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Critique of the Gravity Vector Alignment Method for Motion Simulation

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Conventional simulators tilt the motion platform to align the gravity vector with the resultant specific force vector of the aircraft. But, false cues can still arise with the gravity vector alignment method. In fact, this method provides real cues only for limited maneuvers. In this paper, a new theory of tilt and motion perception is reviewed. Equations defining the current gravity vector alignment approach and its modification with the new approach are derived. A technical explanation is given of inherent errors and limitations of the conventional approach, along with a quantitative comparison with the new approach.

Nomenclature

a	= aircraft acceleration vector
$a_{x_a}, a_{y_a}, a_{z_a}$	= aircraft translational acceleration components along aircraft body axes $= \dot{u} + qw - rv, \dot{v} + ru - pw$, and $\dot{w} + pv - qu$, respectively
e_1, e_3	= unit vectors for the aircraft body x and z axes, respectively
f	= specific force magnitude, g
f_x, f_y, f_z	= components of specific force along otolith coordinates
g	= gravitational vector
n	$= a/g =$ number of g
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
α	= geometric tiltback angle of otolith $\simeq 30$ deg (for more accurate results use $\alpha = 28.7$ deg)
δ	= seat tiltback angle
θ, ϕ	= pitch and roll angles of specific force with respect to head coordinate system (see Fig. 1), respectively
θ_a, ϕ_a	= aircraft pitch and roll angles, respectively
θ_f	= angle between aircraft z axis and specific force vector
θ_s	= simulator tilt angle

Subscripts

a	= aircraft motion
p	= perceived state
s	= simulator motion

Background

IT is common practice[1-4] with simulator motion drive algorithms to tilt the motion platform so as to align the gravity vector acting on the simulator with the resultant specific force vector of the aircraft. That is, the force of gravity in the simulation exercise is used to simulate a steady aircraft acceleration.

Quoting from Parrish,[1] "the representation of sustained longitudinal force cues through rotational tilt to align the gravity vector is almost standard practice in motion simulation." This method stems from the work of Schmidt and Conrad[2-3] where they developed the motion drive equations. Quoting from their work,[2] "...the specific forces resulting from motion of a simulated aircraft should be presented to the pilot in the cab so that it has the same direction with respect to the cab as the true specific force would have with respect to the cockpit of the aircraft." This method represents a good, intuitive approach, especially within the limited state-of-the-art at the time. However, it is not without error.

In this method, it is tacitly assumed that as long as both the simulated and actual aircraft force vectors make the same angle with respect to the aircraft, then the sensation experienced by the trainee is the same as in the aircraft. This is assumed regardless of the magnitude of the aircraft acceleration. It will be shown below that this is not a valid assumption.

New Theory of Tilt and Motion Perception

A new theory of tilt and motion perception[5-7] and the experimental data[8] supporting this theory[5] clearly demonstrate that false cues can still arise with the gravity vector alignment method. This theory is based on the anatomical mechanism for sensing sustained specific forces as experienced in a constant acceleration state or when tilted in a gravitational field, or a combination of both. This physical mechanism in the inner ear, called the utricular otolith, is basically a platform which can only be displaced parallel to its surface. Acceleration normal to the otolith platform is not sensed.

The x and y components of the specific force (gravity vector minus acceleration vector) acting on the otolith in the otolith coordinate system (Fig. 1) are as follows:

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

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

The f_z component is not required since it acts normal to the otolith plane and is not sensed.

Several conclusions can be drawn from these equations:

1) Each acceleration input to the otolith is uniquely defined by the two values f_x and f_y.

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 exist combinations of pitch, roll, and number of g which give rise to the same motion sensation.

