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A REVIEW OF APPROACHES TO DETERMINE THE EFFECTIVENESS OF GROUND-BASED FLIGHT SIMULATION

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Abstract

A review of the current understanding of how key simulation cueing elements affect ground-based flight simulation has been conducted. The objectives are to develop a broad assessment of current approaches in determining simulator effectiveness and to identify future research directions. The review covers the visual cues and human/machine related topics. For visual cueing related issues, the review focuses on visual transport delay, resolution, scene content, and field-of-view. For human/machine interaction issues, the review focuses on human psychophysical characteristics, pilot models, and motion cueing criteria. Results and suggested future work from past investigations are summarized. Additional recommendations are presented.

Introduction

Ground-based flight simulation has a variety of aeronautics applications such as training, research and development, and accident investigations. Safety and cost savings relative to flight test are the most appealing virtues of using ground-based flight simulation. With the advanced technology in digital computing and image generation, the realism and fidelity of today's flight simulators have improved significantly from the old blue box of the thirties.

However, the effectiveness of ground-based flight simulation is difficult to determine. Simulation may be physically similar to flight, e.g., same cockpit layout, control force feel, and tasks. But the fundamental human/machine interaction, specifically in visual-motion interactions, is often very different. In the extreme, the specific force cues are missing from fixed-base flight simulators. Motion-based flight simulators do provide onset specific force cues but can have visual-motion cueing conflicts due to limited travel. Pilots, therefore, must adjust their strategy in using the simulation cues to perform the given tasks. Since humans are adaptive and optimizing in nature, unless these characteristics can be quantified, the effectiveness of flight simulation, e.g., transfer of training and transfer of handling qualities results, with respect to simulator missions cannot be predicted.

The presumption is that, if one can develop a comprehensive understanding of how pilots perceive aircraft states and task parameters from available simulation cues, and how they process and react to that information in given tasks, an analytical methodology can be developed to characterize that behavior process. It may then be used to interpolate and extrapolate results learned from ground-based flight simulations. Thus the effectiveness issue can be determined.

This paper reviews several critical elements associated with ground-based flight simulation's visual and motion cues that are most influential to the human/machine interface. The objectives are to summarize significant results from past studies and to identify future research directions for determining ground-based flight simulation effectiveness.

Visual Cues

Visual cues are the single most important simulation cues in all ground-based flight simulators for determining the orientation and position of the simulated aircraft. From the out-the-window (OTW) scene, instruments, and perhaps a Head-Up Display (HUD) and/or Head-Down Display (HDD), pilots observe the simulated aircraft states to develop appropriate actions to perform the tasks.

Transport Delay

Transport delay has been a critical factor in visual cueing perception. The delay reflects how fast the image generator or displays can present the simulated aircraft's response due to pilot's control inputs. Time delay has been found to have significant effects on pilot workload in several studies.[1,2] FAA Advisory Circulars have suggested no more than 150 msec delay for transport flight simulators,[3] and 100 msec delay for helicopter flight simulators[4] where delay is defined as the time interval taken from the control input to change in the OTW scene. The current technology has improved the transport delay contributed by the image generator alone to under 50 msec (e.g., about 50 msec for E&S ESIG 4530[5] and about 25 msec for SGI Onyx[6]). Time delay due to integration steps in the real-time digital computer, i.e., from accelerations to rates, and rates to displacement, has also improved significantly due to using predictive algorithms[7] and faster real-time computer processors. The technology allows modern simulators to easily meet those recommended criteria.

Visual Resolution

The ability to distinguish and recognize an object or a target from OTW is primarily dependent on the contrast and resolution of the displayed objects and targets. Level of

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contrast depends on the display system technology, e.g., collimation through lens, and projection through light valves. The limiting factor for resolution is the number of polygons that image generators can generate, and the performance and efficiency of all visual system components in the pipeline. The resolution requirement also depends on the distance (range) and flight tasks. Brown[8] showed a process to determine the required resolution for a TA-4J in an aerial combat maneuver. Larsen[9] used Johnson's Criteria,[10] which are dependent on task level, i.e., detection, shape orientation, shape recognition, and detail recognition, to develop the required resolution in line pairs for an air combat training.

