AIAA 80-0047R

New Engineering Approach to Motion Cueing Technology for Flight Simulators

Howard Jaslow*
Gould Inc., Melville, N.Y.

A new and unique approach to motion simulation is presented which provides a simple yet powerful engineering tool. From a study of the physical mechanisms of sensory receptors, perceived sensation of motion can be quantified. With this quantification, a method is presented to evaluate and specify requirements for motion platforms. Calculations are made of real cue regimes vs aircraft maneuvers and simulator excursion limits.

Nomenclature

$a_{x_a}, a_{y_a}, a_{z_a}$ = aircraft translational acceleration components along aircraft body axes $=\dot{u}+qw-rv, \dot{v}+ru-pw$, and $\dot{w}+pv-qu$, respectively
f = specific force magnitude, g
f_x, f_y, f_z = components of specific force along otolith coordinates
p, q, r = aircraft rotational velocity components along aircraft body axes
R_x, R_y, R_z = distance vector components (from aircraft c.g. to head c.g.) along aircraft body axes
u, v, w = aircraft translational velocity components along aircraft body axes
x, y, z = otolith coordinates (see Fig. 2)
x_H, y_H, z_H = head coordinates (see Fig. 2)
α = geometric tilt back angle of otolith (≈ 30 deg
δ = seat tiltback angle
θ, ϕ = head pitch (+ down) and roll (+ right) angles, respectively
θ_a, ϕ_a = aircraft pitch and roll angles, respectively

Subscripts

$(\ )_a$ = aircraft motion
$(\ )_s$ = simulator motion

Introduction

MOTION and force cueing is an engineering problem in need of an engineering solution. It is a perplexing problem which has been with us for many years. There have been some engineering attempts to solve it. But, for the most part they fell short because the actual aircraft motion was used as the basis for the motion methodology and that did not account for human perception. After these attempts failed to eliminate false cues, a scientific approach was taken with in-depth studies of the human sensory mechanisms.

The pendulum has swung from the cut-and-dry methods of the black art of motion simulation to the scientific approach. This change was needed. A meaningful direction had to be taken.

The scientific approach hypothesizes how the perceptual system might work, develops a mathematical model, and tests each hypothesis. Unfortunately, the state-of-the-art had not advanced enough to quantify human perception adequately. The simulation community is still in need of a solid, practical data base from which to define motion simulation requirements. This data base must reflect real life experiences. It must be practical. It has to relate to experienced sensations, not hypothesized sensations.

It is the intent of this paper to introduce a new engineering approach to meet these practical requirements. How far we can go with this approach is not yet known, but it does have potential. It represents a logical engineering approach which should complement, not negate, current investigations.

The approach is simple and commonly understood, but it is only now formulated into a quantitative technique. Basically, the premise is that everything can and must relate back to our prior experiences, i.e., to what we have learned.

By studying the human sensory mechanisms at the receptor level, we can quantitatively define the role the receptors play as the interface between us and the outside world. Everything we know of the outside world comes to us by way of our sensory receptors. We interpret the world through "the eyes of our receptors" and their repeated messages. Our past experiences have been built one upon another until we learned to give meaning to each sensation. The approach of this paper is to relate the receptor information to our past experiences.

The key is in the receptors and how they filter the enormous amount of information coming to us. Each receptor provides specific information, sometimes reinforcing other receptors, sometimes conflicting. Whether it reinforces or conflicts depends on how we learned to integrate the information based on our past experiences.

Each cue is recognized by the information that our sensory receptors are capable of accepting and how we have learned to interpret this information over a lifetime of experiences. This approach is termed the "stimulus vector approach."

The definition of the stimulus vector evolves naturally from the interface role of the sensory receptors. The stimulus vector is primarily important for sustained cueing technology. For onset cueing technology there is a natural extension from the stimulus vector to the sensation and perception vectors. The present paper concentrates on sustained cueing technology.

