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PRELIMINARY INVESTIGATION OF THE MOTION FIDELITY CRITERION FOR A PITCH-LONGITUDINAL TRANSLATIONAL TASK

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Abstract

While the ground-based flight simulation community is increasingly interested in determining the required motion fidelity to meet mission requirements, little has been done to determine the motion fidelity requirements for the pitch and longitudinal degrees-of-freedom. Typically, the pitch and longitudinal motion fidelity is determined by following the same criteria as the roll and lateral degrees-of-freedom. However, pitch visual cues are typically different from roll visual cues. Since visual and motion cues are known to interact, investigation of the pitch and longitudinal motion fidelity criteria is warranted

This investigation used a helicopter model with satisfactory handling qualities to translate longitudinally between two points 20 feet apart. A simulation cueing baseline was developed such that the motion and visual cues were one to one. Motion cueing reductions were subsequently evaluated from this baseline case. Two angular motion and eleven translational motion configurations were flown by four test pilots. Results indicate that as longitudinal phase distortion is increased, motion fidelity ratings decreases and also as longitudinal motion gain decreases, the motion fidelity ratings also decrease. Both results are consistent with the roll-lateral motion requirements.

Nomenclature

g	gravitational acceleration, $\mathrm{ft/sec^2}$
$M_{\delta_{lon}}$	pitch control power, $\mathrm{rad/sec^2/in}$
M_q	pitch acceleration due to pitch rate, $\mathrm{1/sec}$
q	pitch angular rate, $\mathrm{rad/sec}$
$\dot{q}$	pitch angular acceleration, $\mathrm{rad/sec^2}$
r_z	vertical displacement between pilot's abdomen and simulator rotational center, positive down, ft
u	groundspeed along x-body axis, $\mathrm{ft/sec}$
$\dot{u}$	vehicle acceleration along x-body axis, $\mathrm{ft/sec^2}$
δ_{lon}	pilot longitudinal stick input, in.
θ	pitch attitude, rad
$\dot{\theta}$	pitch rate, $\mathrm{rad/sec}$

Introduction

Studies have been conducted to investigate the cueing fidelity requirements for roll-lateral interactions but little has been done for the pitch-longitudinal interactions[1-3]. From a psychophysics point of view, there is little perceptual difference as provided by a human's angular sensors[4]. In Zacharias's[5] assessment of the pilot's motion sensor models, the mathematical treatment of the roll and pitch angular rate sensing characteristics are also similar. However, in most motion-based simulators, the pitch and longitudinal visual cues are typically poor as compared to roll-lateral visual cues. Vertical field-of-view (FOV) is usually more constrained so that the horizon can disappear taking away the pilot's pitch attitude awareness. Also little ground is seen in front or below the pilot providing little if any longitudinal position awareness. Depth cues are also typically poor, thus damaging the pilot's longitudinal awareness. Furthermore, from a tactile consideration, the pilot's contacts with the seat and restraint system in the pitch-longitudinal axes are different from the roll-lateral axes. Taking these differences into account, the cueing fidelity requirements for pitch-longitudinal interactions need to be examined in their own right. This investigation was undertaken to provide some preliminary insights into the motion requirements for combined pitch-longitudinal motion.

In flight simulation, pitch and longitudinal motion

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need to be treated together. For a coordinated maneuver, longitudinal platform motion provides an acceleration to counteract the "leans" that would result from only pitching the cockpit. Typically, the longitudinal motion used for this purpose does not eliminate the leans completely but is conventionally attenuated through a washout filter to maintain the simulator within its physical travel limit. This compromise introduces an erroneous specific force[6] depending on the magnitude of the pitch attitude. This investigation examined the effects of this erroneous cue and compared the results to the roll-lateral requirements.