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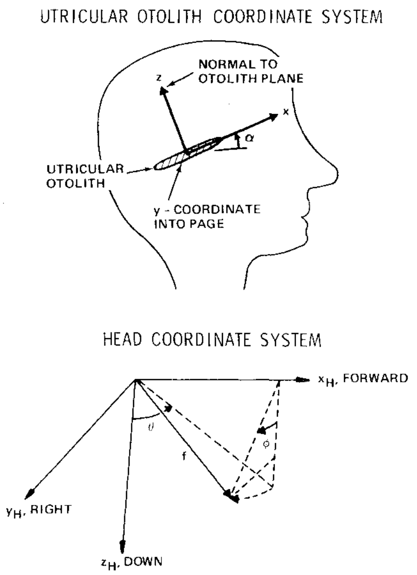

Fig. 1 Coordinate systems.

5) The value of (f_x, f_y) provides a definite numerical value to be used in quantifying tilt perception.

Equations (1) and (2) can be used to relate pitch angle to a combined pitch and acceleration experience. As shown in Ref. 5, for pitch only ($\phi=0$), Eq. (1) yields

$$\text{pitch and acceleration: } f_x = f\sin(\theta-\alpha) \quad (3)$$

$$\text{perceived pitch: } f_x = \sin(\theta_p-\alpha) \quad (4)$$

For the same input f_x to the otolith sensor coming from a combined pitch and acceleration experience [Eq. (3)] and from a normal experience in a 1 g field [Eq. (4) with $f=1$], there results for the perceived pitch angle

$$\theta_p = \sin^{-1}[f\sin(\theta-\alpha)]+\alpha \quad (5)$$

This equation is plotted in Fig. 2 for α = 28.7 deg where it can be seen how the specific force f influences the perceived pitch angle. For example, a pitch of 15 deg with a specific force of 2 g results in a perceived pitch of zero. Note also that all curves pass through $\theta=28.7$ deg because a specific force acting at this head pitch down angle is normal to the otolith and any change in specific force acting normal to the otolith is not sensed.

Equations (1) and (2) express the otolith components of the specific force vector in terms of the magnitude (f) and orientation of f with respect to 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:

$$\begin{aligned} f_x = &-[\cos(\alpha+\delta)\sin\theta_a+\sin(\alpha+\delta)\cos\theta_a\cos\phi_a] \\ &-[a_{x_a}\cos(\alpha+\delta)-a_{z_a}\sin(\alpha+\delta)] \\ &-[(\dot{q}R_z-\dot{r}R_y)\cos(\alpha+\delta)-(\dot{p}R_y-\dot{q}R_x)\sin(\alpha+\delta)] \\ &-[\{p(qR_y+rR_z)-R_x(q^2+r^2)\}\cos(\alpha+\delta) \\ &-\{r(pR_x+qR_y)-R_z(p^2+q^2)\}\sin(\alpha+\delta)] \end{aligned} \quad (6)$$

$$\begin{aligned} f_y = &\cos\theta_a\sin\phi_a-a_{y_a}-[\dot{r}R_x-\dot{p}R_z] \\ &-[q(pR_x+rR_z)-R_y(p^2+r^2)] \end{aligned} \quad (7)$$

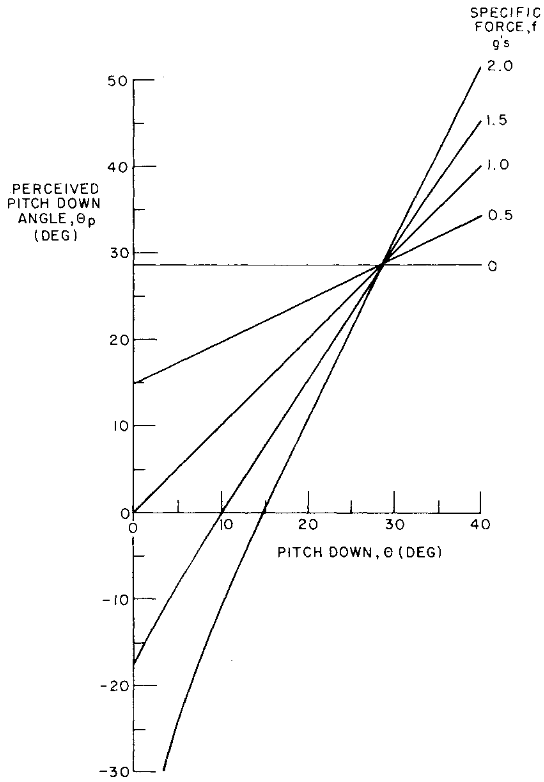

Fig. 2 Effect of specific force on perceived pitch angle.