Polygon count, though convenient, is not a good measurement of the resolution nor provides a good comparison between systems since each manufacturer has its own polygon definition. A recommended measurement common in industry is to use the Modulation Transfer Function (MTF)[11] which combines the contrast and resolution as a single parameter to determine the entire display pipeline performance,[12] i.e., from image generator to display. Therefore, a logical recommendation to quantify the display system resolution performance is to develop a standard test pattern and measuring procedure, and then use MTF as an objective measurement.

Scene Content

Out-the-window scene content plays an important role in pilot's perception in estimating position, attitude, and their rate of change. Lintern,[13] in a simulation bombing training study with 42 student pilots, compared results in dusk condition with limited scene features and from day light with extensive scene features. He found that scene content produced significant effects in pilots' bombing error performance. Lintern has also found that training effectiveness improves with increases in visual scene detail.[13-15] In a separate bombing study with 32 pilot subjects, Lintern[16] found that scene content, i.e., landscape vs. grid pattern, has a significant effect on pilots pitch control performance and transfer of training, all in favor of the landscape case.

The shape of objects and application of texture also play significant roles. Kleiss,[17] in his discussions of visual scene properties for low-altitude flight, found that change of global optic flow rate and change of optical edge rate are useful for perceiving change in speed. In a visual environment at a speed of 600 knots and 150 ft above ground with 21 A-10 pilots, DeMaio[18] found objects are effective for estimating altitude. He suggests that a density of about 12 to 15 objects per square mile is necessary and sufficient for maintaining altitude. The same study also finds equivalent cueing effectiveness can be provided by a two-dimensional texture pattern. Kellogg[19] in his investigation with 10 experienced C-130 pilots found that texture had a significant and positive effect in centerline positioning and altitude control in an assault landing task. That conclusion is consistent with findings from DeMaio[18] and Kraft.[20]

Additional studies have been recommended by DeMaio to develop better understanding of what types of texture patterns contribute to effective altitude cueing. Kleiss indicates variations in terrain shape and object size or spacing are important parameters for the simulator designer, and suggests further investigation to determine level of terrain resolution requirements.

Visual Field-Of-View (FOV)

The effectiveness of FOV is a very practical issue for ground-based flight simulators. For realism purposes, one would naturally keep the visual cueing environment as close to the simulated aircraft as possible, i.e., wide FOV for most of simulated aircraft. From the visual self-motion perspective, peripheral vision is also important.[21] However, wide FOV can be an expensive proposition. It typically demands a high cost in image generation systems and monitors even if added weight and space are not issues.

In a single roll degree-of-freedom (DOF), Moriarty[22] has shown peripheral vision has significant effects in a compensatory tracking task when subjects using a sidestick to control higher order control element dynamics ($\sim k/s^3$). With peripheral vision, results showed that pilots were able to provide more phase lead in the frequency range below the crossover frequency.[23] In the same study, however, he did not find peripheral vision had a significant effect when a lower order control element ($\sim k/s^2$) was used. This suggests that wide FOV may have significant benefit when the simulated aircraft dynamic characteristics become higher in order.

A review of the effectiveness of wide FOV in multiple degrees-of-freedom flight simulations has produced mixed results. Several studies[13,19,24-27] have been identified which cover a range of tasks and types of aircraft. These investigations all have used a large number of test subjects and used statistical analysis to determine the significance of their results, as summarized in Table 1. As shown, results from the same flight simulator differ as tasks and test subjects varied which suggest more systematic investigation in determining the effectiveness of FOV is required.

Man/Machine Interaction

Effectiveness of motion vs. no-motion in ground-based flight simulations is a heatly debated issue. Platform motion has been shown to improve pilot-vehicle performance when compared with fixed-based flight simulators. Using a roll attitude stabilization task in hover, Stapleford[28] found that motion cues increased pilot phase lead and led to higher pilot crossover frequency and gain. In a dogfight scenario investigating the effects of motion vs. no-motion, Jex[29] found that under the full motion case test subjects were able to provide more phase lead at low frequency which helped avoid drifts and overshoots in target tracking, and to provide higher gain (a factor of 1.6 over no-motion condition) in disturbance rejection. These results support the applications of motion platforms in ground-based flight simulations. For training effectiveness, however, no significant transfer of training due to motion was found in several military studies[25,27] even though motion cues were found to have significant effects to improve pilots performance in some measurements and tasks.[27] A comprehensive understanding of man/machine interaction involving visual and motion cues is therefore required to determine the effectiveness of the ground-based flight simulator.

