Human Perception of Angular Acceleration and Implications in Motion Simulation

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Data on human subjective response to angular acceleration collected on the Ames Man-Carrying Rotation Device are presented, and the implications of these data to motion simulation are discussed. Threshold data have been obtained for several stimulus durations, three axes of rotation, and two response indicators. These thresholds indicate that the average pilot can be very sensitive to angular acceleration. First-order approximations to the human dynamic response to angular accelerations are derived from four experiments, and resulting time constants vary from 4 to 10 sec, depending on the observer's task. It is demonstrated that a simple static washout concept requiring continuous rotations at subthreshold levels provides essentially useless reductions in simulator travel. Another washout scheme based on the dynamics of the vestibular system is considered. The variation in the apparent dynamics derived from the psychophysical data suggest that simulator washout characteristics may have to be tailored to each simulated flight configuration or piloting task.

Introduction

ONCE it has been decided to include motion capability in a flight simulator, a vast array or problems, options, and considerations develop. Although the cost and complexity of the simulator structure and associated computer facility increase rapidly as the motion and the motion capabilities are expanded, the most perplexing questions concern the effects of motion fidelity on the pilot. Consideration must be given to the effects of spurious motions resulting either from unavoidable mechanical deficiencies or from washout characteristics introduced deliberately to reduce the simulator travel required. One approach is to determine the effects of these spurious motion cues from available information on the response of man's motion perception system. A potential difficulty with this approach is that the data available on human perception of motion, in addition to being very limited in quantity, are for psychophysical tests in which the tasks are very different from piloting tasks.

Several investigators[1–8] have developed mathematical models for human response to angular acceleration and these constitute a step toward application of physiological and psychological data to manual control. The models reported in Refs. 1–4 apply to subjective responses, whereas, nystagmus, an involuntary oscillation of the eyeball, was the indicator of response for those reported in Refs. 5–8. The nystagmus results will not be discussed since they involve a reflex neural pathway that may not be appropriate to pilot control tasks. Stapleford[9] has taken another approach, that of obtaining a multimodality pilot model for the pilot's control operation in which the visual and motion feedback effects are separated. The application of either of these approaches to flight motion simulation may be limited by both the wide variability in perception of motion among pilots and by the dependency of motion perception on the task to be performed.

These effects can be illustrated with reference to existing threshold and suprathreshold data on human subjective responses to angular acceleration. Most of these data have been collected during the last three years employing the Ames Man-Carrying Rotation Device to provide the angular acceleration stimuli. These studies have been carried out in collaboration with B. Clark of San Jose State College. In this paper, the pertinent findings of several of these psychophysical studies are reviewed and their applications in motion simulation problems are discussed.

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Human Response to Angular Acceleration

The data to be presented define human sensitivity to angular acceleration in terms of thresholds and then a first-order approximation to the dynamics of the perceptual system. These data have been determined for two subjective indicators using accepted psychophysical methods. The two indicators consisted of the perception of rotation (POR) and a visual illusion first referred to as the oculogyral illusion (OGI) by Graybiel and Hupp.[10] The POR refers to the perception of rotary motion in the dark with the eyes closed, and the OGI is the visual perception of apparent motion of an isolated target that rotates with the observer in the enclosed cockpit. In the experiments to be disucssed, the target was a cube made of wire, 10 cm on a side, painted with luminous paint that was illuminated by an ultraviolet light in the darkened cab. The Ames Man-Carrying Rotation Device (MCRD) (Fig. 1) was used to rotate the observers for most of the studies to be discussed. The MCRD (described in detail in Ref. 11) consists of a simple rectangular cab supported by a stiff platform that rotates on a 4-ft-diam hydrostatic bearing to reduce friction and allow very precise control of the angular acceleration. The cab and platform are rotated by an electronically controlled d.c. motor. Figure 1 shows the slipring assembly mounted above the device and driven by its own synchro-controlled motor to further reduce friction. These efforts to minimize friction, allow the MCRD to accelerate through zero velocity without the spurious accelerations that are usually apparent to observers in earlier devices.