Stimulus Vector Approach

Over the past few years, the field of simulation has made great strides. One of the major breakthroughs in the approach to simulation can be succinctly stated as follows[1]: *Simulate, don't duplicate.*

Although this rule may now seem very obvious, all too often in the past the actual aircraft motion cues were duplicated. This rule is also implied in the papers by Albery, Young, et al.[2,3] where they note that it is the preception of

Received Jan. 8, 1980; presented as Paper 80-0047 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16, 1980; revision received May 22, 1980.

*Manager, Advanced Simulation Technology, Simulation Systems Division. Member AIAA.

motion that has to be duplicated, not the actual aircraft motion.

This approach of matching perceived sensation (MPS) represents a logical procedure for motion simulation: simulate, don't duplicate. The conventional approach of matching actual aircraft motion and then washing out this motion while returning the motion platform to its neutral position below the threshold of motion has been the most expedient approach, especially since few sensory models have been available. However false cues can arise in the conventional approach. If properly performed, the MPS approach should have no false cues since its objective is to match the same sensation.

Basically, in the MPS approach there is a transformation which relates the actual aircraft motion to the perceived sensation. Now, the key point is that the perceived sensation as experienced in the simulator must be the same as that experienced in the actual aircraft. To effect this simulation, we must know the transformation and we must have a quantitative measure of perceived sensation. The transformation can be derived from models of the sensory mechanisms. In seeking a quantitative measure of perceived sensation, we were guided by the success of the science of color vision where an infinite variety of spectra are reduced to three quantities, namely, the trichromatic coordinates. Two of these quantities are sufficient to define the hue, and the sum of the three defines the brightness.

To find a quantitative measure of perceived sensation, we stepped back to look at the entire picture. We asked "What does the student actually experience?" In Fig. 1, we show how the sensory receptors are the interface between the student and the outside world. He can only "feel" what the receptors are capable of transmitting. Each motion receptor is essentially mechanical in nature and will filter the external inputs. The filtered information is then applied to the sensory cells which transmit the neural signals for internal processing. The inner circle in Fig. 1 is very important for defining washout and sneakback algorithms. It is equally important to examine the sensory receptors since we need only match the filtered inputs to assure that the perceived sensation will be the same for both simulated and actual aircraft motion.

This approach to simulation has led us quite naturally to the concept of a stimulus vector. The stimulus vector is defined as an n-dimensional vector of which the components are the inputs that we receive from a particular sensory receptor. Each receptor has its own stimulus vector. The stimulus vector represents the n-dimensional coordinates of a stimulus in the sensation space.

The trichromatic coordinates used in color vision can be written as a color stimulus vector. The motion stimulus vector provides a unique way of defining each motion and tilt as we receive them. The characteristics of a stimulus vector can be

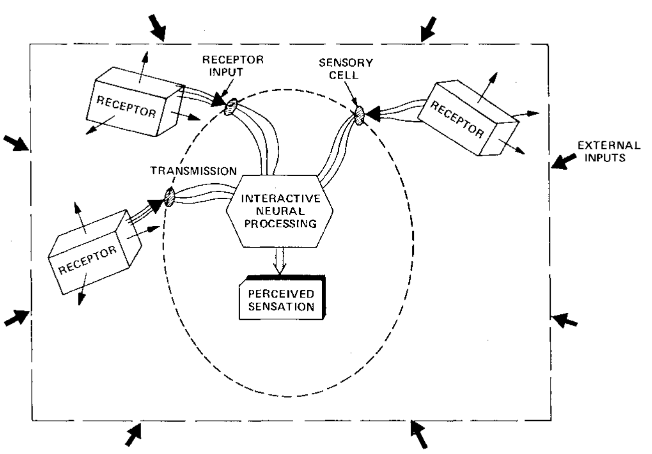

Fig. 1 Sensory receptors as interface with outside world.

summarized as follows:

1) It defines the outside world as we receive it.

2) It defines a unique perceived stimulation for each vector value.

3) It provides an answer to how different stimuli are input to each receptor.

4) The components are the individual inputs to each sensory cell.

5) It is valuable for determining realistic and false cues.

6) It is necessary for simulation input.

It is now obvious that we need to stimulate the receptors such that we reproduce perceived motion, not the actual motion. To remind us of this, we may now add another rule of simulation: *Do unto the receptors as they do unto you.*

As simulation develops and becomes more of an engineering science, we may expect additional rules of simulation.

