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Experiments in Sensing Transient Rotational Acceleration Cues on a Flight Simulator

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SUMMARY

This paper presents the results of two transient motion sensing experiments which were motivated by the identification of an anomalous roll cue (a "jerk" attributed to an acceleration spike) in a prior investigation of realistic fighter motion simulation. The experimental results suggest the consideration of several issues for motion washout and challenge current sensory system modeling efforts. Although the subject paper represents no sensory modeling effort in itself, the argument is made as to the necessity of incorporating into such models the ability to handle transient inputs of short duration (some of which are less than the accepted latency times for sensing) and representing separate channels for rotational acceleration and velocity sensing.

INTRODUCTION

A major emphasis in motion simulation technology is currently centered around modeling human sensory mechanisms, including vestibular, tactile, and proprioceptive sensors, and the interaction of these sensors with visual sensors (refs. 1 to 8). The general goal of such efforts, aside from insight, is to provide a quantitative means for determining motion fidelity requirements for flight simulation tasks. Unfortunately, the validation of such models is based mainly on steps or ramp-type inputs rather than on aircraft-related inputs. A major concern of this paper is the fact that inputs of a transient nature and with relatively high-frequency content (i.e., 1 Hz) must be considered. Provisions in the current digital implementations of these models to handle inputs of high-frequency content are inadequate, with integration algorithm step sizes at a minimum of 0.1 sec (p. 33 of ref. 6).

Of equal concern is the equivalence given to rotational acceleration and velocity sensing by means of latency arguments (refs. 6, 8, and 9). It is argued that it is necessary to represent only one sensory input channel. Velocity is commonly chosen and the reasoning then follows: since an angular acceleration above its threshold is not sensed unless it endures for some finite time (the latency time) and since the angular velocity threshold can be theoretically equated to the integration of this acceleration over the period of the latency time, the representation of the acceleration channel is unnecessary (ref. 7). A need for some independent representation of both velocity and acceleration channels is presented in the present paper.

The concerns expressed here are directed toward efforts underway to use human sensory models to determine simulator requirements, particularly in the realm of motion requirements for tactical fighters. These concerns were prompted by the investigations of transient motion sensing reported herein. The motivation for these investigations arose from the study of pilot acceptance of simulator platform motion for fighter airplanes. An anomalous roll cue was reported in reference 10 to be of major consequence in realistic fighter motion simulations. This anomalous cue was presented to the pilot by the motion base upon stick release. It is not present, at least subjectively, in actual flight in conventional fighter airplanes. Additionally, reference 10 identified a method for producing potentially realistic roll cues which eliminates this objectionable stick release cue.

This paper reviews in some detail the roll cueing situations of reference 10, and then discusses two separate experiments in acceleration sensing. No sensory modeling efforts based on the results of these experiments are attempted. However, the deficiencies of current models upon which these results impinge are identified. The first experiment provided specific information to implement the proposed washout scheme suggested in reference 10. The second experiment was conducted to explore additional acceleration profiles that were suggested by the sensory impressions encountered during the first experiment. Results of the two experiments demonstrate that current sensory models are inadequate to handle the roll cueing situations described in reference 10 and the additional cueing situations to be reported in the subject paper.

THE ANOMALOUS ROLL CUE

Figure 1, taken from reference 10, illustrates the anomalous roll cue identified by the pilots participating in that study. The maneuvers involved are (a) a quick 30° roll from straight and level and (b) a quick roll back to straight and level. The figure presents the time histories of the stick input, the responding airplane's (a simulation of a YF-16) roll acceleration, roll velocity, and lateral acceleration, and the measured roll acceleration, the measured lateral acceleration, and the commanded roll velocity from a synergistic six-degree-of-freedom motion base driven by a "nearly linear" first-order washout in roll. (See ref. 10.) The following description was given by a pilot of his motion perceptions during the (a) portion of the maneuver, a simple rapid bank to the right:

> "I felt a jerk to the right as I applied the stick input, and then an increasing roll rate to the right, which was halted by a jerk to the left when I released the stick. This second jerk is not encountered in actual flight and is totally unrealistic and unacceptable."

This description is typical of all pilot reactions to the roll channel response of the motion base as reported in reference 10. Although "jerk" is defined in the vernacular of engineering as the derivative of acceleration, the participating pilots were not familiar with that definition and were not sure of just what they were feeling. However, they were insistent that whatever they were feeling at stick release, marked with asterisks in figure 1, was unrealistic.

It should be noted that none of these pilots had flown either a YF-16 or an F-16 airplane, although all were experienced in conventional fighter airplanes. A recent description (p. 18 of ref. 11) of a flight evaluation of an F-16 mentions that "the abrupt halt caused by simply releasing pressure on the stick is enough to straighten the second pilot's hardhat on the other side of the canopy." In conventional fighter airplanes, "stopping the roll seldom presents the same problem." This description is of an unconventional motion cue encountered at stick release in actual flight in a similar airplane; however, it is believed to be a description of a translational acceleration cue resulting from a high rotational acceleration about the airplane center of gravity, rather than the anomalous rotational cue encountered on the motion base. The motion base cue was believed to be a definite rotational cue. Translational acceleration cues to the pilot's head on the motion base resulting from roll motion of the base were small and not considered to be a part of the jerk cue.

To identify the motion sensations described in the preceding pilot quotation, the following supposition was advanced after much discussion and thought: The jerks felt upon stick activation and release are roll acceleration cues; the roll rate is sensed as a continuous velocity cue.

For each of the two pulse-type stick inputs ((a) and (b)) in figure 1, there are two airplane roll acceleration peaks (one positive and one negative). Pilots expect in flight to feel the first peak, but not the second one. Since the peaks are approximately equal in magnitude and time duration, one might expect both peaks to be sensed.

The motion base, driven by the washout, experiences three roll acceleration peaks. All three motion base peaks are well above the maximum reported rotational acceleration threshold (0.07 rad/sec^2, from p. 28 of ref. 8), and yet only two were sensed by the pilots in the simulator (ignoring for now the question of latency times). The pilots state that they should only sense one jerk, as in a conventional fighter, rather than two.

Before pursuing the cause of this anomalous jerk, the remaining motion cues presented to the pilot in the simulator (fig. 1) are discussed briefly. The positive peak velocity is above the commonly accepted rotational velocity threshold (0.035 rad/sec, p. 35 of ref. 6) while the negative peak velocity (the washout) is below the threshold. The pilots did not detect either this washout or the misalignment of the gravity vector due to the bank angle of the motion base and its limited translational capabilities. The false side force generated by the misalignment of the gravity vector may be removed in a coordinated washout scheme by translational acceleration in the opposite direction.