Note that the f_z component is not required since it does not contribute to sensation.

For simulation with real cues, f_x and f_y must be the same in the simulator as they are in the aircraft. Therefore, Eqs. (6) and (7) are used as the basis for critiquing and modifying the gravity vector alignment method.

Conventional Gravity Vector Alignment Method

The conventional gravity vector alignment method directs the line of force acting through the trainee in the simulator to be the same as he would actually experience in the aircraft. This appears to be a logical approach for simulating sustained acceleration; and it would be correct if the magnitude of the forces were the same in both cases. But, this is not necessarily so. The false cues introduced by this method are discussed in the next section.

To assure that the lines of force in the simulator and the aircraft are the same, the current practice is to tilt the simulator such that the angle subtended by the body axis with respect to the gravity vector is the same as that in the aircraft between the body axis and the specific force vector. This method is illustrated in Fig. 3 for longitudinal motion with aircraft acceleration along the body x axis. For this case, the angle θ_f between the aircraft z axis and the specific force vector is derived as follows.

The specific force vector is given by

$$\boldsymbol{f}=\boldsymbol{g}-\boldsymbol{a} \quad (8)$$

From Fig. 3,

$$\boldsymbol{g} = -g\sin\theta_a\boldsymbol{e}_1 + g\cos\theta_a\boldsymbol{e}_3 \quad (9)$$

$$\boldsymbol{a}=a\boldsymbol{e}_1 \quad (10)$$

Therefore,

$$\boldsymbol{f} = -(a+g\sin\theta_a)\boldsymbol{e}_1 + g\cos\theta_a\boldsymbol{e}_3 \quad (11)$$

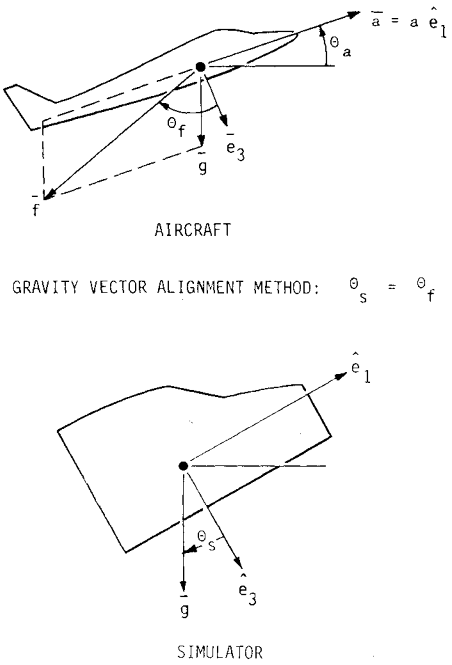

Fig. 3 Gravity vector alignment method.

The angle θ_f between the body z axis and the specific force vector is thus given by

$$\tan\theta_f = \frac{f\cdot(-e_1)}{f\cdot e_3}$$

therefore

$$\tan\theta_f = \frac{n+\sin\theta_a}{\cos\theta_a} \tag{12}$$

For the same line of action on the simulator, we impose the condition that the simulator tilt angle θ_s is equal to θ_f. Therefore,

$$\tan\theta_s = \frac{n+\sin\theta_a}{\cos\theta_a} \tag{13}$$

θ_s is the gravity vector alignment angle or simply the tilt angle of the simulator (see Fig. 3). This equation is plotted in Fig. 4.

False Cues

The gravity vector alignment method assures the same direction of the net force acting through the pilot's body for both simulator and aircraft regardless of the magnitude of the force (or, equivalently, number of g). But as shown in Fig. 2, the number of g strongly influences the perceived pitch angle which must be matched in the simulator,[6] not the line of action of the force. Thus, the gravity vector alignment method does indeed give rise to false cues. Quantitatively, this is described below.

