown by the $P2$ curve in Fig. 5c. Unlike the lower threshold, the upper threshold for surge motion was not influenced by the pitch stimulus and remained relatively constant around 0.6. With respect to the sustained pitch stimulus, the realistic motion range was unaffected by the initial surge stimulus (Figs. 5e and 5f, see also μ values in Table 3). On average, the lower and upper gain thresholds for pitch motion amounted to 0.31 and 0.68, respectively. Interestingly, for both the initial and sustained acceleration, the gain at the upper threshold was considerably less than unity. For pitch motion this gain was slightly but significantly higher than for surge motion (Student-test, $p < 0.05$). Moreover, the σ values indicate that the slope of the psychometric curves was generally steeper for pitch than for surge motion (Student-test, $p < 0.05$). Consequently, the range of realistic pitch motion extended to higher gain values than that of surge motion (compare Figs. 5c and 5f). However, judgements of surge motion did not only depend on the filter's gain, but on the natural frequency as well. The probability that surge motion became too powerful (Fig. 5c) was significantly correlated with the probability that the transition between the initial and sustained acceleration was not perceived as smooth ($R = 0.86$, $p < 0.05$). The latter probability is presented in Fig. 6. Note that the scaling of the surge axis is reversed for a better view angle (the arrow indicates increasing gain).

Overall Judgement

The detailed findings of the psychometric curves were validated with an overall judgement of each trial. The averaged pilot ratings on the four-point scale are plotted in Fig. 7. It can be seen that the overall judgement depended on both surge and pitch motion. Indeed, the subjective ratings correlated significantly with judgements of the initial ($R = 0.74$, $p < 0.05$) and sustained acceleration ($R = 0.67$, $p < 0.05$). The best overall result was obtained with HP2 ($k_x = 0.2$, $\omega_{\mathrm{HP}} = 0.73$ rad/s) and LP4 ($k_\theta = 0.6$). The corresponding acceleration profile is shown in Fig. 8.

Discussion

The systematic choice of motion stimuli provided insight in the ranges of parameter settings that produce realistic sensations of the longitudinal acceleration during a simulated takeoff run. An intriguing outcome is that pilots unanimously believed platform motion to be unrealistic when the gain of the motion filters was unity. In the case of surge motion, this finding cannot be solely attributed to the acceleration magnitude because the marked deceleration cues inherent to increasing bandwidth of the high-pass filter should be taken into account as well. The limitations of a Stewart platform make it difficult to create smooth transitions between the specific force generated by the initial surge motion and the successive tilt coordination. To attain higher surge gain within the displacement of 1.30 m, we had to adjust the surge filter bandwidth. It has been shown before that, in relation to handling qualities, the motion filter natural frequency is more critical than its gain.[14] In our study, the high correlation between perceived discontinuity and perceived magnitude of surge motion suggests that pilots tolerated variations in the natural frequency less than variations in the gain. Still, the relatively small gain (0.2) of surge motion did produce realistic sensations of self-motion, according to the maximum observed probability of about 0.8. In the absence of surge

Table 3 Estimated parameters of psychometric curves describing the perception of motion magnitude

	Surge motion							Pitch motion					
	$P1$ (lower threshold)			$P2$ (upper threshold)				$P1$ (lower threshold)			$P2$ (upper threshold)		
k_θ	μ	σ	R^2	μ	σ	R^2	k_x	μ	σ	R^2	μ	σ	R^2
0	0.27	0.25	87.2	0.56	0.32	98.2	0	0.31	0.23	96.5	0.67	0.16	99.4
0.2	−0.11	0.83	85.4	0.61	0.29	97.4	0.2	0.30	0.13	99.0	0.69	0.31	96.4
0.4	−0.77	1.34	92.8	0.64	0.39	95.3	0.4	0.32	0.21	96.7	0.67	0.12	99.9
0.6	−0.12	0.22	91.5	0.60	0.31	98.6	0.6	0.27	0.16	99.7	0.68	0.20	97.3
0.8	−0.22	0.28	99.5	0.54	0.32	91.7	0.8	0.30	0.13	99.9	0.72	0.19	99.6
1.0	−0.06	0.06	40.0	0.51	0.27	96.8	1.0	0.34	0.22	95.7	0.68	0.22	97.5