If we match the components of a stimulus vector for an actual aircraft motion to that for a simulated motion, then we have a true simulation.

In summary, the approach is as follows.

1) Define the stimulus vector for each sensory receptor.

2) Find the stimulus vector components for each maneuver.

3) Reproduce the stimulus vector in the simulator.

Human Tilt Perception

By examining the biophysical mechanisms with which we receive our information from the outside world, a theory has been developed which provides a numerical coding for all motions. This theory, as applied to the tilt and linear acceleration sensing mechanism, is described in detail in Ref. 4.

The receptors sensitive to tilt and linear acceleration are located in the inner ear. These receptors are called the otoliths. Displacement of the otolith results in a neural signal. Each otolith can be displaced only along its own plane, i.e. motion normal to the otolith plane does not provide any signal. There are two types of otoliths, each located in a different part of the inner ear, one in the utricle, the other in the saccule. The utricular otolith is in a horizontal plane tilted back approximately 30 deg, and the saccular otolith is normal to the utricular otolith.

It would appear that the saccular otolith is primarily responsible for sensing gravity since it is nearly vertical, whereas the utricular otolith senses gravity through a 30 deg component. However, many authors have noted that, in animal experiments, removal of the saccular otolith has had no observable effect on the animal's balance, whereas removal of the utricular otolith has had a very pronounced effect.[5-9] On the other hand, other authors have measured neural signals from the saccular otolith.[10] It is our contention that the saccular otolith has a negligible effect on motion perception. This contention is further substantiated by the correlation of the theory presented in Ref. 4 with experimental data for head pitch down angles up to 35 deg and accelerations from 0 to 1.9 g. As such, we assume that the saccular otolith contribution can be neglected, even for large rotation angles and large accelerations.

Considering only the utricular otolith as the inner ear sensing mechanism for linear acceleration, the x and y coordinates of the specific force (gravity vector minus acceleration vector) in the otolith coordinate system (Fig. 2) is as follows:

$$f_x = f(\cos\alpha\sin\theta - \sin\alpha\cos\theta\cos\phi) \tag{1}$$

$$f_y = f\cos\theta\sin\phi \tag{2}$$

Several conclusions can be drawn from these equations.

1) Each acceleration input to the otolith is uniquely defined by two values: f_x and f_y. These are the stimulus vector components.

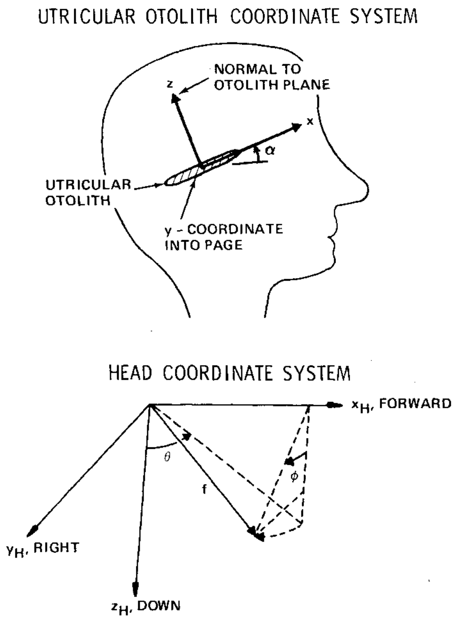

Fig. 2 Coordinate systems.

2) Therefore, all linear acceleration inputs can be mapped onto a "sensation plane" having the coordinates (f_x, f_y).

3) Any two linear acceleration inputs having the same value of (f_x, f_y) are sensed as being one and the same motion.

4) f_x and f_y are two variables which are functions of three independent variables. This implies that there indeed exists combinations of pitch, roll, and number of g which give rise to the same motion sensation.

5) The value of the stimulus vector (f_x, f_y) provides a definite numerical quantity to be used in the MPS approach to simulation.

It is evident that parameters such as f_x and f_y can be found for the other motion-sensing mechanisms, thus providing a means of quantifying all motion.