Experiment Description

Aircraft Model, Force Characteristics, and The Task

A two DOF helicopter model with a pitch rate command and a fully coordinated pitch-longitudinal response about hover is given by equation 1,

$$\begin{bmatrix} \dot{q} \\ \dot{u} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} M_q & 0 & 0 \\ 0 & 0 & -g \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ u \\ \theta \end{bmatrix} + \begin{bmatrix} M_{\delta_{lon}} \\ 0 \\ 0 \end{bmatrix} \delta_{lon} \qquad (1)$$

The pitch acceleration due to pitch rate (or the pitch damping stability derivative), M_q, was set at –4.0 1/sec and the pitch control power, $M_{\delta lon}$, was 0.67 rad/sec^2/in. The rotational center was set at the pilot's abdomen. The pitch rate response to the stick was developed to have the satisfactory handling qualities according to the Reference 7 specification. The longitudinal stick force feel characteristics was set at 2 lb/in with a 0.5 lb breakout force.

The Task

The task was a 20 ft dash-and-stop task performed at a constant altitude of 23 ft as shown in Figure 1 along the center of a runway. The piloted task started with a 20 ft translation towards the desired hover position situated in front of the helicopter's initial hover position, followed by 20 seconds of stationkeeping. The stationkeeping point was denoted by a series of four walls located 100 ft to the right and 100 ft in front and positioned at an angle of 45 degrees. At the desired stationkeeping point, the pilot should see the walls "edge on" out the right window. At the proper position, a building in the background appeared in the middle of the two inner walls. The walls were spaced such that the distance between the two inner walls translated to a distance of ±5 ft with respect to the desired stationkeeping point in the axis of travel. Likewise, the distance between the two outer walls translated to a distance of ± 10 ft with respect to the desired stationkeeping point in the axis of travel. A bob-up target was placed in the center of the runway and various red cones were placed on the runway visible through the right chin window for additional visual cueing.

Pilots were instructed to complete the dash-and-stop task in one smooth maneuver within the performance standards shown in Table 1. A sum-of-sines, Table 2, was added to the pilot's stick input to simulate wind gusts.

Procedure

Four experienced test pilots participated in the test. Each pilot practiced with randomly selected motion configurations at the beginning of each session. During the data collection, each pilot evaluated the motion configurations in a random order. The pilots were asked to fly each motion configuration three times and to evaluate the third repetition. Pilots were asked to give handling qualities ratings (HQRs)[8] and motion fidelity scale (MFS) ratings as shown in Table 3. A questionnaire was also given to elicit comments from the pilots regarding control strategy and motion fidelity.

Test Facilities

The NASA Ames Vertical Motion Simulator (VMS) was used for this investigation, which is shown in Figure 2. The cockpit was oriented such that the longitudinal axis of the simulator cab traveled along the beam which has a usable travel of 40 ft. The large longitudinal travel of the VMS allowed for the 20 ft dash-and-stop task without any motion cue attenuation. The motion system responses were collected using white noise with a Gaussian distribution and checked with frequency response technique developed for system identification called CIFER®[9]. For this investigation, each motion axis had an equivalent time delay of 60 msec. The visual FOV of the helicopter cab is shown in Figure 4.

The visual system was an Evans and Sutherland ESIG 4530 image generator. The out-the-window scene was presented on four monitors with a collimation/beam-splitter system. The visual system time delay was measured at 60 msec, which matches the equivalent time delay in the pitch and longitudinal motion axes.

Test Configurations

Two second-order washout filters, Figure 3, were developed for this investigation. A pitch washout filter generated the pitch motion commands, and a coordinated longitudinal washout filter provided the longitudinal motion to counteract the leans due to pitch. Two pitch washout filter configurations and eleven longitudinal washout filter configurations, shown in Tables 3 and 4 respectively and presented in Figure 5, were selected to investigate the interaction between pitch motion and longitudinal motion. Each configuration consisted of the gain and filter frequency for the respective washout filter. The configurations were selected to represent low, medium, and high motion fidelity as defined in Reference 10.