Psychophysics

In fixed-based simulators, even without a motion device, visual cues generate self-induced motion. The self-motion is dependent on the peripheral vision, spatial frequency, and background of the scene.[30] The approximate frequency response of the visually induced motion bears a first order characteristic which falls off at 0.1 Hz.[21] This indicates a significant delay in integrating the acceleration to rate and/or position to perform the task if the acceleration information is solely derived from visual cues.

To determine the simulation cueing effects one approach is to develop a structured model such that pilot/vehicle interaction can be analyzed. It is desired that a closed-loop mathematical structure can represent pilot's physical interaction with controls, simulation cues, and the task. A representative structure developed from manual flight control concepts is shown in Figure 1.[31] If each key element in this closed-loop structure can be characterized and quantified, the complicated man/machine interface with simulation cues in ground-based flight simulations may be explained analytically.

The human's motion sensing mechanism primarily comes from vestibular system, and proprioceptive feedback via organ, limbs, and surface pressure. Gum[32] discussed these sensing devices characteristics and developed mathematical models for each sensing mechanism. Peters[33] did a summary review on both angular and translational motion sensing studies in 1969, followed by another extensive review by Zacharias[34] in 1978. Both reviews identified a wide range of studies and results in specific human sensory characteristics and modeling. Most of the results, however, have been found in a single degree-of-freedom only. The established understanding indicates that angular rates are sensed by semi-circular canals in the vestibular system,[34,35] low-frequency linear accelerations are sensed by the otoliths, and high-frequency linear accelerations are sensed by other tactile mechanisms, including the neck muscles and receptor in a pilot's seat-of-pants.[34-36] A clear and brief summary including block diagrams of key motion sensory characteristics models is presented by Schroeder[36] in his 1999 report.

Threshold is one of the nonlinear human sensing characteristics of particular interest since it is directly related to the time delay in sensing the onset acceleration and the perception of smoothness of motion cues. Table 2 summarizes findings from several representative investigations.[34-35,37,38] The range of variations reflects empirical effects due to different test subjects, test apparatus, and methods. In addition, as a common practice in motion-based flight simulators, low frequency longitudinal and lateral accelerations are generated by tilting the platform, e.g., $a_x = g \sin\theta$. The translational acceleration threshold, therefore, has an effect on angular tilt threshold. Similarly, the angular rate threshold also has a direct impact on the tilting motion which may lead to a conflict with visual perception and a sensation of vertigo due to pilot sensing uncommanded rotational cues.

A lot of work has been done in this area but knowledge of human sensing characteristics is still incomplete. Understanding of otolith characteristics is limited to the longitudinal DOF only. The tactile model needs more refinement and validation. Angular motion sensing characteristics are mainly developed from pure rotational motion alone. Data have shown significant angular rate threshold increases when translational motion is added which suggests there is a dependency in angular motion sensing characteristics on otolith sensing.[35] Most importantly, most of the past works are done in single DOF. The need to develop an integrated cueing model for multiple DOF as recommended by Zacharias[34] still exists.

Pilot Modeling

With pilot-in-the-loop ground-based flight simulation, a feedback loop is formed with the pilot closing the control loop with a task using the perceived simulated aircraft response via visual and motion cues. The goal is to utilize a structured approach for human characteristics and behavior to determine the effectiveness of given flight simulation cues. If such loop structure and simulation feedback cueing characteristics can be identified, criteria can then be developed to determine and predict the simulation effectiveness based on the missions.

McRuer[23] investigated such a logical approach by formulating a pilot model based on plant characteristics in a tracking task with fixed-based flight simulations. One important aspect from his investigation was developing a crossover model, which relates the operator (pilot) and controlled element (simulated aircraft) transfer characteristics in the frequency domain. This model has been widely used among the researchers and investigators with its key parameters, crossover frequency and phase margin, to measure pilot's response due to specific variations in a closed-loop system.

One specific application using the pilot crossover characteristics to determine the simulation cueing effectiveness with a closed-loop structural pilot model is by

Hess.[39] In a series of studies, Hess investigated a single loop maneuver, i.e., vertical (bob-up and bob-down), and a multi-loop maneuver, i.e., roll-lateral (a sidestep), by comparing simulator data and flight test data from an Army UH-60 Black Hawk.[40] In a closed-loop system representation, a structural pilot model was developed based on psychophysics characteristics that included central nervous system and neuromuscular inner loop modeling, and a procedure using pilot crossover parameters to determine the loop closure performance was developed to determine simulation fidelity. This approach shows promise, but has not been fully validated.