The application of Eqs. (1) and (2) to perceived sensation and its correlation with experiment is presented in Ref. 4. The approach taken there is to match these equations with the 1 g counterpart ($f=1$) which represents our past experiences to which we have learned to associate a perceived sensation. For the purpose of simulation however, it is sufficient to relate any input motion to its corresponding values of the stimulus vector (f_x, f_y). This is done in the following section.

Basic Motion and Force-Sensing Equations

Equations (1) and (2) express the otolith components of the specific force vector in terms of the magnitude f and orientation of the head (θ, ϕ). For simulation, we need to express f_x and f_y in terms of the aircraft and simulator motion input. These are given as follows with accelerations in g units.

$$f_x = -[\cos(\alpha+\delta)\sin\theta_a + \sin(\alpha+\delta)\cos\theta_a\cos\phi_a] - [a_{x_a}\cos(\alpha+\delta) - a_{z_a}\sin(\alpha+\delta)] - [(\dot{q}R_z - \dot{r}R_y)\cos(\alpha+\delta) - (\dot{p}R_y - \dot{q}R_x)\sin(\alpha+\delta)] - [\{p(qR_y + rR_z) - R_x(q^2+r^2)\}\cos(\alpha+\delta) - \{r(pR_x + qR_y) - R_z(p^2+q^2)\}\sin(\alpha+\delta)] \quad (3)$$

$$f_y = \cos\theta_a\sin\phi_a - a_{y_a} - [\dot{r}R_x - \dot{p}R_z] - [q(pR_x + rR_z) - R_y(p^2+r^2)] \quad (4)$$

Since the utricular otolith reacts only to forces parallel to its surface, the magnitudes of f_x and f_y are what we actually sense. The f_z component does not contribute to sensation. Therefore to simulate the tilt and linear acceleration actually sensed by the vestibular system, we equate only the stimulus vector components (f_x, f_y) of the simulation input to those of the aircraft input. This is the MPS approach discussed earlier. This is accomplished by using Eqs. (3) and (4) along with the following conditions:

$$f_{x_s} = f_{x_a} \quad (5)$$

$$f_{y_s} = f_{y_a} \quad (6)$$

Equations (3-6) completely define the simulator requirements for the aircraft motion. However, it should be noted that, although this simulation is true as regards the inner ear, there are other force-sensing mechanisms in the body which must be evaluated. The relative importance of each will determine the utility of the present approach which concentrates only on the vestibular-sensing mechanism.

The aircraft dynamics are fed in Eqs. (3) and (4) to define the stimulus vector (f_{x_a}, f_{y_a}). This defines the points on the sensation plane. Equations (3) and (4) along with the simulator degrees-of-freedom are then used to define the simulator inputs such that Eqs. (5) and (6) are satisfied, i.e., the same sensation is experienced in the aircraft.

Motion Platform Evaluation

Equations (3-6) are used to define the simulator motion cues and to evaluate the limits of real cue capability of specific motion platforms. These equations can also be used to define motion drive algorithms and the magnitude of false cues which may be inherent in a motion system.

Motion platforms have been built to simulate different degrees-of-freedom (DOF). Some have only pitch, others have pitch and roll, and still others have all six degrees-of-freedom (pitch, roll, yaw, heave, surge, and sway). There are 63 different combinations of degrees-of-freedom ranging 1-6 DOF. All 63 need not be considered since many are unrealistic. Nine have been examined using this new technique. These include a pure longitudinal 3-DOF system, a pure lateral system, and the seven combinations of heave, pitch, and roll. These are identified in Table 1.

Because space does not permit, only two of these cases are presented: pitch only and pitch and roll. (A supplement containing the evaluation of all nine is available by writing the author.)