Thresholds for Response to Angular Acceleration

Engineers concerned with moving flight simulators are frequently interested in data on thresholds for response to angular acceleration as a guide for specifying the level of motion fidelity required. Figure 2 presents a summary of threshold data for 10-sec pulses of acceleration reported in Refs. 12 and 13. These thresholds were determined using a forced-choice double staircase procedure documented in

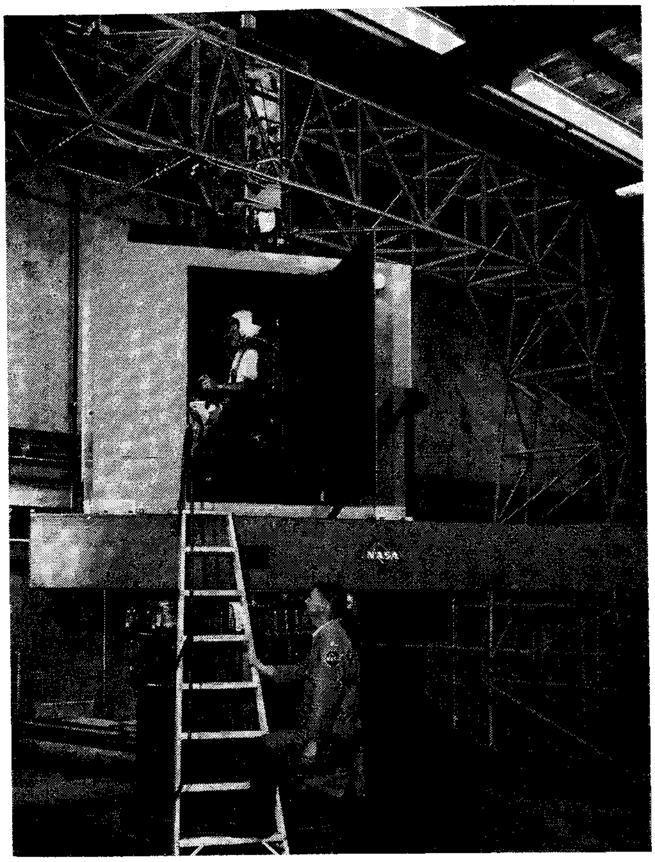

Fig. 1 Ames Man-Carrying Rotation Device.

Ref. 11, for POR and OGI response indicators for rotations about the z axis and for the POR about the three major body axes. The observers were in the same seated position and rotated about a vertical axis at their head. A special seat was employed for the x and y axis data that placed the observers on their backs and right sides, respectively. A comparison of these results with earlier data[14] may not be appropriate because of differences in method, rotation equipment, and numbers of subjects. It is obvious in Fig. 2 that most men with apparently normal vestibular organs are extremely sensitive to angular acceleration and that the range of individual differences for POR are large. The mean POR threshold about the z axis for 53 men was $0.41°/\text{sec}^2$ with a range of 0.05–$2.20°/\text{sec}^2$, and no significant difference was found between the x, y, and z axis thresholds for a smaller group of 18 observers. In fact, the mean thresholds about the x and z axes were identical to the second decimal at $0.41°/\text{sec}^2$ compared to $0.67°/\text{sec}^2$ for the y axis. The range of thresholds about all axes was large as would be expected from the z axis data on 53 men. Similarly, the study comparing POR and OGI resulted in mean thresholds of 0.37 and $0.11°/\text{sec}^2$, respectively, for 32 observers and a substantially smaller range of 0.04–$0.28°/\text{sec}^2$ for the OGI. Also noteworthy is the skewness of the thresholds toward the low stimulus levels evident in the results presented in Fig. 2.

At least as important as the threshold values quoted are the findings that the correlations between the various conditions are not significantly different from zero. In other words, an individuals z axis POR threshold cannot serve as a basis for predicting either his x or y axis POR threshold or his z axis OGI threshold. In the case of the POR-OGI comparison, several reasons have been suggested previously.[12] The most likely explanation was felt to be that, although these two indicators are the results of stimulation of the semicircular canals, relatively independent psychophysical mechanisms are involved. Similarly, the lack of significant correlation between the thresholds for pairs of axes would