An attempt to identify a source other than the second acceleration peak for the objectionable cue was made. The potential sources investigated included the washout process, motion base hardware turnaround bump, sway force induced by the inertial side acceleration, and the airplane math model. The motion base was driven directly with scaled airplane bank angle, and the anomalous cues were still present. Thus, the washout process was eliminated as a potential source of the cue. Hardware turnaround bump occurs during position turnaround, as the velocity changes sign. Investigation into the sequence of events revealed that the objectionable cue occurred prior to position turnaround and that the magnitude of the turnaround bump was too small (0.018 rad/sec^2) to be considered as a source of the problem.

The inertial side acceleration contribution to sway, observable in figure 1 as notches appearing in the side force, was eliminated by setting the translational channel input to zero. The objectionable cues, which are not subjectively present in flight, were still presented to the pilots on the motion base.

The remaining source of the second jerk (supposed to be an acceleration spike) to be investigated was the airplane math model. A roll stick pulse command to each of the real-time fighter simulation models currently available on the Langley differential maneuvering simulator (DMS, ref. 12) revealed similar airplane response. These models include the F-14, F-15, F-16, A-10, F-4, and YF-16. Most of these models include actuator servos and the models cover a wide range of control systems and control force systems. The airplane response referred to is the large reversal in roll acceleration necessary to return the roll rate to zero upon stick release (fig. 1). Since the model responses are similar, it was presumed that the objectionable roll cue would be present in moving base simulation of these models also. Yet each model had been rigorously validated against available flight data; unfortunately, no stick pulse data were available from flight. The airplane math model is thus an unlikely source of the objectionable cue, since the large reversal in roll acceleration is common to all for pulse-shaped stick inputs.

All four potential sources of the objectionable cue have been examined and eliminated from consideration, leaving unanswered the problem of the second jerk. However, although no explanation is offered as to why the pilot feels the second jerk in the simulator and may not in actual flight, it is possible to make the second peak in the simulator subliminal to the pilot. Identification of the jerk as an acceleration cue or as a true jerk or as something not yet considered is unnecessary from the viewpoint of removing the anomalous cue.

DESCRIPTION OF THE EXPERIMENTS

Table I presents the ratio of the second acceleration peak to the first peak, resulting from a roll stick pulse input, for the airplane math models currently in the DMS inventory. From observation of these data, a question naturally arises as to what the ratio must be for the second peak to be subliminal in a simulator. Figure 2, taken from reference 10, presents time histories obtained by driving the motion base with a sequence of three sine-wave pulses in rotational acceleration from which pilots were unable to detect any unrealistic cues. The peak ratio for this case was 0.625. Pilots subjected to this input contended that a washout scheme which involved motion cues for roll inputs similar to those invoked by the sine-wave pulse sequence of figure 2 would be realistic. To prepare the basis for such a washout scheme, the first experiment was conducted to determine the acceptable ratio of acceleration peaks, under both instrument only and out-the-window visual scene conditions.

A sequence of three sine-wave pulses in rotational acceleration was programmed to drive the Langley visual/motion simulator (VMS, refs. 13 and 14). Each sine-wave pulse, with amplitude and frequency ω as parameters, progressed through half a cycle ($0 \leqq \omega t \leqq \pi$, where t is time) before being succeeded by the next pulse. (See fig. 3.) The VMS is a position-driven servo system of finite bandwidth and, as such, introduces some distortion in both amplitude and phase, although compensation techniques have extended the bandwidth to above 4 Hz (ref. 14). Additional minor distortion of the acceleration profiles was introduced by the discrete numerical integration of velocity to position commands. The velocity drives were obtained analytically from the desired acceleration profiles and then integrated in real time using the same integration routine utilized in Langley washout implementations to yield the position drives for the motion base. Although all these minor distortions of the acceleration profiles have some importance in future vestibular modeling considerations, their importance is nebulous for current models which cannot account for the undistorted case. The distortions have no significance from the washout point of view, since the same distortions will be encountered by the washout commands for the VMS in any simulation application.

The Langley VMS is provided with an out-the-window virtual image system of the beam-splitter, reflective-mirror type. This system, described in detail in reference 10, was used in part of the first experiment to determine the acceptable ratio of acceleration peaks under visual conditions. A terrain model-board scene was driven in either roll or yaw, dependent on the experimental condition, by the airplane motion that would have accompanied an acceleration profile consisting of two half-sine waves of equal but opposite magnitude and of the same frequency. Amplitude and frequency were the same as those of the first sine wave in the acceleration profile for the motion base (e.g., fig. 4).

A second experiment was also conducted. The first experiment utilized a very low amplitude third acceleration peak merely to return velocity and position to zero simultaneously. The second experiment investigated third peaks of sufficient magnitude to be sensed by the subjects. Motivation for this experiment arose from the fact that the third peak acceleration functionally drives the velocity to zero, which duplicates the functional situation of the second acceleration peak in an actual flight vehicle. As in figure 1, the second acceleration peaks, induced by stick release, drive the roll rate to zero. Note that the second peak of the sine-wave sequences (e.g., fig. 3) of the first experiment drive the roll rate through zero to a washout velocity level. The third sine wave in the sequence then returns velocity and position to zero simultaneously.

RESULTS FOR THE ACCEPTABLE RATIO, EXPERIMENT I

Table II contains the amplitudes A_i and frequencies ω_i of the three sine-wave pulses making up each acceleration profile sequence that was utilized in determining the acceptable ratio. For this experiment, A_1 and ω_1 were chosen to provide a maximum rotational velocity of 0.15 rad/sec, A_2 was chosen to control the acceleration ratio, ω_2 was chosen to provide a maximum negative rotational velocity (the washout rate, desired to subliminal) of -0.025 rad/sec, and A_3 and ω_3 were chosen to return the velocity and position to zero at the same time.

Eight subjects participated in four separate determination subexperiments. The subexperiments determined the acceptable acceleration peak ratios for roll inputs under (1) instrument only and (2) visual conditions, and then for yaw inputs under (3) instrument and (4) visual conditions. Each subject was to be exposed to two profiles at a time, and then asked to pick the profile which has the lesser stick-release cue, or lesser second jerk. Four of the subjects were considered experienced and the other four were considered naive concerning airplane motions. The subjects were trained by one exposure to the 1.5 ratio profile contrasted with the 0.5 ratio profile. All subjects declared, after such exposure, that their task was obvious. They were instructed that in the event of indecision, a choice of one profile over the other had to be made on some basis. Each subject was exposed to nine contrasts of two profiles, with six random repetitions of each contrast for the four separate subexperiments.