Since we are presently concerned with the steady-state motion sensed by the otoliths, angular velocity and acceleration are omitted. For this condition, Eqs. (3-6) reduce to the following for the simulator motion with respect to the aircraft motion.

$$f_{x_a} = a_{z_s}\sin(\alpha+\delta) - a_{x_s}\cos(\alpha+\delta) - \cos(\alpha+\delta)\sin\theta_s - \sin(\alpha+\delta)\cos\theta_s\cos\phi_s \quad (7)$$

Table 1 Motion platforms evaluated

Number of degrees-of-freedom	Simulator degree-of-freedom: Pitch	Roll	Heave	Surge	Sway
1	X				
1		X			
1			X		
2	X	X			
2	X		X		
2		X	X		
3	X	X	X		
3 (longitude)	X		X	X	
2 (latitude)		X			X

$$f_{y_a} = -a_{y_s} + \cos\theta_s \sin\phi_s \tag{8}$$

where $(\ )_a$ = aircraft conditions defined by Eqs. (3) and (4).

Pitch-Only Degree-of-Freedom Simulator

For a pitch-only simulator

$$a_{x_s} = a_{y_s} = a_{z_s} = \phi_s = 0$$

and Eqs. (7) and (8) reduce to

$$\sin(\theta_s + \alpha + \delta) = -f_{x_a} \tag{9}$$

$$f_{y_s} = 0 \neq f_{y_a} \tag{10}$$

f_{x_a} and f_{y_a} are defined by substituting the actual aircraft motion into Eqs. (3) and (4).

Note that Eq. (10) cannot be satisfied in general. This is expected since a pitch-only simulator cannot provide lateral motion simulation, it can only simulate longitudinal motion.

For aircraft longitudinal motion, Eq. (9) states that real cues are provided when

$$\theta_s = \sin^{-1}(-f_{x_a}) - (\alpha + \delta) \tag{11}$$

This equation defines the simulator motion with respect to the aircraft motion.

For a pitch-only simulator, there is a limit to the simulation capability, namely, the resultant number of g cannot exceed one. Mathematically, this is seen by noting that

$$|\sin(\theta_s + \alpha + \delta)| = |f_{x_a}| \leq 1 \tag{12}$$

Beyond this limit, the pitch-only simulator is not capable of providing meaningful cues. This equation is equivalent to restricting sensations to be within the unit circle on the sensation plane.

For climb maneuvers at constant forward acceleration, Eq. (3) for f_{x_a} reduces to

$$f_{x_a} = -\sin(\alpha + \delta + \theta_a) - a_{x_a}\cos(\alpha + \delta) \tag{13}$$

Equations (11) and (13) define the simulator pitch angle, namely

$$\theta_s = \sin^{-1}[\sin(\alpha + \delta + \theta_a) + a_{x_a}\cos(\alpha + \delta)] - (\alpha + \delta) \tag{14}$$

Since physical constraints limit the capability of a motion platform, it is important to identify these limitations. From Eqs. (12) and (13), the maximum capability that a pitch-only motion platform can provide for climb maneuvers is defined by

$$-1 \leq \sin(\alpha + \delta + \theta_a) + a_{x_a}\cos(\alpha + \delta) \leq 1 \tag{15}$$

Imposing a ± 0.2 radian limit on the motion platform pitch, the capability is defined by

$$\sin(\delta + 17.2\ \text{deg}) \leq \sin(\alpha + \delta + \theta_a) + a_{x_a} \times \cos(\alpha + \delta) \leq \sin(\delta + 40.2\ \text{deg}) \tag{16}$$

These limits are plotted in Fig. 3 for an erect seat ($\delta = 0$); those due to Eq. (15) are defined by the double cross-hatch and those due to Eq. (16) are bounded by the single cross-hatch. The real cues that can be provided are clearly seen in this figure. A similar plot is presented in Fig. 4 for a seat tilt-back angle of $\delta = 30$ deg. Note the different limits for each seat angle.

Pitch and Roll Degrees-of-Freedom Simulator

For a pitch and roll only simulator, $a_{x_s} = a_{y_s} = a_{z_s} = 0$ and Eqs. (7) and (8) reduce to

$$f_{x_a} = -\cos(\alpha + \delta)\sin\theta_s - \sin(\alpha + \delta)\cos\theta_s\cos\phi_s \tag{17}$$

$$f_{y_a} = \cos\theta_s \sin\phi_s \tag{18}$$

Since the envelope of these equations is the unit circle on the sensation plane, only those aircraft motions with f_{x_a} and f_{y_a} falling within this unit circle can be simulated. This envelope is meaningful only if the simulator pitch and roll are unrestricted. However, practical constraints limit pitch and roll.