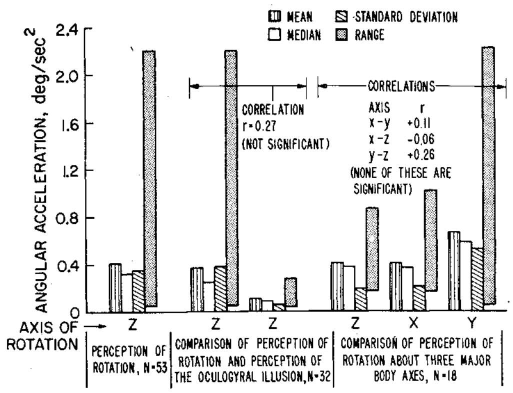

Fig. 2 Threshold data for 10-sec pulses of angular acceleration.

substantiate differences in the perceptual system between axes. One might expect that the z axis threshold would not be related to the other two since the horizontal pair of canals is stimulated maximally, whereas the two pair of vertical canals are primarily involved in the x and y axis threshold measures. Hence, the POR sensitivity about each of the major body axes may involve neurological pathways from the semicircular canals to the perception of rotation that contain independent components and that these are distinct from those responsible for the oculogyral illusion. The foregoing statements apply to threshold data obtained for pulses that are relatively long by standards for aircraft maneuvers.

Doty[15] reported on the effect of stimulus duration on OIG thresholds for stimulus durations from 0.5 to 6 sec. Figure 3 presents these data and indicates that the minimum threshold is produced for pulses with durations of 6–10 sec. These data result in products of angular acceleration and stimulus duration (αt) that exhibit a constantly increasing function with stimulus duration, in contrast to the long accepted Mulder's law that (αt) equals a constant for pulses shorter than 3 sec. Further examination of Fig. 3 indicates that these data for 10 observers do not indicate the skewness found in the thresholds determined for the 10-sec pulses.

Dynamic Models Deduced from Psychophysical Measures

Examination of the literature on the vestibular system reveals that the dynamics for the perception of rotation have been deduced from two types of experiments. These dynamics are based on the assumption that the semicircular canals alone are of primary importance in human response to angular acceleration and that the canal operation can be approximated by a first-order system. The earliest modeling effort that can be traced to van Egmond, Groen, and Jongkees[1] was based on the assumption that the semicircular canals operate as an overdamped torsion pendulum. Although the equations of motion for a pendulum are second order, the canals are so heavily damped that the effect of the shorter

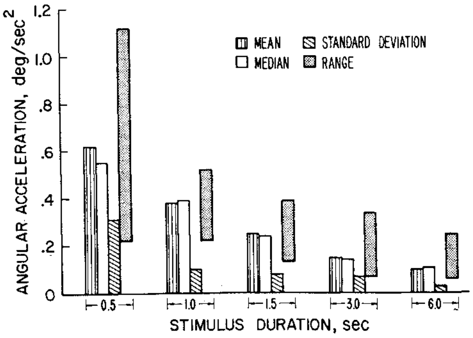

Fig. 3 Variation of threshold data for the oculogyral illusion with simulus duration.

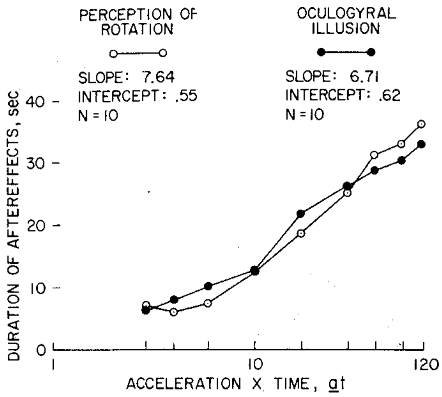

Fig. 4 Mean cupulograms for the preception of rotation and the oculogyral illusion for 10 observers.