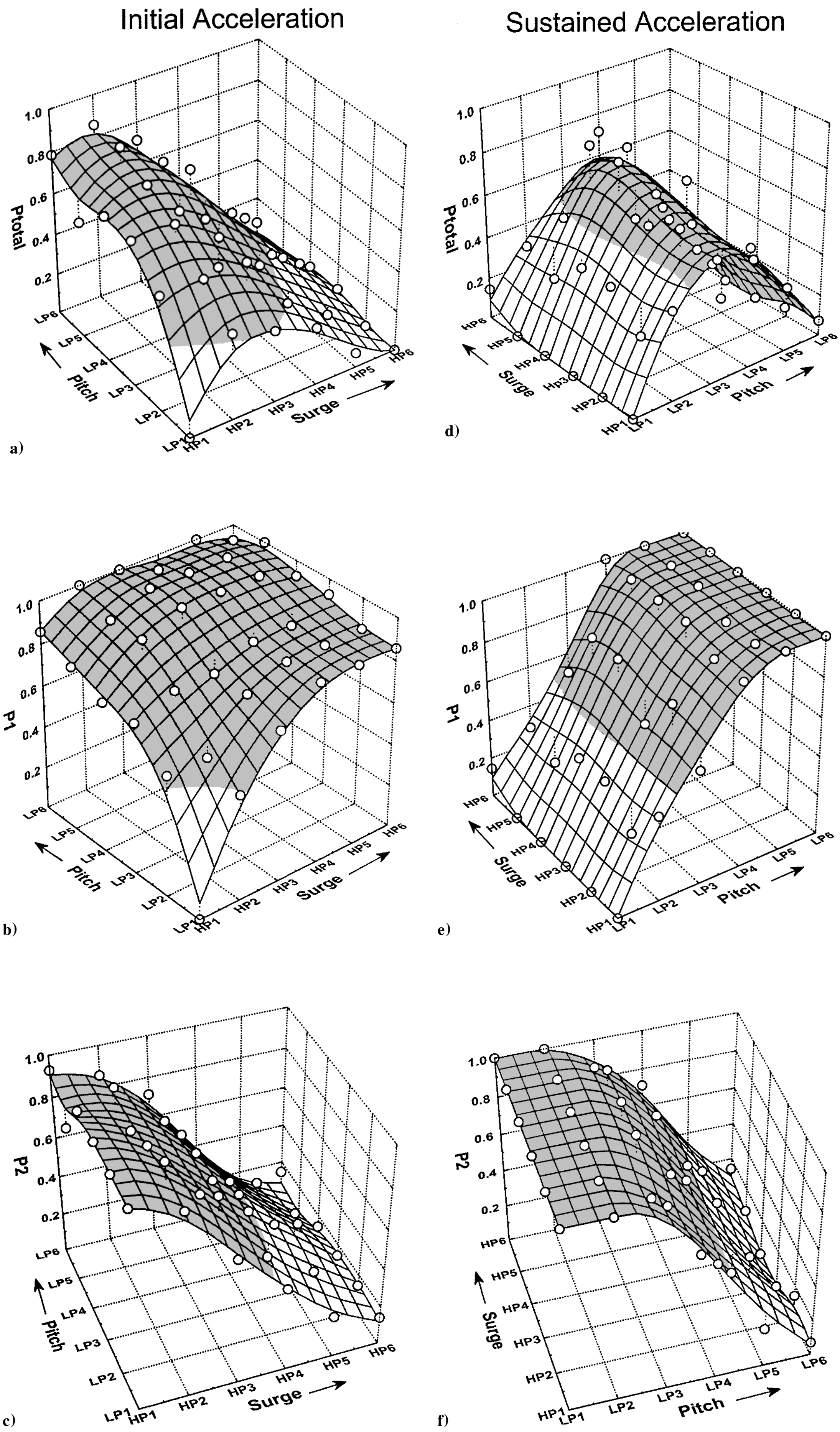

Fig. 5 Judgements of perceived magnitude of P total, P_1 and P_2 of initial surge motion (a, b, c); P total, P_1 and P_2 of sustained pitch motion (d, e, f).

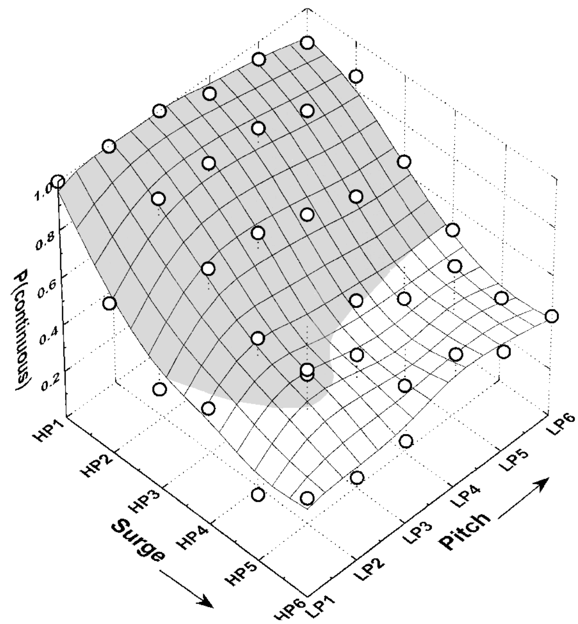

Fig. 6 Probability of perceived continuity between the initial surge and sustained pitch motion.

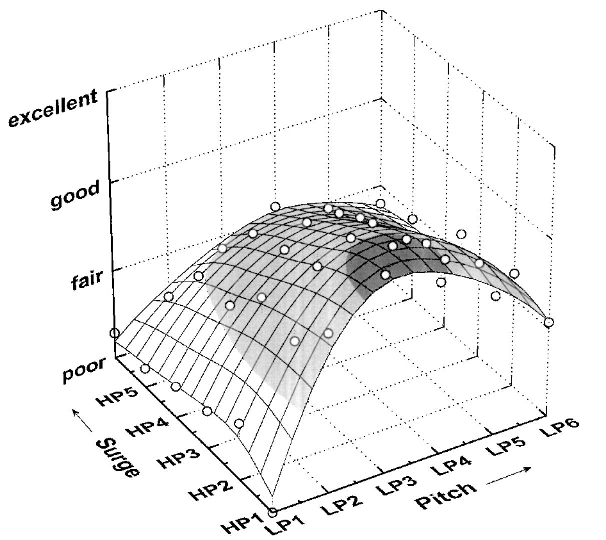

Fig. 7 Mean overall judgement (n = 7) of each condition, scored on a four-point scale (0–3).

motion, some pilots reported that platform motion corresponded to the gradual increase in acceleration experienced during a rolling takeoff rather than to the acceleration step during a static takeoff. Because the visual acceleration profile was constant for all conditions, this demonstrates that perceived self-motion during the initial phase was dictated by platform motion, not by visual motion. This concurs with the knowledge that the human visual system is tuned to velocity and the vestibular system to acceleration. Thus, at the onset of a simulated takeoff, physical motion is detected before simulated velocity builds up sufficiently to be noticeable by the visual system.