The Roll Ratios

Figure 5 summarizes the results of the roll cue experiments for both instrument and visual conditions. Identical results in terms of statistical significances were obtained under the two conditions. The brackets indicate the contrasting profiles used in the subexperiment, and the asterisks represent the contrasts that were statistically significant at the 95-percent confidence level, based on a one-tailed χ^2 test (p. 263 of ref. 15). As indicated in the figure, the subjects could not differentiate among the 0.625, 0.5, and 0.375 profiles. However, the subjects consistently preferred any of these three profiles when contrasted with the other three. The 0.25 ratio profile invokes a bank angle of about 13° over a period of 20.6 sec, which creates a noticeable side force that all subjects found readily apparent and objectionable. Therefore, the 0.25 ratio profile was consistently rejected on that basis, rather than on an objectionable second-jerk basis.

The Yaw Ratios

Since any substantial bank angle induces a side force through the gravity vector which cannot be compensated because of the limited translational capability of the VMS, the yaw axis, with no gravitational interaction, was also investigated. As was true in the roll axis investigation, the significant statistical results were identical for the instrument-only and visual conditions. Figure 6 summarizes these results. For the yaw axis, the 0.75 profile was indistinguishable from the 0.625, 0.5, and 0.375 profiles, and the subjects consistently preferred any of these four profiles when contrasted with the other two profiles. The 0.25 case was again rejected, although the rationale of the subjects was different from that for roll. Under visual conditions for the 0.25 ratio profile, the yaw motion of the base continued for some time at a rate above threshold after the out-the-window scene had halted. (See fig. 4.) The rationale for the instrument case was not too clear, although some of the subjects cited the excessive hydraulic system noise for this case as being responsible for its consistent rejection. No one suggested that a second jerk was present for this 0.25 profile.

The Selected Ratio

Based on the results of the roll and yaw studies and the design philosophy of washout circuitry which requires washout in the minimum acceptable time in order to be prepared to present subsequent cues, the ratio of 0.625 is identified as the acceptable ratio of acceleration peaks. The contention of pilots exposed to that ratio was that a washout scheme which invoked similar motion cues would be potentially realistic, mainly because no false stick release cues would be detectable.

RESULTS FOR ACCELERATION SENSING, EXPERIMENT II

The second experiment, acceleration sensing, was suggested by the following facts. In an actual flight vehicle the second acceleration peak, induced by stick release, drives the sensed roll rate to zero. However, in the simulator, the second acceleration peak of the sine-wave pulse sequences just discussed functionally drives the rotational rate through zero to the washout velocity, rather than to zero. The third peak in the sequence drives the rotational rate from the washout velocity to zero. If the second sine-wave pulse were to drive the rate through the washout velocity to a velocity above threshold, and if the third peaks of the sequence were increased to sufficient magnitude to be sensed, the second and third peaks might more accurately represent the first and second peaks of a flight case - that is, a final acceleration peak that functionally drives a sensed velocity to zero.

Two conditions were envisioned. The first condition would deal with velocities above threshold, as in the flight case (although rotational rates of much higher levels are encountered in flight). The second condition would deal with velocities below the threshold (generally accepted to be around 0.035 rad/sec) in order to investigate latency arguments, which have been interpreted (ref. 7) to state that an angular acceleration above its threshold will not be sensed until the angular velocity exceeds its threshold. Motivation for this later investigation arose from the fact that the subjects in the previous experiment, as well as the pilots of reference 10, all stating that they sensed the jerk first, followed by a rotational rate cue - two separate cues.

The Above-Velocity-Threshold Profiles

Table III lists the amplitudes and frequencies, along with the extremum velocities, for the sine-wave sequences utilized. The profiles are illustrated in figure 7, with minor liberties taken to collapse to a uniform time scale. At the end of the first sine-wave pulse of each profile, the velocity had reached a maximum value (usually 0.15 rad/sec). At the end of the second sine-wave pulse, the velocity had reached a minimum value (usually -0.15 rad/sec). The third sine-wave pulse then returned both position and velocity to zero. Two subjects experienced the profiles under instrument-only conditions in both roll and yaw axes. Asterisks represent peaks that were reported as jerks consistently, and squares represent peaks that were reported as not being noticeable. Roll and yaw results were identical.

These results agree with the ratio results discussed previously. That is, peaks that are not sensed (squares) are less than 0.625 of the preceding peak, whereas peaks that are sensed (asterisks) are equal to or greater than the preceding peak. Some type of saturation model for the sensory mechanism involved is possibly suggested by these results.

The Below-Velocity-Threshold Profiles

Table IV lists the amplitudes and frequencies, along with the extremum velocities, for the sine-wave pulse sequences that were used to examine accelerations that, according to latency explanations, should not have been sensed by the vestibular system. The extremum velocities are all less than 0.035 rad/sec, and the time durations of the accelerations fall well below latency curves such as figure 8. Figure 9 illustrates, in the manner of figure 7, the below-velocity-threshold profiles. Again, two subjects experienced the profiles in both yaw and roll axes, with the same results in each axis. Subjective sensations of only jerk cues, with no rotational or translational cues, were reported, along with jerk directions and relative magnitudes.

The first combined profile of figure 9, with a second-to-first peak ratio of 0.5, was reported as consisting of two jerks to the right for three of the four cases. The last case, with a third-to-second peak ratio of 0.5, consisted of only one jerk to the right. These results are identical to the above-velocity-threshold results.

The second combined profile, with a second-to-first peak ratio of 1.0, was reported to consist of a jerk to the right followed by a jerk to the left. A third jerk, to the right, was reported for the third-to-second peak ratio of 2.0 only. In the above-threshold results, the third jerk was reported for the third-to-second peak ratio of 1.0, also.

The results for the third combined profile, with a second-to-first peak ratio of 2.0, differed from the above-threshold results again for the third-to-second peak ratio of 1.0. The results for the other two ratios, 2.0 and 0.5, agreed with the above-threshold results.

Modeling Acceleration Sensing

The subjective results from two participants in one unstructured experiment certainly cannot be used to develop a basis for a new model of the vestibular system. However, these results do suggest further investigation into perception of angular acceleration cues that are separate from angular velocity perceptions. The fact that the sensing of acceleration spikes violates latency-time arguments should be justification enough for further investigation. Of particular interest to the washout system designer is the question of why a pilot in flight may not sense the second acceleration peak while his counterpart on the ground does (fig. 1). Perhaps the different magnitudes of velocity and side force have some effect, as perhaps was the case for the third peak differences between above- and below-threshold results.