time constant has been ignored frequently. Their method for defining the dynamics involved the use of cupulometry, which is a modification of the early turning test initiated by Barany. This technique requires the observers to report on the duration of their perception or rotation following an impulsive angular acceleration stimulation resulting from the sudden stopping of the rotating device from various constant velocity rotations from 5 to 60°/sec. This procedure requires that the rotating device accelerate the observer slowly to a constant velocity, allow him to remain at the constant speed for a period of time until the effects of the acceleration subside, and then stop the rotation in 0.5–3 sec. The observer then signals the end point of his perception of rotation, and the experimenter records the time between the cessation of motion and the observer's signal. These durations are then plotted as a function of the logarithm of the rotational velocity prior to the stop (Fig. 4), and the resulting curve is a cupulogram. The slope of the cupulogram is the time constant of the first-order system. Dobie[16] obtained cupulometric data on 1000 aircrew personnel that resulted in a mean slope of 7.7 sec for the OGI. Dockstader's[17] results (Fig. 4) for 10 observers yielded similar results with mean slopes of 7.64 sec for POR and 6.71 sec for OGI. An interesting sidelight on cupulometry is that the intercept has been referred to as a threshold in terms of velocity. Dockstader[17] found no relation between the threshold determined by cupulometry and the staircase method. Hulk and Jongkees[18] found that the slopes for normal individuals ranged from 4.0 to 16.0 sec. The time constant based on cupulometry therefore is 7 or 8 sec.

At least two investigators[2,3] have derived this time constant from data on reaction latencies. This determination assumes the cupula deflection is some minimum value at the time the observer responds, and this minimum deflection remains the same for different levels of acceleration. Therefore, it should be possible to fit the data on the variation of reaction latency with angular acceleration to a curve computed for a first-order system providing the proper time constant is chosen. Figure 5 presents the data and the curve for a 10-sec time constant obtained by Meiry[3] for three observers. Reaction latencies reported by Clark and Stewart[19] agree with those determined by Meiry. The curve was computed to pass through the data point at 1°/sec² corresponding to a reaction latency of approximately $2\frac{3}{4}$ sec. Although Meiry's data were for the POR, Guedry's[2] data for the OGI indicate longer reaction latencies.

If the assumption of the equal minimum cupula deflections is made for the OGI threshold data reported in Ref. 15, a procedure that seems more reasonable than for the reaction latency, another time constant can be computed. Figure 5 also presents the curve obtained assuming a 4-sec time constant for the threshold data. This curve was fitted through the data for 3-sec pulse.

A modification of Stevens' magnitude estimation procedure[20] results in a fourth set of data for computing the time constant. The procedure, similar to that used by Brown,[21] is described in detail in Ref. 22 and simply requires the observer report estimates of his perceived velocity of rotation frequently during and following stimulation by angular acceleration. The observer used a number scale he developed during several practice trials to report the magnitude of his perception of velocity. This subjective procedure would raise a question with many engineers as to the accuracy with which an observer could accomplish this task. Nevertheless, Elsner[23] determined the power fuction for both POR and OGI for angular acceleration impulses of 5-sec duration. The correlations between the magnitude estimates and the power function were found to be greater than 0.99 for the mean data for 12 observers for both indicators with only one individual's estimates resulting in a correlation of less than 0.96. Figure 6 from Ref. 24 is a sample of the curves representing the mean reports of 10 observers during and following four acceleration pulses of 6°/sec² for durations from 1 to 9 sec. It is obvious. of course, that these data represent the response of a system of higher than first order. Similar data were obtained for accelerations of 2°, 3°, and 9°/sec² producing acceleration impulses (or velocity prior to the stop in cupulometry) ranging from 2° to 81°/sec. If the durations from the end of the acceleration to the first zero magnitude estimate are plotted as a function of the acceleration impulse, a curve very similar to a cupulogram will be produced. The slope computed for these data result in a time constant of 4 sec.

Implications to Motion Simulation

The data presented can provide a basis for evaluating motion simulation washout schemes that involve modification of the angular acceleration inputs to the pilot. These data

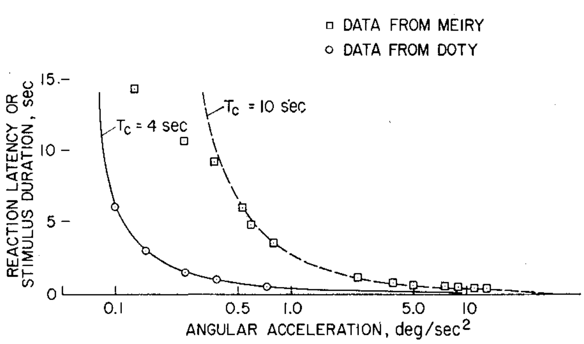

Fig. 5 Variation of reaction latency and threshold with angular acceleration.