Results

Four pilots took part in this test. Their average MFS ratings and the average HQR are shown in Figures 6 and 7 respectively. All pilots rated the fixed-base case as low fidelity. In general, the amount of longitudinal platform motion increases as both the longitudinal filter's predicted fidelity and the pitch filter's predicted fidelity increases, i.e., increasing motion gain and decreasing phase distortion. However, as the amount of required longitudinal motion increases any parasitic differences in the dynamics between the pitch and longitudinal motion become exacerbated and potentially objectionable. Pilots commented on the sharpness of the motion cues due to the high gains. This is evident in the full-motion case (A1, T1) in that the pilots felt the motion cues to be objectionable and rated it as low fidelity. As pitch motion is attenuated (A3, T1), the longitudinal platform motion decreased and artifacts such as above were reduced significantly which resulted in an improved motion fidelity rating.

In both the full and the attenuated pitch motion cases, the motion cues became objectionable when the longitudinal phase distortion was 80 degrees at 1 rad/sec (ω_x = 0.9). Figure 8 shows the average MFS as a function of ω_x. As expected, the MFS decreases as longitudinal phase distortion is increased regardless of pitch motion. This is consistent with the roll-lateral motion requirements.

In both the full and the attenuated pitch motion cases, it is clear that pilots felt the motion cues to be objectionable when little coordinated motion was provided, i.e., cases where the longitudinal motion gain was at or below 0.2. This is consistent with Schroeder[2] and Chung[3] in their roll-lateral motion fidelity requirement investigations. Figure 9 shows the average MFS as a function of G_x. For the attenuated pitch motion case (A3), MFS ratings generally decrease as longitudinal motion gain decreases. Again this is consistent with roll-lateral motion requirements. For the full pitch motion case (A1), there is no clear trend due to the low rating for the (A1, T3) case where it is expected to be rated medium fidelity. Undesired motion artifacts might have played a role in receiving the low fidelity rating while the longitudinal motion gain is still considerably high at 0.8.

One observation is made from Figure 6 when comparing the average MFS between the full pitch motion (A1) and the attenuated pitch motion (A3). For the cases that represent the medium and high fidelity region, i.e., cases T2, T3, T5, T6, the average MFS ratings for the attenuated pitch motion case are noticeably improved when compared with the full pitch motion case. This improvement may be contributed to less pitch motion resulting in less "leans". Therefore any objectionable situations would be expected to occur less frequently, and consequently result in the noticeable improvement in MFS ratings.

For both the full and attenuated pitch motion cases, the averaged HQR consistently followed the averaged motion fidelity ratings, i.e., HQR improves when MFS improves.

Concluding Remarks

1) Large phase distortion in longitudinal motion due to the pitch motion is detrimental to the motion fidelity. Pilots found it to be objectionable. This is consistent with the roll-lateral motion requirements.

2) Ratings generally improved as the longitudinal motion gain increased until the undesired motion artifacts became noticeable.

3) Additional testing is recommended to further investigate the pitch-longitudinal motion cueing fidelity requirements.

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Table 1. Task performance standards

	Desired	Adequate
Longitudinal translation completion time	7 sec	11 sec
Stationkeeping position tolerance	+/- 5 ft	+/- 10 ft

Table 2. External disturbance

Frequency (rad/sec)	0.28	0.49	0.80	1.50	2.67	4.63	8.50
Amplitude (in)	0.002	0.006	0.014	0.032	0.054	0.068	0.06

Table 3. Motion fidelity scale

	Description	Score
High Fidelity	Motion sensations are not noticeably different from those of visual flight	3
Medium Fidelity	Motion sensations are noticeably different from those of visual flight, but not objectionable	2
Low Fidelity	Motion sensations are noticeably different from those of visual flight and objectionable	1

Table 4. Angular motion washout gains and filter frequencies configurations

Pitch Motion Configurations	Motion Gain G_q	Washout Filter Frequency, ω_q (rad/sec)	@ 1 rad/sec	
			Gain	Phase distortion (degree)
A1	1.0	0.0001	1	0
A3	0.6	0.5	0.58	43