CONCLUDING REMARKS

The results of the transient motion sensing experiments presented have implications for two areas of current motion simulation technology efforts. The washout system designer, and indeed the fighter motion simulation user, must be aware of the possibility of an anomalous roll cue presented upon stick release to the simulator pilot. The fact that elimination of this cue during the washout process is possible, through use of an acceptable ratio of succeeding acceleration peaks, may suggest many new washout schemes.

The implications of these results to the area of sensory modeling are clear. For fighter airplanes at least, present models are inadequate to handle realistic inputs, that is, transient inputs of relatively short duration (i.e., higher frequency content). Present models must incorporate both the velocity and acceleration channels and provide some representation of the jerk cue identified in this paper. Also, the validity of latency-time considerations is certainly challenged by these results, as is the validity of current efforts to determine motion fidelity issues utilizing current sensory models.

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TABLE I.- DMS CURRENT INVENTORY

Airplanes	Ratio of roll acceleration peaks (second to first) for pulse input
F-4	0.90
F-15	.80
F-16	1.40
YF-16	1.00
A-10	.90
F-14 (SAS off)	.85
F-14 (SAS on)	.90

TABLE II.- SINE-WAVE SEQUENCE DATA

[A_i = Amplitude of ith sine-wave pulse; ω_i = Frequency of ith sine-wave pulse]

Ratio (a)	A_1, rad/sec^2	ω_1, rad/sec	A_2, rad/sec^2	ω_2, rad/sec	A_3, rad/sec^2	ω_3, rad/sec
1.5	0.4	5.33	-0.6	6.85714	0.00674	0.53933
1.00	.4	5.33	-.4	4.57143	.00563	.45070
.75	.4	5.33	-.3	3.42857	.00484	.38710
.625	.4	5.33	-.25	2.85714	.00435	.34783
.50	.4	5.33	-.2	2.28571	.00377	.30189
.375	.4	5.33	-.15	1.71429	.00309	.24742
.25	.4	5.33	-.1	1.14286	.00227	.18182

[a]Ratio of second acceleration peak to first peak.

TABLE III.- ABOVE-VELOCITY-THRESHOLD PROFILES

[A_i = Amplitude of ith sine-wave pulse; ω_i = Frequency of ith sine-wave pulse]

A_1, rad/sec^2	ω_1, rad/sec	A_2, rad/sec^2	ω_2, rad/sec	A_3, rad/sec^2	ω_3, rad/sec	Maximum roll rate, rad/sec	Minimum roll rate, rad/sec
0.45	6.5751	-0.225	1.5686	0.9	12.04453	0.13688	-0.15
	6.0	-.225	1.5	.45	6.0	.15	-.15
	6.0	-.225	1.60772	.225	3.4638	.15	-.1299
	6.0	-.225	1.75747	.1125	2.12068	.15	-.10605
.45	6.92308	-.45	3.21429	.9	11.94690	.13	-.15
	6.0	-.45	3.0	.45	6.0	.15	-.15
	6.0	-.45	3.30154	.225	3.68178	.15	-.1226
.225	4.24128	-.45	3.51425	.9	11.97697	.1061	-.15
	3.67347	-.45	3.30275	.45	5.995	.1225	-.15
	3.0	-.45	3.0	.225	3.0	.15	-.15

TABLE IV.- BELOW-VELOCITY-THRESHOLD PROFILES

[A_1 = Amplitude of ith sine-wave pulse; ω_i = Frequency of ith sine-wave pulse]

A_1, rad/sec^2	ω_1, rad/sec	A_2, rad/sec^2	ω_2, rad/sec	A_3, rad/sec^2	ω_3, rad/sec	Maximum roll rate, rad/sec	Minimum roll rate, rad/sec
0.3	32.87671	-0.15	7.84314	0.6	60.24474	0.01825	-0.02
	30.0		7.5	.3	30.0	.02	-.02
	30.0		8.0429	.15	17.25915	.02	-.0173
	30.0		8.77193	.075	10.69384	.02	-.0142
.3	34.68208	-.3	16.08579	.6	60.42905	.0173	-.02
	30.0		15.0	.3	30.0	.02	-.02
	30.0		16.50619	.15	18.4164	.02	-.01635
.15	21.20141	-.3	17.56955	.6	59.80042	.01415	-.02
	18.4091		16.52893	.3	30.22137	.0163	-.02
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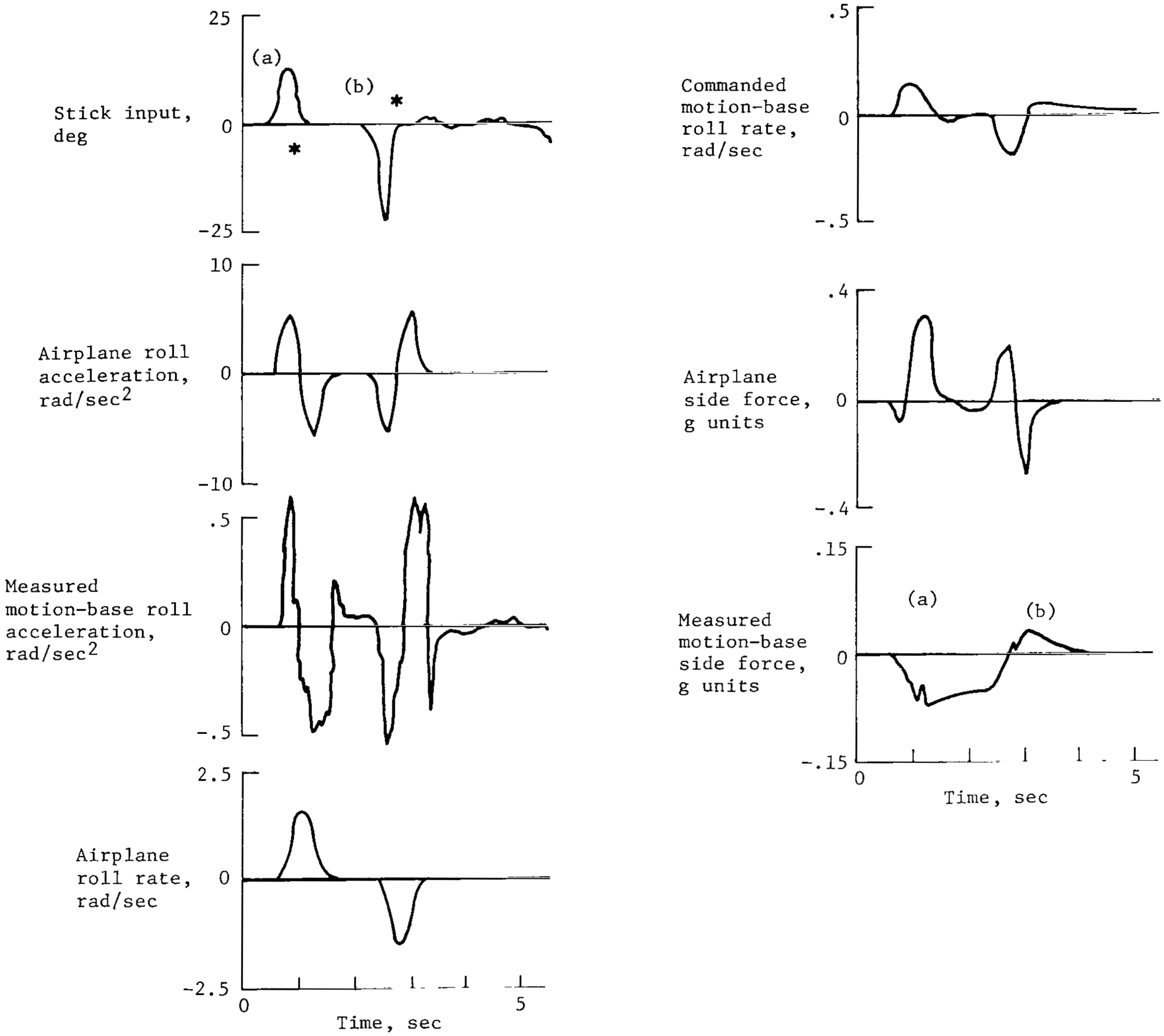