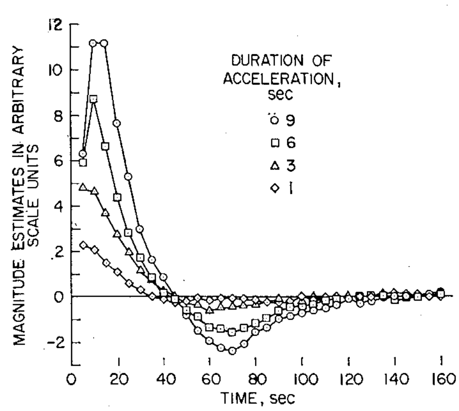

Fig. 6 Magnitude estimates for 10 observers; 6°/sec² angular accelerations varying in duration from 1 to 9 sec: estimates in the direction +; in the opposite direction −.

will be used to illustrate the difficulties that can occur in two washout concepts. First, threshold data will be used to demonstrate that an elementary washout concept that requires continuous rotations at subthreshold levels can provide only a small essentially useless reduction in linear travel. Second, dynamic models determined from psychophysical data do not describe the response of a simple mechanical system but do represent the operation of a complex psychophysiological system.

Assessment of an Elementary Washout (Static Washout Concept)

An essentially static washout concept that has persisted throughout the history of motion simulation assumes that the simulator cockpit can be rotated at subthreshold levels of angular acceleration to allow a component of gravity to be substituted for a sustained linear acceleration without the pilot being aware of the rotation. The sequence of events for this washout maneuver requires that the initial lateral or longitudinal acceleration be imposed and then a component of gravity gradually substituted for the linear acceleration by slowly rolling or pitching the cockpit at subthreshold levels. Similarly, it should be possible to reduce the lateral travel required to simulate a coordinated turn by reducing the bank angle resulting from the turn entry roll accelerations gradually to level flight, thereby reducing the lateral acceleration to zero. Combining the mean threshold for the OGI from Fig. 2 with Doty's data on the variation of threshold with stimulus duration (Fig. 3) allows the variation of the maximum angle of cockpit rotation resulting from subthreshold levels of angular acceleration to be computed. Figure 7 presents the variation of these maximum "unperceived angles of rotation" with time. Even the relatively long pulse of 10 sec results in a rotation of only 5.5°. The variation in the maximum simulated linear acceleration with time will be equal to the component of gravity resulting from the unperceived rotations in Fig. 7. As would be expected by the small angles, the linear accelerations are small with less than 0.1 g available in 10 sec.

The reduction in simulator travel can be computed for a simple special case. If one wishes to simulate a step change in linear acceleration, it is necessary to impose initially the linear acceleration that would be reduced gradually as the contribution of the gravity component increased. Figure 8 presents time histories of the desired acceleration, simulator linear acceleration, and the contribution of the gravity component. The travel required to provide the step acceleration can be computed simply as

$$l_d = (\tfrac{1}{2})a_d t^2$$

where a_d is the desired linear acceleration in ft/sec², t, time in sec, and l_d, travel without gravity substitution in ft. The angular acceleration threshold can be substituted for a_d if it is assumed that a_d is the maximum acceleration for which a