Another approach in analyzing and determining simulation cueing effectiveness is through application of optimal control theory.[41] Levision and Junker[42] investigated a structured closed-loop model which applied bank angle error and roll acceleration in a cost function for a roll tracking task and a disturbance rejection task. They found that motion cues were much more effective in the disturbance task than in the tracking task, and led to significant increase in gain-crossover frequency of pilots. This is consistent with findings from Stapleford[28] and Jex.[29] In addition, to check the general application of the model, a typical set of pilot parameter values were chosen and remained fixed, which included adding control rate to the cost function, to be tested in eight different test conditions. The model results showed good agreement with experimental measures, i.e., RMS tracking error. In the same investigation, efforts were made to include vestibular sensor dynamics to determine the significance of the sensory characteristics in the disturbance rejection task. The results did not find significant differences compared with the simple informational representation.

Structured pilot model approaches have shown promise in providing analytical ways of characterizing and estimating man/machine interaction with simulation cues. The findings, however, have been limited to small samples of control tasks and limited degrees-of-freedom. The interaction between the visual cues and motion cues are not fully understood.

Motion Cueing Criteria

Motion cues have been shown to improve pilot performance. False cues due to limited motion travel, however, could have severe impact on the effectiveness of the motion.[43] It should be noted that motion cues are a combination of the motion system dynamics and the motion drive algorithms, i.e., washout filters. Therefore, the characteristics of both must be considered in evaluating motion cueing effectiveness.

For motion system dynamics, AGARD-AR-144[44] has identified five key system characteristics. They are: excursion limits for single DOF, describing function, linearity and acceleration noise, hysteresis, and dynamic threshold. However, no objective performance criteria were recommended. FAA AC 120-63[4] proposes a minimum describing function requirement in the frequency domain for helicopter simulators, Figure 2, and is supported by an investigation using a 20-ft sidestep with motion cues fully matching the visual cues.[5] Logically, the linearity and acceleration noise criteria can be developed from the human's motion sensing threshold.

To determine the motion cueing fidelity requirement due to washout filter applications, Sinacori[45] first developed criteria using the magnitude and phase of motion cues at 1 rad/sec for angular rate and specific force, Figure 3, to correlate with pilots' subjective perception of motion cues in an "S" maneuver at 60 knots with a high performance helicopter simulation. High, Medium, or Low motion fidelity region was established based on motion sensation relative to visual flight (as perceived through the use of the visual display). Jex[46] developed a lateral washout filter criterion, also shown in Figure 3, based on four pilots comments using an air-to-air gunnery type evasive maneuver and a roll washout filter of s/(s+0.4). Schroeder[36] refined Sinacori's criterion based on his work in yaw and vertical motion DOF with helicopter tasks. White[47] takes a different approach in defining motion fidelity criterion that is dependent on the magnitude of false specific force cues, Figure 4. This approach is justified based on human motion sensory threshold characteristics.

There are two specific motion drive components that typically are overlooked by simulator operators but have significant effects in cueing conflict with visual cues. One relates to translational motion relative to the angular motion, and the other is the tilting. Translational travel that is required to fully coordinate with roll and pitch angular motion is normally heavily attenuated due to available travel. The resulting specific force false cue has been found to significantly affect pilots' perception of motion and their workload.[48] A roll-lateral coordination criterion[49] was developed independently for this specific cueing application from a sidestep task.

Tilting is another visual-motion cueing conflict that bears a significant effect. Usually, low frequency longitudinal and lateral specific force cues are generated by tilting the cab as discussed previously. Excessive angular rate can easily lead to severe visual-motion cueing conflict. A rate limit tied to human angular-rate sensing threshold is recommended.

The criteria being reviewed provide some guidelines to the flight simulation community that may affect the effectiveness of motion-based flight simulators. However, these criteria are developed from limited empirical data with selected tasks, and from single DOF and two degrees-of-freedom investigations. Extending the investigation into multiple degrees-of-freedom, and developing correlation with visual cueing parameters, e.g., FOV and delay, and pilot crossover characteristics, which are simulated aircraft dynamics and task dependent, are recommended.