Figure 1.- Lateral maneuver illustrating anomalous roll cue during a 5-sec period (from ref. 10). Maneuver (a) is a quick 30° roll from straight and level; maneuver (b) is a quick roll back to straight and level; asterisks mark responses consistently reported as jerks.

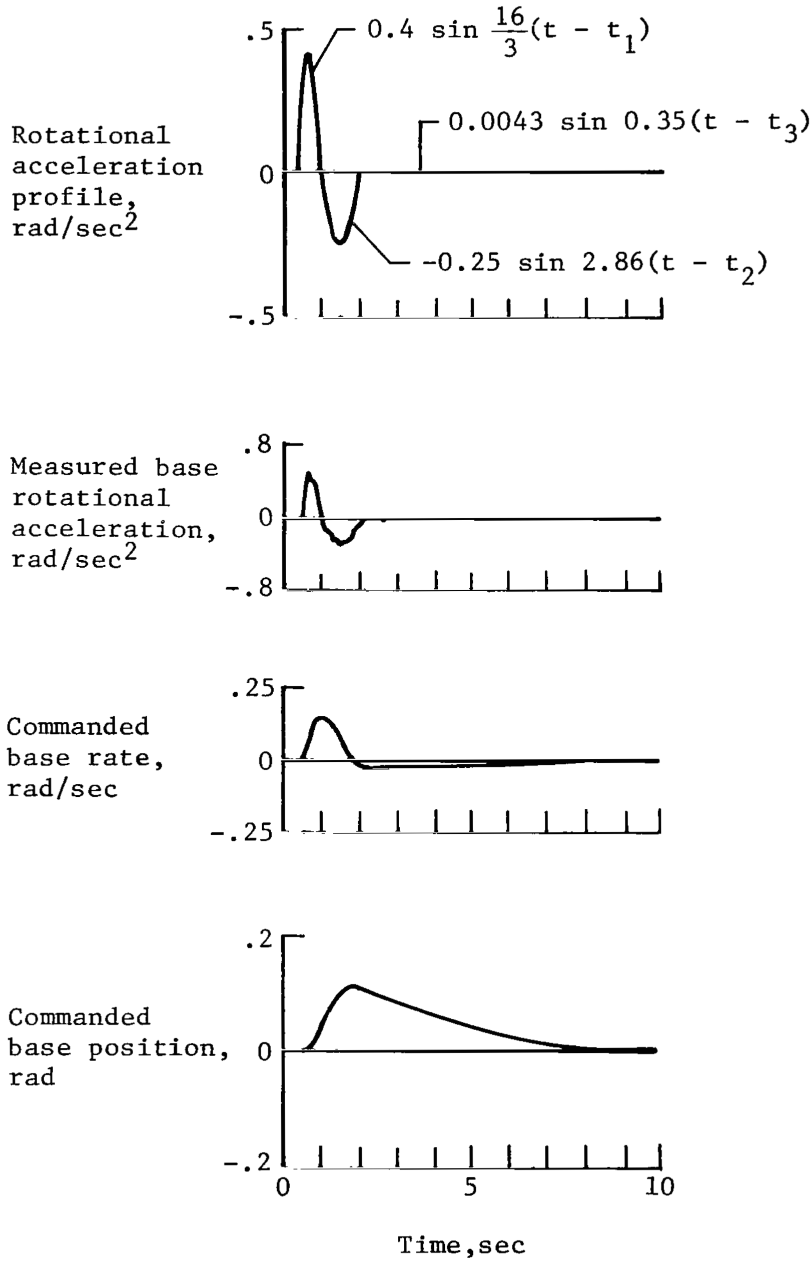


Figure 2.- Sine-wave pulse sequence which was acceptable (from ref. 10). (t_i is time of ith sine-wave pulse; t = 10 sec.)