The results of tilt coordination can be directly related to the pitch motion filter gain. The finding that unity gain was considered too powerful is in agreement with laboratory studies showing that physical motion is generally overestimated with respect to simulated visual motion.[21,22] Those studies were performed using a visual display with narrow field of view. The present study demonstrates that also in an advanced flight simulator with a wide visual display, the maximum permissible gain for the simulation of specific

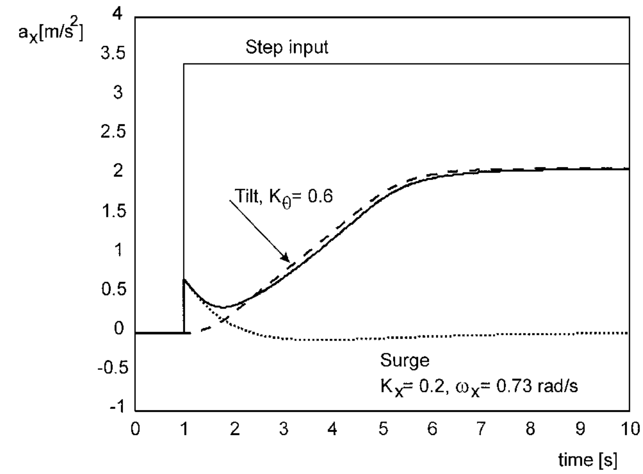

Fig. 8 Acceleration profile of the optimal configuration of the surge filter (· · · ·) and pitch filter (– – –).

force is less than one. In the real world, of course, motion gains are always one, and the question arises why visual–vestibular interactions would be different in simulators. Although there is no conclusive answer to this, there is an interesting theory stating that actual self-motion results in an increased threshold for visual motion perception.[23] This would explain why the velocity of a moving visual scene is perceived to slow down during linear acceleration.[24] Therefore, it seems better to regard the visual–vestibular discrepancy described in the present paper as an underestimation of visual cues, rather than an overestimation of vestibular cues. The idea that visual factors play an important role is supported by the observation that car drivers always tend to increase their speed under indirect viewing conditions, for example, with a camera system.[25] Further research should provide insight in the background of these effects.

The implication of the optimal motion range falling off before unity gain seems to be that, in the case of specific force, platform motion should be downscaled to achieve realistic self-motion perception. Although this conclusion is supported by common practice of motion tuning (e.g., see Ref. 7), the results should be verified for other simulation conditions before making such a generalization. The main restriction of the present study is that the simulation was limited to the first 12 s of a takeoff run and that subject pilots were passive observers rather than in control of the aircraft. Moreover, only two degrees of freedom of the motion base were used. Undoubtedly, the interaction with flight tasks during normal flight simulation will complicate motion tuning. It is known that, for effective training of piloting skills, simulator motion should respond to the pilot's control behavior as in the actual aircraft. For a good sensation of flight, however, motion cuing is less critical, as long as the motion stimuli stay within the realistic motion range.[26,27]

The model presented in Fig. 4 illustrates that the (total) probability for a realistic simulation arises from the product of the probabilities that motion cuing is sufficient ($P1$) and, at the same time, not too powerful ($P2$). Hence, P total only approaches one when $P1$ and $P2$ fully overlap. As Fig. 5 makes clear, this was not the case. The calculated probability reached a maximum of about 0.6–0.8, comparable to findings from previous studies that used the same psychophysical method in a less advanced simulator.[8,21] It should be taken into account that the psychometric curves were fit to the pooled responses of all pilots and that a curve determined for each individual pilot may have been more discriminative, that is, a steeper slope σ. Unfortunately, time was not available to collect the larger amount of data needed for the construction of individual thresholds. Nevertheless, the overall judgements showed that the subjective rating excellent was only given occasionally, indicating that the individual probabilities never reached the maximum of one.

Conclusions

The present study showed the following results.

1) For the typical hexapod platform, the takeoff maneuver can be more effectively simulated by providing less than the full mathematical model acceleration.

2) For self-motion perception, downscaling of the simulated specific force seems desired, although other simulation conditions and piloting tasks make other demands to motion cuing.

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