Summary

A brief summary is presented as follows,
Transport delay: Modern technology can meet current FAA specifications.
Visual resolution: Guideline for required visual resolution relative to task level exists. Developing a universal procedure to measure the visual resolution is recommended.
Scene content: Scene content has significant effects in transfer of training and pilot performance. Future studies in texture patterns, terrain shape, and object size and spacing are recommended.
Field-of-view: Large FOV has been shown to have significant effects with higher-order simulated aircraft dynamics. Results from various transfer of training studies were mixed. More empirical data with a range of tasks and simulated aircraft characteristics are recommended to establish the FOV effect.
Psychophysics: Human angular motion sensing characteristics have been established. Translational motion sensing characteristics from the otoliths are limited to the longitudinal DOF. The tactile model needs refinement and validation. Future studies in interaction between multiple sensing mechanisms and integrated cueing model in multiple degrees-of-freedom are recommended.
Pilot modeling: The existing approaches to determine simulation effectiveness in limited DOF studies have shown promises. More empirical data from a variety of tasks, simulated aircraft, and visual and motion cueing conditions are recommended to improve the modeling techniques and to validate the approach.
Motion cueing criteria: Developing a more comprehensive motion system dynamic specification is recommended. More empirical data to support the established motion fidelity criteria and expand the criteria to multiple degrees-of-freedom are recommended.

Concluding Remarks

This review covers only a small but important part of issues related to ground-based flight simulation effectiveness. Extensive work has been done and quite a bit knowledge has been gained in past decades yet few definite answers are offered to determine the effectiveness of the simulation. The statement reflects limited knowledge in man/machine interaction using simulation cues and suggests additional research is required.

In addition to preceding recommendations and summarized future work, additional recommendations are presented for future research.

1. A more organized effort in following recommendations suggested by past investigators and researchers to fill in the blanks.
2. A universal test procedure that documents the key simulation cueing characteristics and effects that include, but not limited to, simulated aircraft, visual cueing characteristics, and motion cueing characteristics, to facilitate exchanging information and lessons learned.
3. Develop tie-in with past works when designing future investigations to reaffirm experiment procedures, set-up, and results.

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Table 1. Summary of Field-of-View (FOV) effectiveness results

Irish[24]	Advanced Simulator for Pilot Training (ASPT), T-37	Air Force Human Resources Laboratory	5 experienced T-37 pilots
	Summary: Used three levels of FOV, 300°H(orizontal)×150°V(ertical), 144°H× 36°V, and 48°H× 36°V. Found FOV to be significant in favor or large FOV in aileron roll, barrel roll, ground controlled approach, and 360° overhead pattern.		
Nataupsky[25]	Advanced Simulator for Pilot Training (ASPT), T-37	Air Force Human Resources Laboratory	32 inexperienced student pilots
	Summary: Two FOV levels being investigated, i.e., 300°H(orizontal)×150°V(ertical), and 48°H× 36°V in takeoff, steep turn, slow flight, and straight-in and landing tasks. Found FOV bears no significance in student pilots performance and type of maneuvers.		
Kellogg[19]	C130 Weapon System Trainer (WST)	Little Rock AFB	10 experienced pilots
	Summary: Two FOV levels, i.e., 160°H×35°V and102°H×35°V in an assault landing task. All tests were done with motion system on. Found FOV significance in pilots' control of descent rate and angle of attack (AOA) at touch down.		
Dixon[26]	C130 Weapon System Trainer (WST)	Little Rock AFB	12 experienced pilots
	Summary: Two FOV levels, i.e., 160°H×35°V and102°H×35°V, in a low-level navigation to a drop and escape task. Found FOV to be significant. However, the effects are neither large nor dramatic.		
Westa[27]	Visual Technology Research Simulator (VTRS), T-2C	Navy Training Equipment Center, Orlando, FL	32 experienced pilots (16 T-38 and 16 P-3C)
	Summary: Two FOV levels, i.e., 160°H×80°V and 48°H×36°V in carrier approach and landing. Found FOV had substantial transient effects on final approach lineup and AOA performance. But no effect on transfer landing performance.		
Lintern[13]	Visual Technology Research Simulator (VTRS), T-2C	Navy Training Equipment Center, Orlando, FL	42 student pilots
	Summary: Three FOV levels, i.e., 160°H×80°V, 135°H×59°V and 103°H×60°V in radial bombing task. Found no FOV significance in bombing error performance.		