Table 5. Translational washout gains and filter frequencies configurations

Longitudinal Motion Configurations	Motion Gain G_x	Washout Filter Frequency, ω_x (rad/sec)	@ 1 rad/sec	
			Gain	Phase distortion (degree)
T1	1.0	0.0001	1.0	0
T2	0.8	0.25	0.8	20
T3	0.8	0.5	0.78	43
T4	0.8	0.9	0.63	80
T5	0.5	0.25	0.5	20
T6	0.5	0.5	0.49	43
T7	0.5	0.9	0.4	80
T8	0.2	0.25	0.2	20
T9	0.2	0.5	0.2	43
T10	0.2	0.9	0.16	80
T11 (fixed base)	0.0	0.0	0.0	0

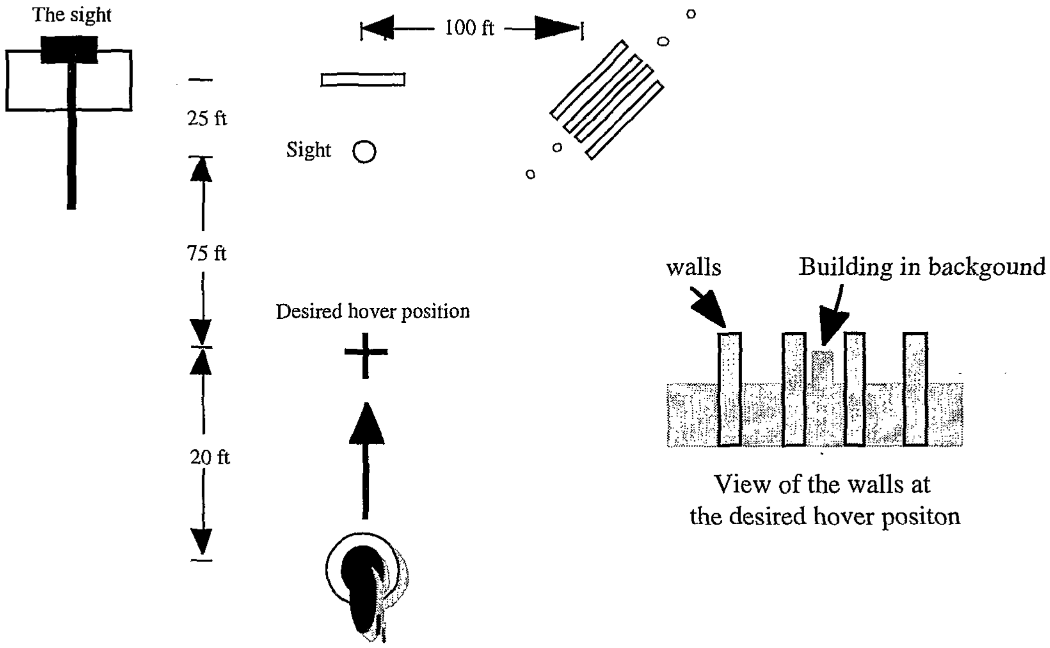
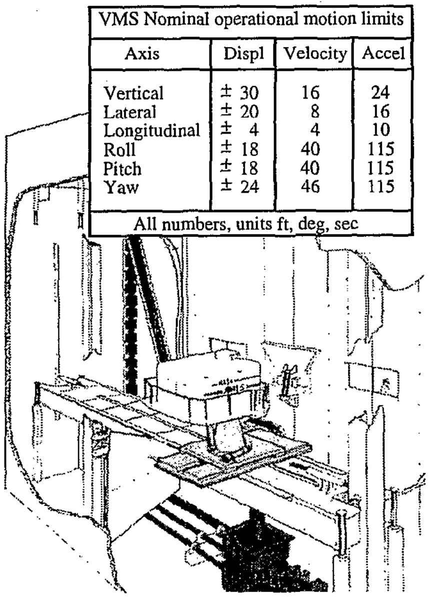