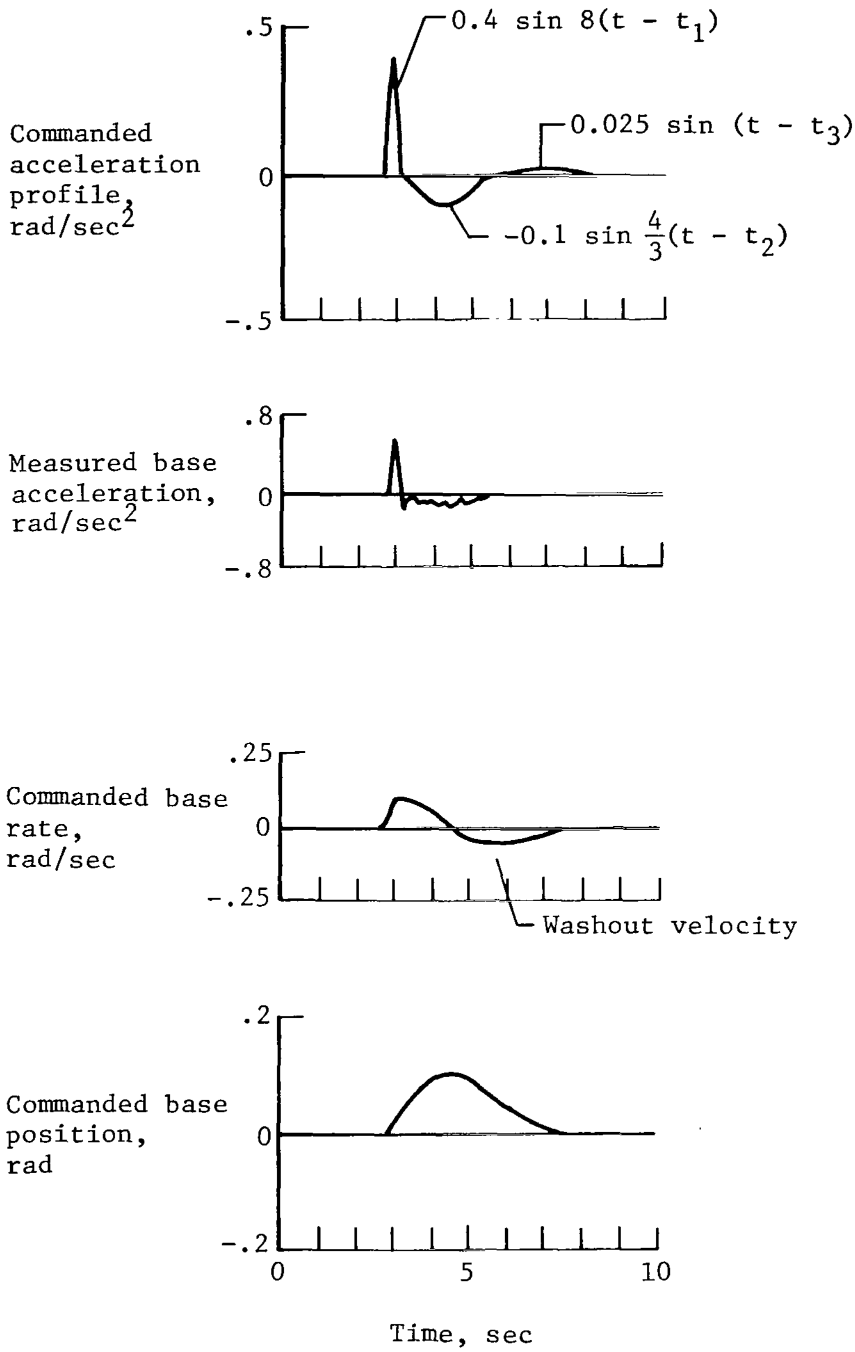


Figure 3.- Sine-wave pulse sequence to illustrate first experiment. (t_i is time of ith sine-wave pulse; t = 10 sec.)

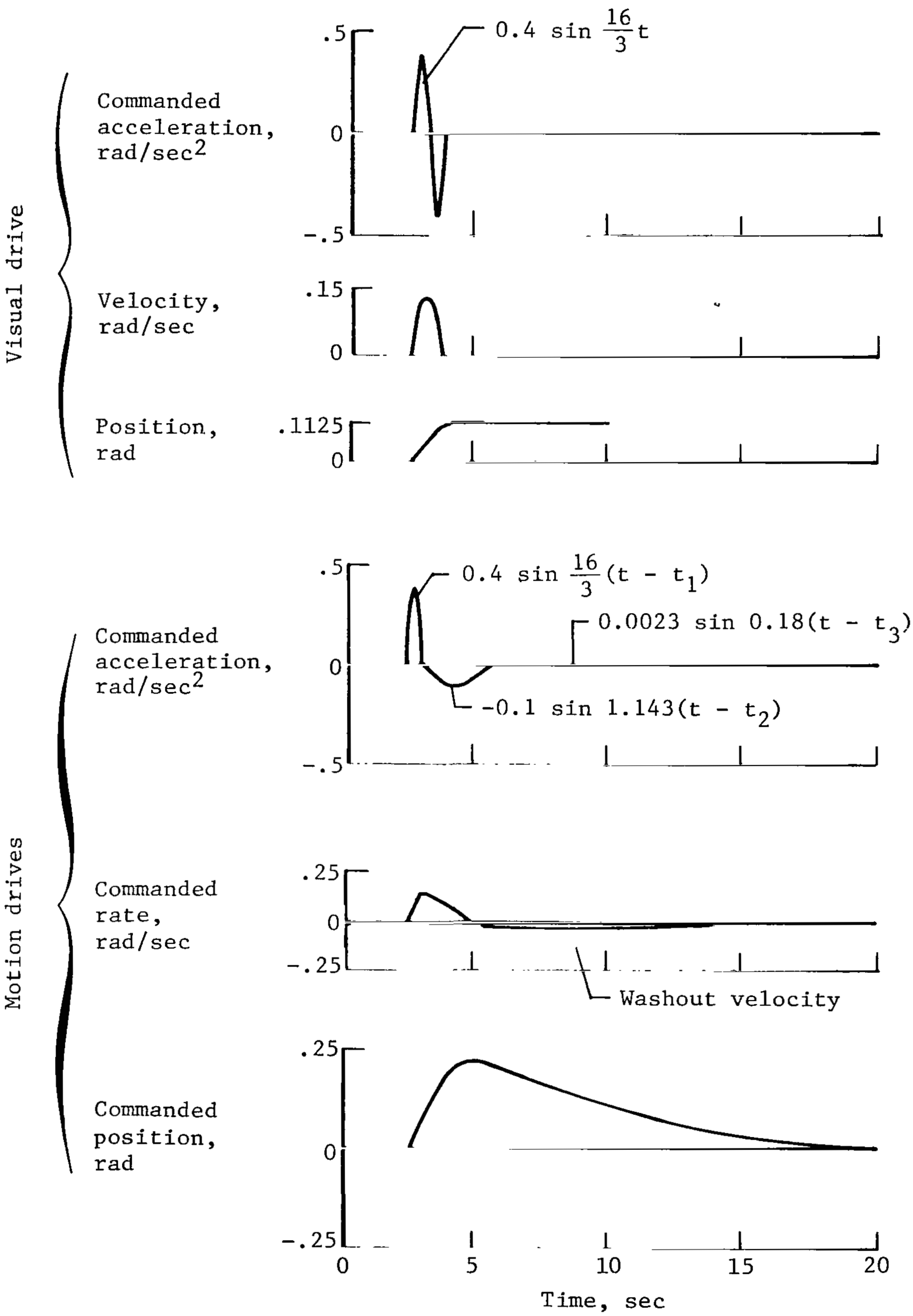


Figure 4.- Sine-wave pulse sequence to illustrate visual drives of first experiment. (t_i is time of ith sine-wave pulse; $t = 20$ sec.)