Figure 5 shows the effect of real simulator constraints on motion simulation capability. In this figure, the angular constraints are ± 0.2 radian. Two cases are presented: erect seat and seat tilt-back angle of 30 deg. The regions of real cues can clearly be seen. Those maneuvers with sensation plane coordinates (f_x, f_y) outside the shaded regions will experience false cues on the motion platform. It can be seen that aircraft with zero seat tilt-back and those with a 30 deg seat tilt-back do not have common maneuvers which can be simulated by the same motion platform.

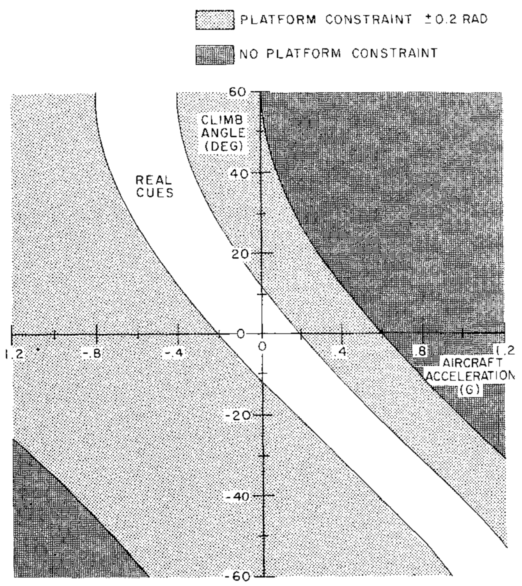

Fig. 3 Pitch-only simulator, real cue limits, erect seat.

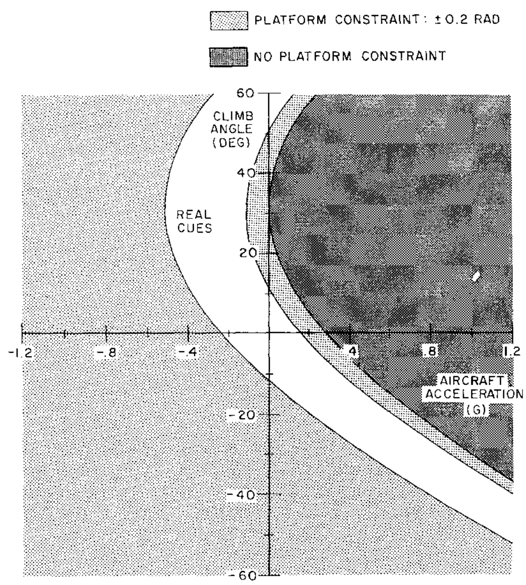

Fig. 4 Pitch-only simulator, real cue limits, 30 deg seat tilt.

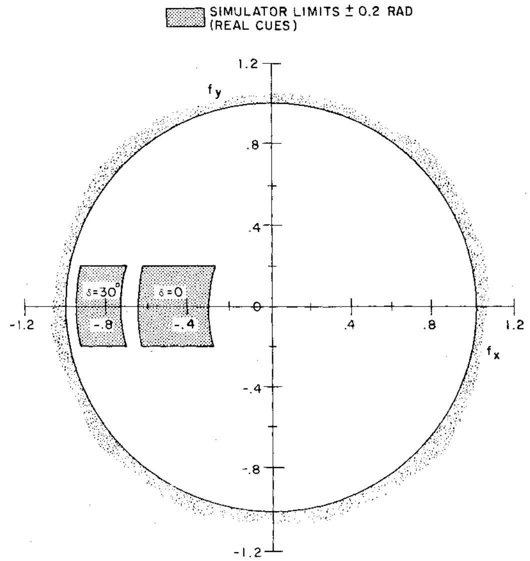

Fig. 5 Pitch and roll degrees-of-freedom simulator capability.

Superposition of the aircraft maneuvers on the sensation plane as defined by Eqs. (3) and (4) will serve as a design aid in defining the motion platform excursion limits. This will graphically identify those maneuvers which can be fully or partially simulated with real cues and those which will induce false cues. As an engineering tool, it can also be used to evaluate changes in platform design to accommodate required maneuvers or, conversely, it can be used to set requirements on motion platforms.