Figure 1. The longitudinal dash-and-stop task



VMS Nominal operational motion limits			
Axis	Displ	Velocity	Accel
Vertical	± 30	16	24
Lateral	± 20	8	16
Longitudinal	± 4	4	10
Roll	± 18	40	115
Pitch	± 18	40	115
Yaw	± 24	46	115
All numbers, units ft, deg, sec			

Figure 2. Vertical Motion Simulator (VMS)

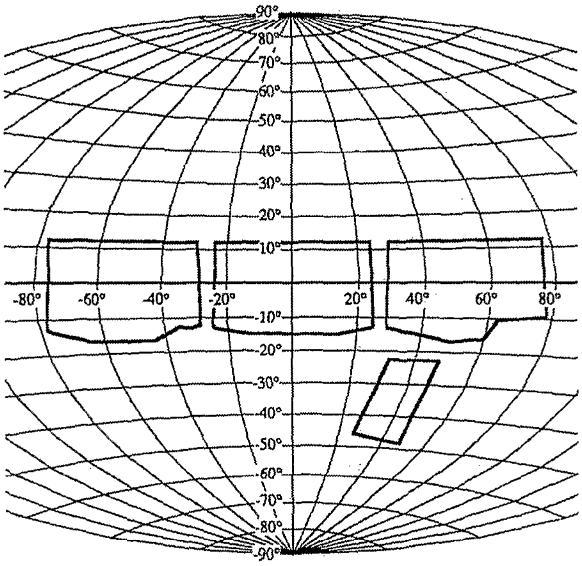


Figure 3. VMS cockpit field-of-view

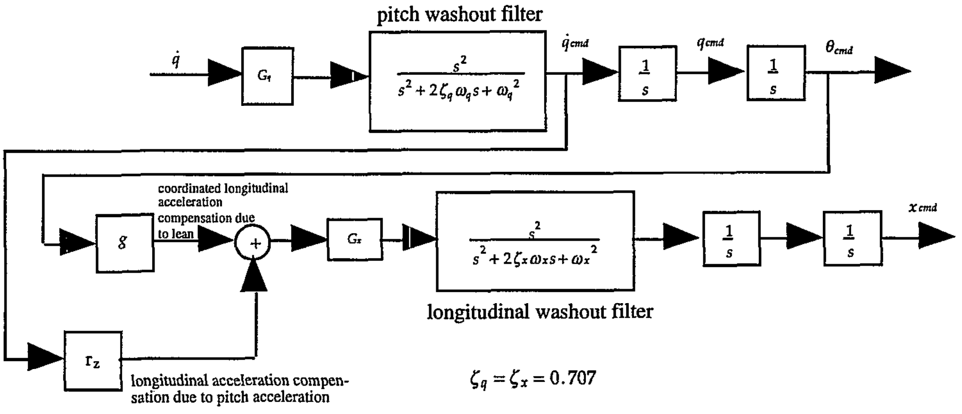


Figure 4. A representative motion drive command block diagram for pitch and longitudinal drives.