* Statistically significant differences at the 95-percent confidence level

///// Preferred ratios

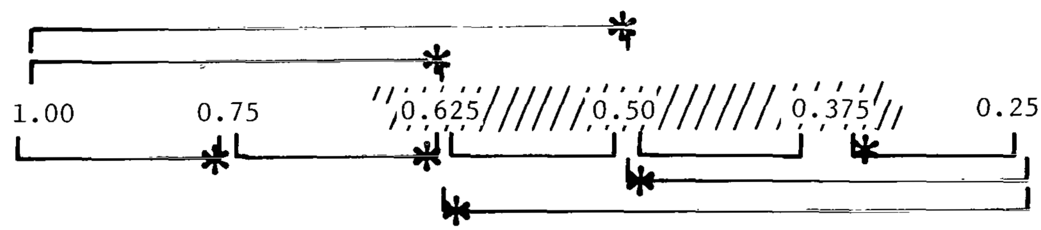


Figure 5.- Results of acceptable-ratio experiment for roll axis under instrument-only and visual conditions.

* Statistically significant differences at the 95-percent confidence level

///// Preferred ratios

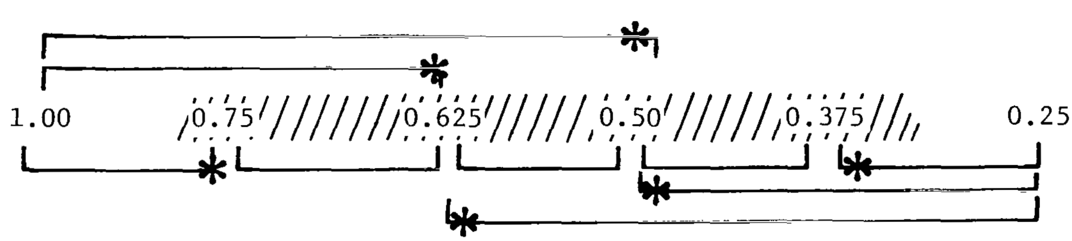
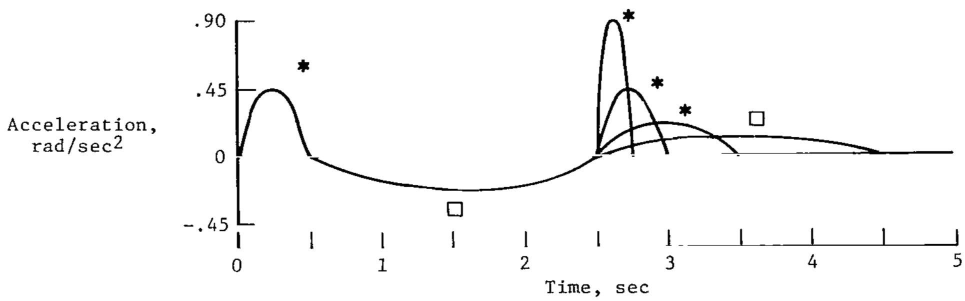
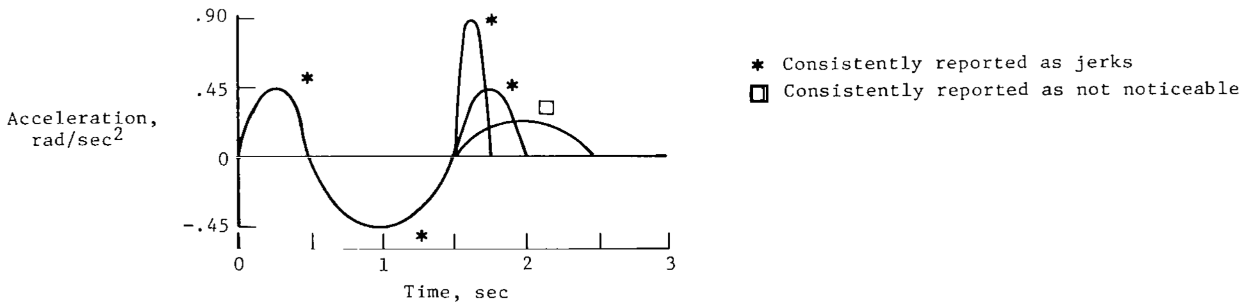


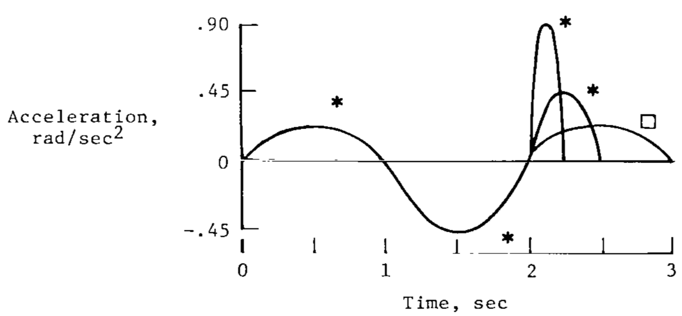
Figure 6.- Results of acceptable-ratio experiment for yaw axis under instrument-only and visual conditions.



(a) 0.5 ratio.



(b) 1.0 ratio.



(c) 2.0 ratio.

Figure 7.- Acceleration profiles, above-velocity thresholds.