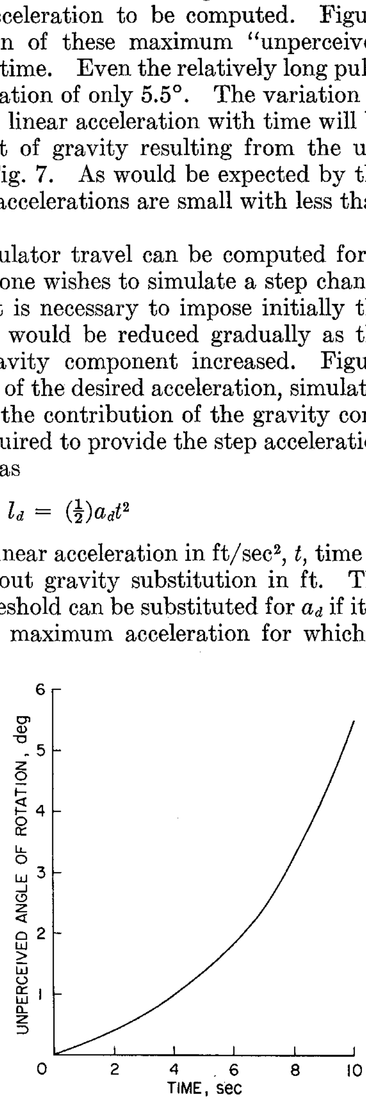

Fig. 7 Variation of "unperceived angles of rotation" with time.

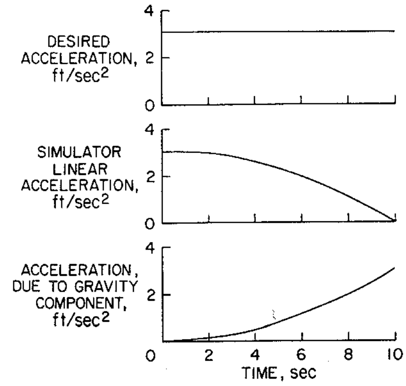

Fig. 8 Variation in the components of linear acceleration for an elementary static washout scheme.

component of gravity can be substituted. For small angles the travel becomes

$$l_d = \tfrac{1}{2}g[\tfrac{1}{2}(\alpha_{th}/57.3)t^2]t^2 = (g/4)(\alpha_{th}/57.3)t^4$$

where α_{th} is the angular acceleration threshold in deg/sec² and g is the acceleration of gravity in ft/sec². The travel l with gravity substitution can then be computed from

$$l = l_d - \int_0^t \int_0^t \tfrac{1}{2}g(\alpha_{th}/57.3)t^2 dt dt$$

which upon integration yields

$$l = l_d - \tfrac{1}{6}[(g/4)(\alpha_{th}/57.3)t^4]$$

and then substituting l_d for $g/4(\alpha_{th}/57.3)t^4$,

$$l = (\tfrac{5}{6})l_d$$

This saving of only $\frac{1}{6}$ of the travel by gravity substitution indicates that this concept of washout has little value in simulations of normal aircraft maneuvers. This reduction in travel would amount to only about 26 in 155 ft for a linear acceleration slightly less than 0.1 g.

There are several reasons for having reservations regarding the foregoing calculations and conclusions based on psychophysical data. The first and most basic reason concerns the definition of threshold. The thresholds quoted here are the mean of the angular acceleration values for thirty pairs of trials resulting from the forced-choice random double staircase procedure evaluated in Ref. 11, and not "the point at which a physiological or psychological effect begins to be produced," as threshold is defined by Webster.[25] In other words, a psychophysical threshold is a characteristic of a distribution of responses and not a distinct point. Therefore, it is possible for an individual to receive information and make correct judgments below his computed threshold occasionally and as a result, the unperceived turning angles would be less than indicated in Fig. 4. For a forced choice procedure the distribution of correct responses ideally ranges from 50% or chance at very low or zero accelerations to 100% at high accelerations with the threshold usually defined at or near the 75% point. Data for the study reported in Ref. 6 indicate that the observers would respond correctly to angular accelerations one-half their threshold nearly 65% of the time. This indicates that the observers were receiving useful information well below their threshold. In addition, as can be seen in Figs. 2 and 3, the lowest threshold for any individual was from $\frac{1}{2}$ to $\frac{1}{3}$ of the mean. The consequence of these statements is that the "unperceived rotations" and gravity components would have to be reduced by a factor of 5 or 6 to insure that no pilot would perceive the effects of this washout.