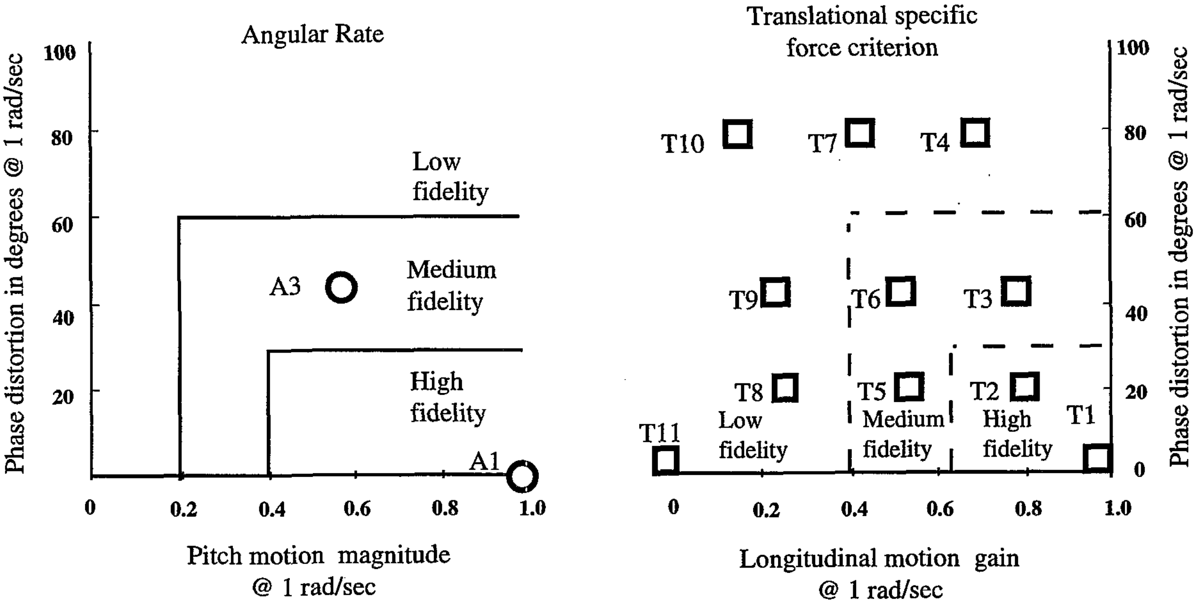
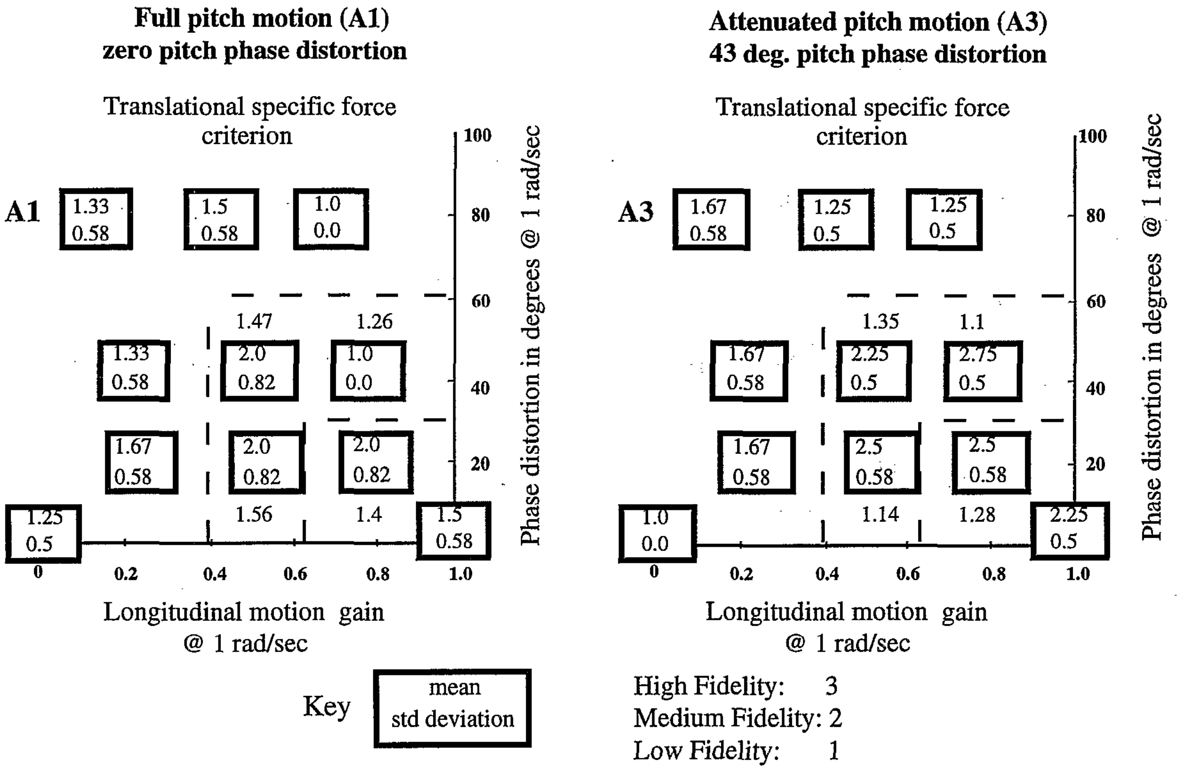