Conclusions

A new engineering approach to cueing technology has been derived: the stimulus vector approach. Although we have barely scratched the surface with the potential of this approach, we have demonstrated that considerable information can be obtained with the stimulus vector approach.

The next logical step is to define a sensation vector. The stimulus vector defines our interface with the outside world; it defines what we can accept from the external environment. The sensation vector will define the sensation we experience from the stimulus vector; the effects of adaptation, threshold, delay, etc., transform the stimulus vector into the sensation vector. Beyond this, there is the perception vector which integrates the different sensation vectors into a perceived state.

Several keypoints relating to this new approach are presented below.

1) Stimulus vector. This new concept can be applied to all motion- and force-sensing receptors. The stimulus vector approach can be used for a rational evaluation of different degree-of-freedom motion platforms.

2) Sensation vector. The sensation vector is an extension of the concept of a stimulus vector, which can be used for both sustained and onset cueing technology.

3) Sensation plane. We have shown that sensations can be plotted on a sensation plane defined by the receptor components. All past experiences (i.e., all perceived sensations) can be superimposed on this sensation plane. This can be done analytically with known sensations and/or experimental tests can be run to fill in unknown regions on this plane. Where data are lacking, meaningful extrapolations can be made directly on the sensation plane. Any flight maneuver can be plotted directly on this sensation plane and the perceived sensation can be immediately identified. The sensation plane can be used to identify real and false cues arising in a motion platform.

4) Quantitative measure of sensation. The stimulus vector provides a quantitative measure of sensation which is directly related to prior experiences. Hypothesized sensations are not necessary.

5) Motion platform evaluation and requirements. This new engineering approach provides us with a simple evaluative technique and a new method of defining cueing requirements for motion platforms.

6) Equiperception flight maneuvers. The stimulus vector approach can be used to identify all those flight maneuvers having the same sensation. Evidently this can extend the capability of motion platforms. The details of equiperception maneuvers are presented in Ref. 11.

Acknowledgment

This work was performed as part of an independent research and development program at the Simulation Systems Division of Gould, Inc.

References

[1] Heintzman, R.J. and Shumway, D.A., "A Systematic Approach to Visual System Requirements and Developments," *Proceedings of the AIAA Visual and Motion Simulation Conference,* April 26-28, 1976.

[2] Albery, W.B., Gum, D.R., and Hunter, E.D., "Future Trends and Plans in Motion and Force Simulation Development in the Air Force," *Proceedings of the AIAA Visual and Motion Simulation Conference,* April 26-28, 1976.

[3] Borah, J., Young, L.R., and Curry, R.E., "Sensory Mechanism Modeling," Air Force Human Resources Laboratory, AFHRL-TR-77-70. Oct. 1977.

[4] Jaslow, H., "Human Tilt Perception in a Dynamic Environment," *Aviation, Space and Environmental Medicine,* Vol. 50, No. 6, 1979, pp. 594-598.

[5] Guyton, A.C., *Textbook of Medical Physiology,* W.B. Saunders Co., New York, 1968, Chap. 54.

[6] Leukel, F., *Introduction to Physiological Psychology,* C.V. Mosby Co., New York, 1972, pp. 167-175.

[7] Carterette, E.C. and Friedman, M.P., "Biology of Perceptual Systems," *Handbook of Perception,* Vol. III, 1973.

[8] Geldard, F.A., *The Human Senses,* John Wiley & Sons, New York, 1972.

[9] Wilentz, J.S., *The Senses of Man,* Crowell, New York, 1968.

[10] Fernandez, C., Goldberg, J.M., and Abend, W.K., "Response to Static Tilts of Peripheral Neurons Innervating Otolith Organs of the Squirrel Monkey," *Journal of Neurophysiology,* Vol. 35, No. 6, 1972, pp. 978-997.

[11] Jaslow, H., "Equiperception Maneuvers," *Aviation, Space and Environmental Medicine,* Vol. 51, No. 9, 1980, pp. 867-871.