There are at least two more valid questions concerning the foregoing analysis of this washout scheme. First, is the OGI the proper indicator, and second, does the performance of

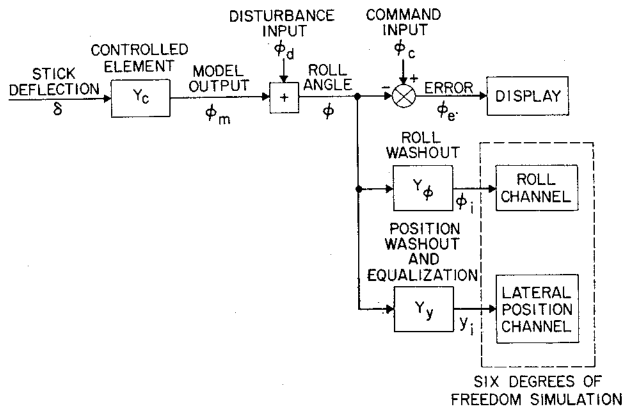

Fig. 9 Block diagram of experiment for developing a pilot model for visual and motion inputs.

realistic flight task reduce the pilot's sensitivity to angular accelerations? A short unreported study was conducted to obtain some information on the first question. Thresholds for four observers were determined for POR, OGI with the target, and OGI with the cab lights on and the observer viewing the cab wall. The results indicated that the two OGI conditions were very similar. Furthermore, the effect of an illuminated instrument panel at night, or under limited visibility conditions, would probably be more comparable with the isolated target than the cab wall. Therefore, the OGI would be the proper indicator for these computations. Regarding the second question, a simulation experiment designed to develop a model for response to visual and motion cues furnishes some information.

Stapleford[9] using both a disturbance input to effect the pilot's visual and motion loops and a command input to the visual systems (Fig. 9) was able to obtain separare describing functions for the visual and motion feedback loops. The pilot's task was precision control of vehicle roll angle in the presence of gusts composed of 10 sinusoids as a disturbance input and a similar sum of 10 sinusoids applied to the visual channel alone. Figure 10 presents the Bodi plots of a pilot's tracking performance fixed base and moving base for both the visual and motion effects. These curves indicate clearly that the pilot does indeed obtain lead information from the motion cues and thereby is able to increase the gain in the visual loop. The resulting increase in the crossover frequency of 0.5 to 1.5 rad/sec found in this experiment is not surprising. Returning to the discussion of the effect of a tracking task on a pilot's sensitivity to angular acceleration, it is noteworthy that the pilot in this experiment apparently obtained useful information from the motion cues at 0.5 rad/sec. The amplitude of the sinusoid near 0.5 rad/sec had a rms angular acceleration of 0.17°/sec^2 which is less than twice the mean OGI threshold found for 32 observers.[12] This evidence would indicate that the threshold for response to angular acceleration during a tracking task could not be much greater than the OGI thresholds determined by psychophysical methods.

Assessment of the "Dynamic Model" Washout Method

The foregoing statements indicate that an acceptable washout scheme based on the static washout concept would result in very small essentially useless reductions in simulator travel requirements. In another, more promising, washout technique the pitching and rolling motions present angular accelerations at high frequencies (greater than 0.3 rad/sec) and linear accelerations at lower frequencies. Senicori[26] using the available information on the dynamics of the semicircular canals applied a high pass filter to allow rotations to present the rolling accelerations above 0.3 rad/sec and a low pass filter to simulate lateral acceleration by a component of gravity below 0.25 rad/sec. The difficulties one might experience in attempting to deduce the appropriate break frequency for such a washout scheme can be inferred from the variation in the apparent time constants computed earlier.

Four sets of psychophysical data have been examined to determine the dynamics of human response to angular acceleration. The resulting time constants have varied from 4 to 10 sec for relatively simple tasks. The time constant differed by a factor of $2\frac{1}{2}$ when the observer's task was to merely indicate the direction of rotation. This was the case for the threshold, and reaction latency measures where the time constants were based on the assumption of equal minimum cupular deflections. Although it is true that the same observers did not participate in both experiments, the more important difference must involve the set of the observer. For the threshold determination, the observers must indicate the direction he is rotating on every trial. If he is not sure, he must respond with his best judgment of the direction. The observer's impression is that his responses are pure guesses at times. In studies of reaction latencies, the observers are usually instructed to respond as soon as they are reasonably sure of the direction of rotation. The observers' criteria for being reasonably sure and his response time probably vary with the level of acceleration. The threshold data therefore should involve more consistent observer operation than the reaction latencies and hopefully involve a more consistent response measure. It should be stated, however, that sufficient reaction latency data to estimate the time constant can be obtained in a half to one hour of testing, whereas, each threshold requires approximately 3 half-hour sessions. Therefore, a time constant based upon threshold measures requires from 7 to 15 times the time for one derived from reaction latency data.