Table 2. Summary of motion sensing threshold

Degree of Freedom	Threshold	Remarks
Roll	3 deg/sec 3.2 deg/sec 2.5 deg/sec 0.4 deg/sec @1 rad/sec	Meiry[37], step commands Peters[33], review summary Zacharias[34], review summary Zaichik et al[35], sine wave, 0.5 - 8 rad/sec
Pitch	3.6 deg/sec 2.6 deg/sec 2.0 deg/sec 0.9 deg/sec @1 rad/sec	Same as above
Yaw	2.6 deg/sec 1.1 deg/sec 4.2 deg/sec 0.65 deg/sec @1 rad/sec	Same as above
Longitudinal	0.01g 0.002-0.02g 0.005g	Meiry[37], step commands Peters[33], review summary Zaichik et al[35], sine wave, 0.5 - 8 rad/sec
Lateral	0.002-0.02g 0.003g	Peters[34], review summary Zaichik et al[35], sine wave, 0.5 - 8 rad/sec
Vertical	0.0088g 0.008g	Hosman[38] sine wave, 1 - 14 rad/sec Zaichik et al[35], sine wave, 0.5 - 8 rad/sec

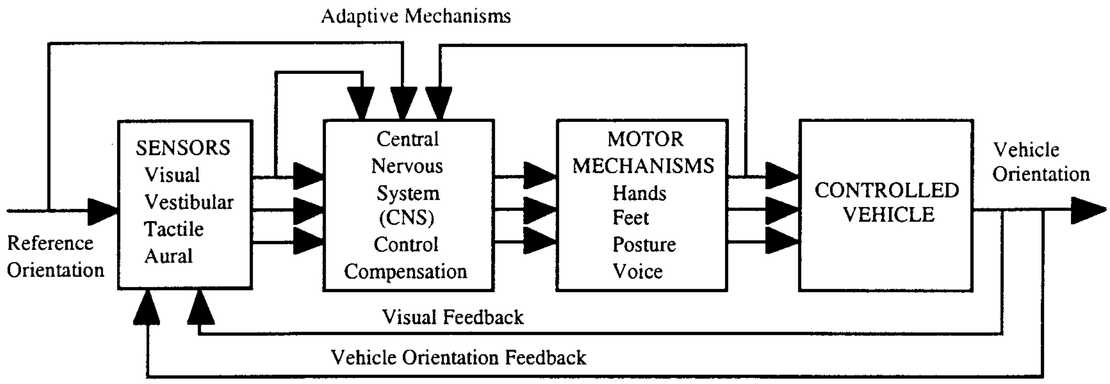


Figure 1. A representative man-in-the-loop manual flight control structure

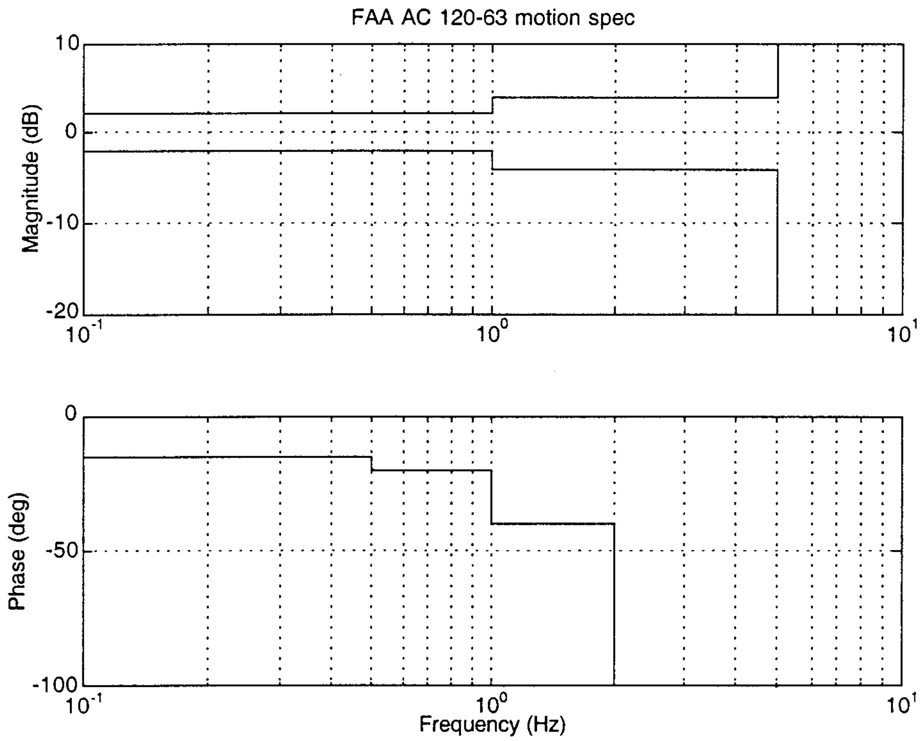


Figure 2. FAA AC 120-63 motion system specification, motion response/motion command