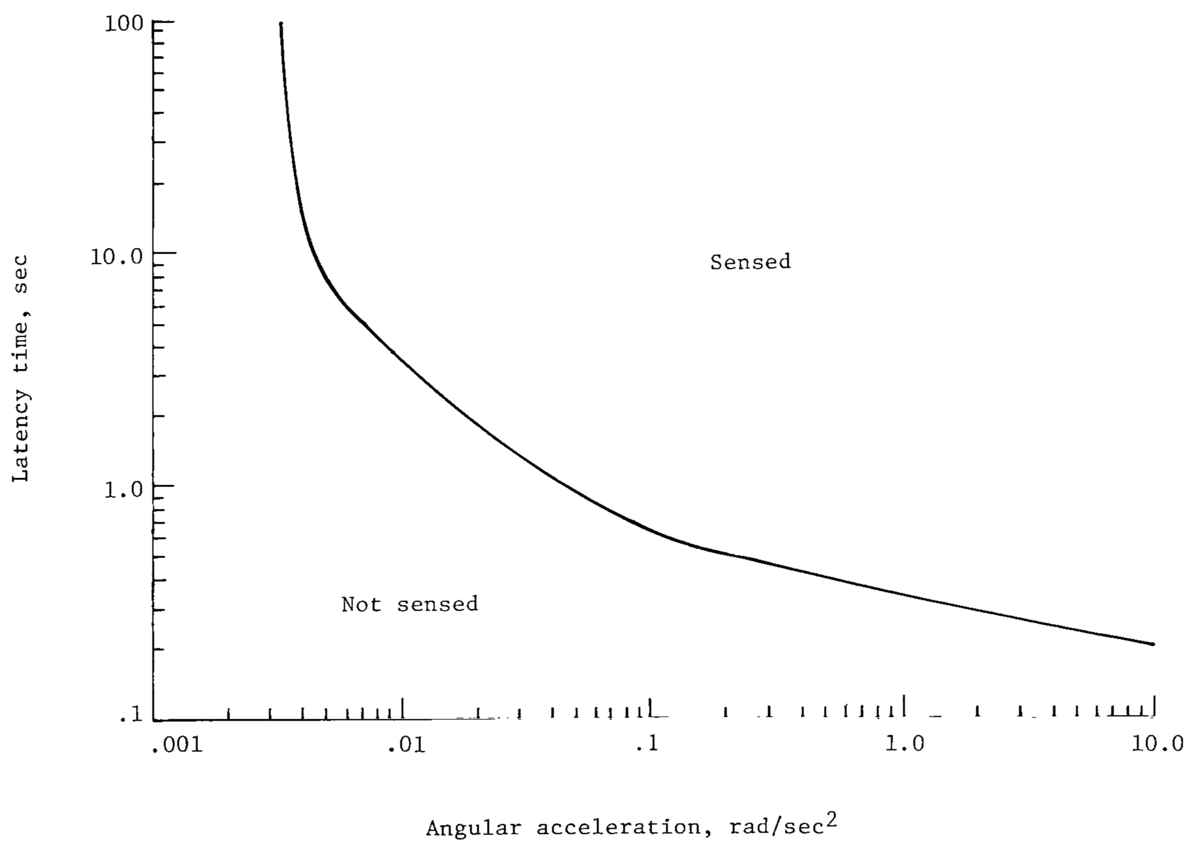
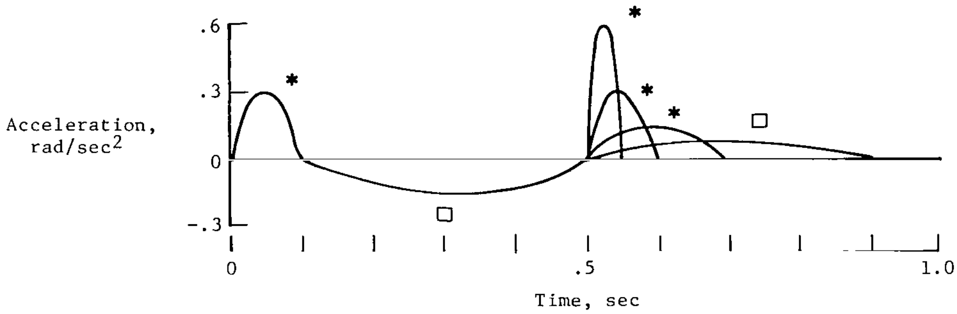
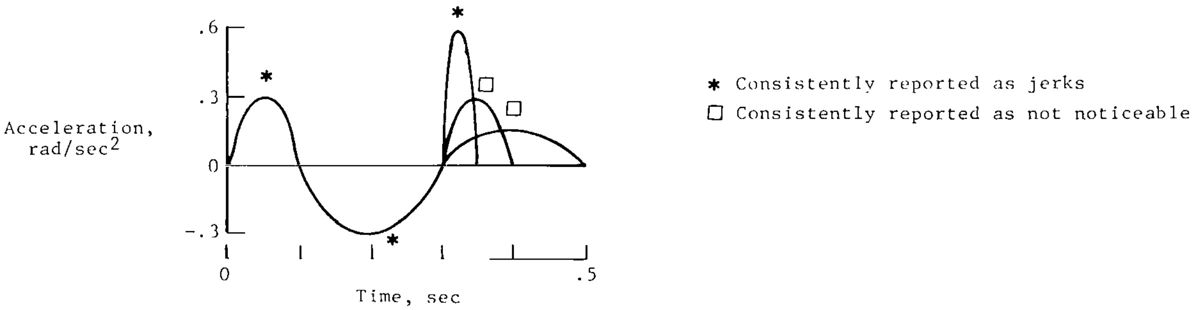


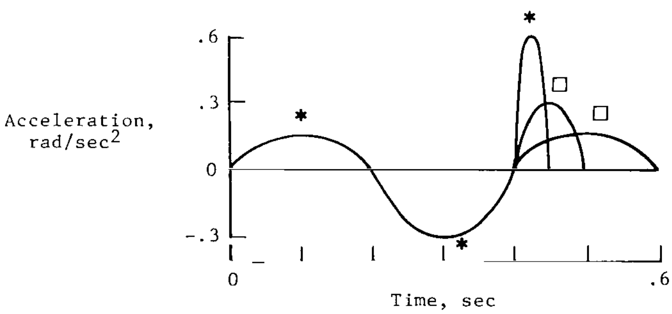
Figure 8.- Latency curve for constant angular accelerations.



(a) 0.5 ratio.



(b) 1.0 ratio.



(c) 2.0 ratio.

Figure 9.- Acceleration profiles, below-velocity thresholds.

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16. Abstract

Results are presented for two transient motion sensing experiments which were motivated by the identification of an anomalous roll cue (a "jerk" attributed to an acceleration spike) in a prior investigation of realistic fighter motion simulation. The experimental results suggest the consideration of several issues for motion washout and challenge current sensory system modeling efforts. Although the paper represents no sensory modeling effort in itself, the argument is made as to the necessity of incorporating into such models the ability to handle transient inputs of short duration (some of which are less than the accepted latency times for sensing) and representing separate channels for rotational acceleration and velocity sensing.

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