Figure 5. Test motion washout filter configurations for the pitch and coordinated longitudinal motion

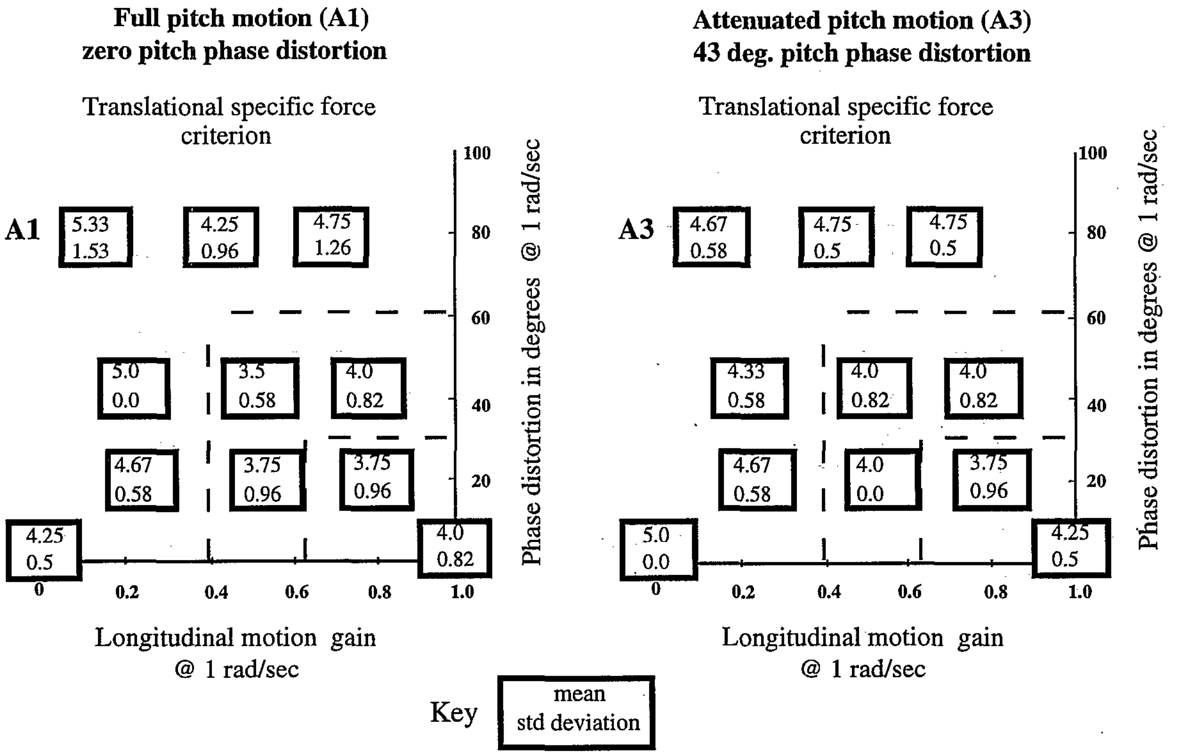


Full pitch motion (A1)
zero pitch phase distortion

Attenuated pitch motion (A3)
43 deg. pitch phase distortion

High Fidelity: 3
Medium Fidelity: 2
Low Fidelity: 1

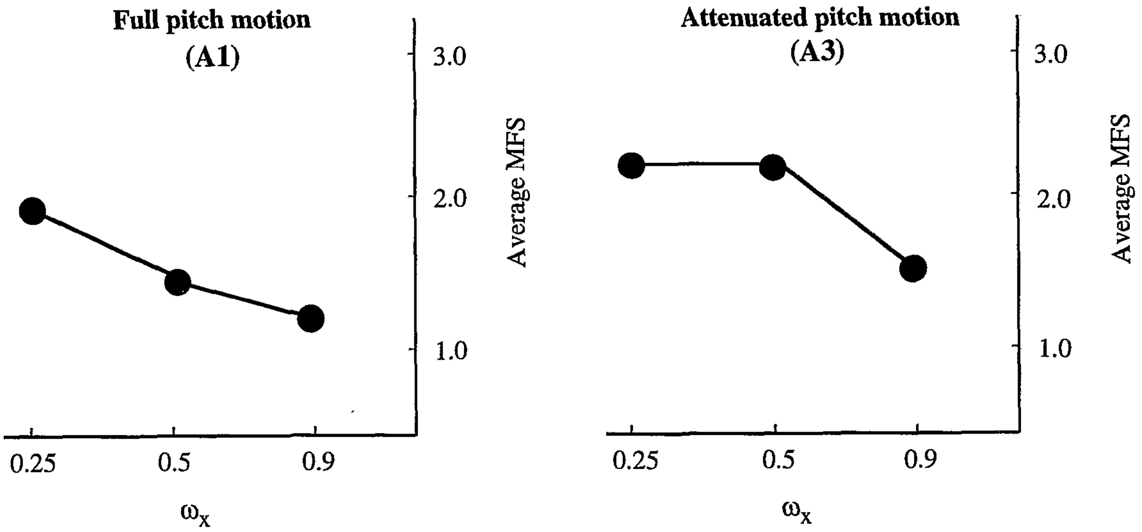
Figure 6. The average MFS