Comparison of the dynamic characteristics derived from cupulograms based on the duration of the OGI with and without magnitude estimates causes concern. The only apparent difference is the greater level of attention of the observer when he is required to report magnitude estimates. Therefore, it must be concluded that the slight change in task modifies or switches between the neural pathways in some still to be understood manner. A difference in apparent time constants of nearly two to one for as simple a task as considered here leads one to ponder the magnitude of the differences that could result in a piloting task. In flight, the pilot must attempt to respond correctly to a wide range of vehicle dynamics, control and display characteristics, and task requirements. It is entirely possible, therefore, that the relative importance of motion cues will differ widely, and hence, force the pilot to modify his motion perception or response system to take advantage of these cues.

The investigations discussed were for human responses to the conscious perception or rotation or of the oculogyral illusion. It does not seem necessary for the pilot to become aware of motion in order to respond to motion cues. During

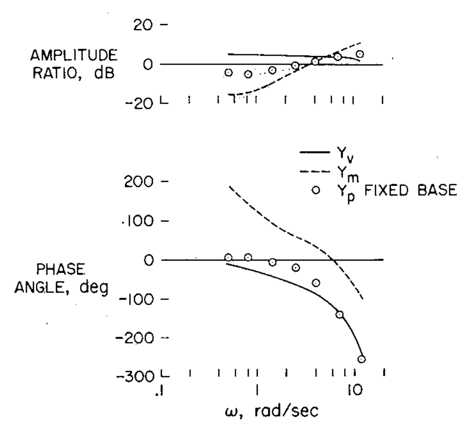

Fig. 10 Visual and motion feedbacks for $Y_c = K_c/s(s + 10)$.

his training, the pilot probably subconsciously transfers his normal balancing responses that he uses during standing or walking to control responses while flying an aircraft. As a result, normal control responses could involve motion information channels that differ in some details from those involved in subjective response to motion. Therefore, the evaluation of the effects of simulator washout on the pilot should be based on his control-response-to-motion-cue describing function as well as his opinion. If this is the case, one would expect psychophysical data to offer no more than a rough guide for evaluating pilot use of motion cues in flight or for determining the characteristics of a simulator washout system.

Concluding Remarks

This paper reviews the results of several investigations of human threshold and suprathreshold responses to angular acceleration and discusses the implications to motion simulation. The threshold data reveal that man is extremely sensitive to angular acceleration with a mean z axis threshold for 32 observers of $0.11°/\sec^2$ for the oculogyral illusion. Mean thresholds about the three major body axes were not found to be significantly different for 18 observers. It is noteworthy that these data indicate that the threshold about one axis cannot be used as a basis for predicting the thresholds about the other two axes for the perception of rotation or the z axis threshold for the oculogyral illusion. These results imply that each sensitivity measure involves neurological pathways that may contain relatively independent components. Data from four psychophysical experiments were examined to evaluate the dynamics of human response to angular acceleration in terms of a first-order system approximation. The resulting time constants varied from 4 to 10 sec with the normal range of individual differences for one of the procedures, cupulometry, reported as from 4 to 16 sec.

An elementary static washout concept was considered in terms of the reported threshold data. This washout was based on the assumption that the simulator cab could be rotated at subthreshold levels to allow a component of gravity to be substituted for a sustained linear acceleration without the pilot being aware of the rotation. It was determined that continuous rotations at subthreshold levels would furnish slightly less than 0.1 g in 10 sec for rotations at the mean threshold level. To ensure that no pilot would perceive these rotations, the angular accelerations would have to be reduced by a factor of 5 or 6. Hence, it is necessary to consider another washout concept. One obvious alternative would be to base the washout concept on the dynamics of the subjective responses. The difficulties involved in this choice would result from the range of both individual differences and range of mean time constants. These results imply that washout characteristics that are acceptable to one pilot may be completely unacceptable to another pilot or for a different task. The available psychophysical data indicate that the washout characteristics may have to be tailored empirically for each pilot and each task.

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