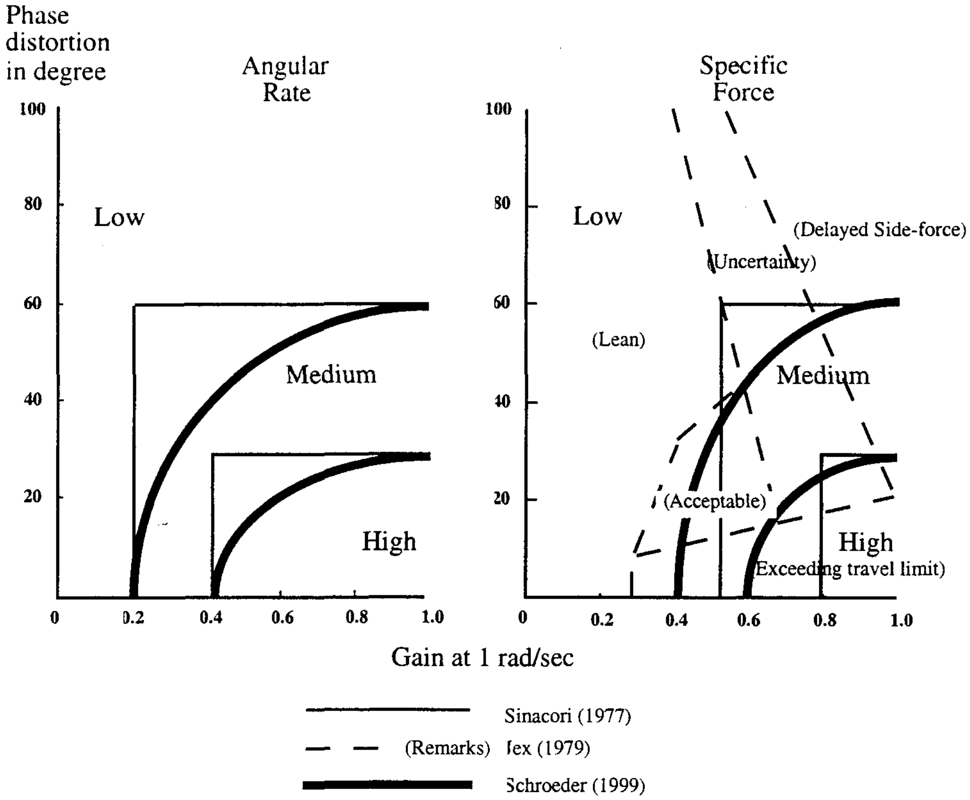
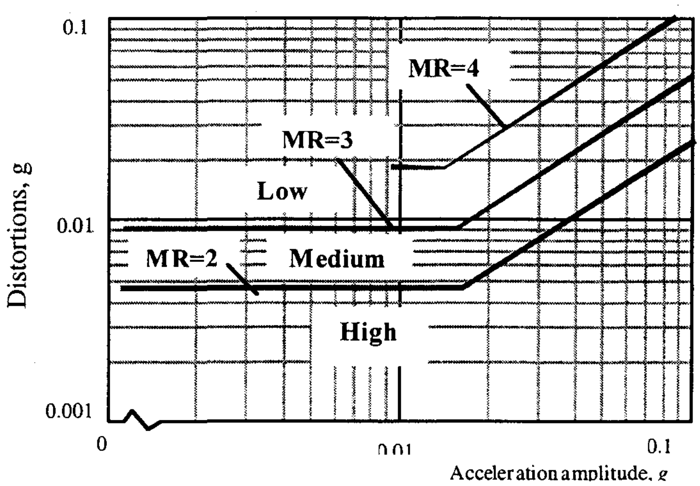


Figure 3. Recommended motion fidelity criterion



MR: Motion Rating, MR=1 being the highest fidelity

Figure 4. The permissible values of nonlinear distortion (Reference 47)