Full pitch motion (A1)
zero pitch phase distortion

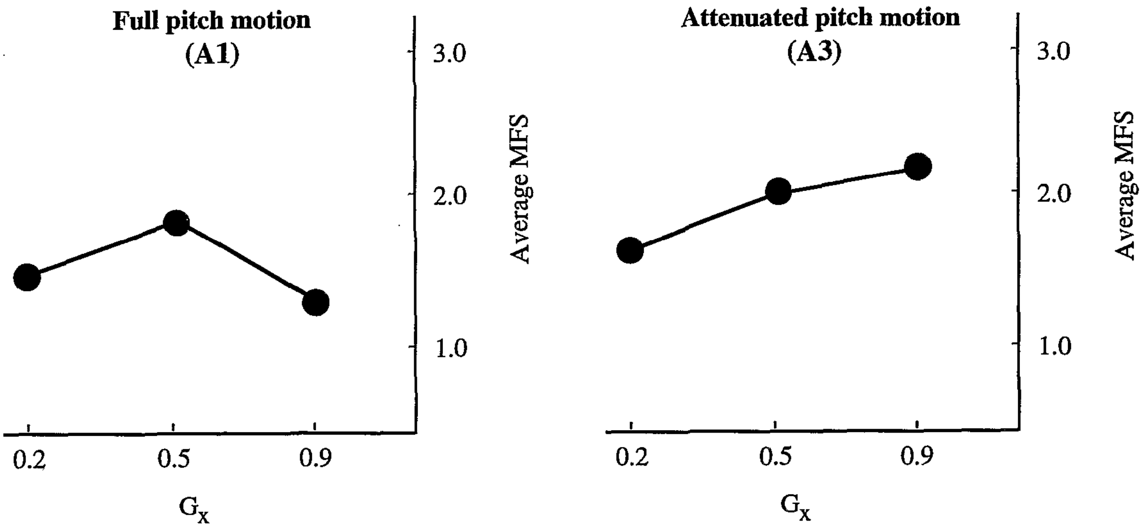
Attenuated pitch motion (A3)
43 deg. pitch phase distortion

Figure 7. The average HQR


Full pitch motion (A1)

Attenuated pitch motion (A3)

Figure 8. The average MFS vs. ω_X


Full pitch motion (A1)

Attenuated pitch motion (A3)

Figure 9. The average MFS vs. G_X