For an aircraft with constant longitudinal acceleration and pitch, Eqs. (6) and (7) reduce to

$$f_x = -\sin(\theta_a+\alpha) - n\cos\alpha \tag{14}$$

$$f_y = 0 \tag{15}$$

The perceived pitch is obtained from the zero acceleration condition for which

$$f_x = -\sin(\theta_{a_p}+\alpha) \tag{16}$$

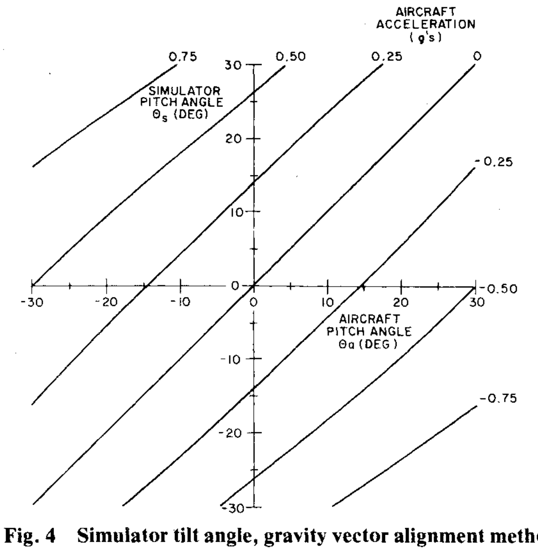

Fig. 4 Simulator tilt angle, gravity vector alignment method.

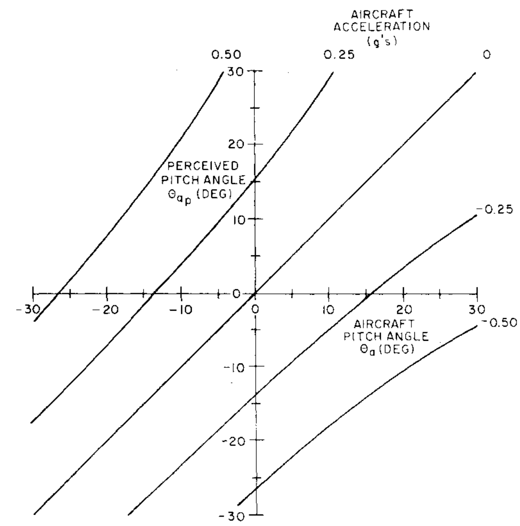

Fig. 5 Effect of aircraft acceleration on perceived pitch angle.

For simplicity, the seat tiltback angle δ in Eq. (6) is set equal to zero in Eqs. (14) and (16) and subsequent calculations. It can be included by replacing α with $(\alpha+\delta)$ using the appropriate aircraft and simulator seat tiltback angles.

Equating Eqs. (14) and (16), there results

$$\theta_{a_p} = \sin^{-1}[\sin(\theta_a+\alpha) + n\cos\alpha] - \alpha \tag{17}$$

This equation is plotted in Fig. 5 for $\alpha = 28.7$ deg where it can be seen that the effect of aircraft acceleration on perceived pitch can be significant. For example, accelerating at 0.25 g at a steady climb angle of 10 deg results in a perceived pitch of 29 deg.

For the simulator tilted through the angle θ_s by the gravity vector alignment method, the perceived pitch θ_{s_p} is equal to θ_s since the simulator is in a zero acceleration state for sustained cueing. Therefore, from Eq. (13),

$$\theta_{s_p} = \theta_s = \tan^{-1}\left[\frac{n+\sin\theta_a}{\cos\theta_a}\right] \tag{18}$$

From Eqs. (17) and (18) we can compare the pitch perceived in the simulator θ_s from the gravity vector alignment method with the pitch perceived in the aircraft, θ_{a_p}. Table 1 lists some of these values.

As can be seen, there are some conditions for which the gravity vector alignment method results in perceived pitch

Table 1 Comparison of perceived pitch

Aircraft flight condition n	θ_a, deg	Perceived pitch in aircraft θ_{a_p}, deg	Perceived pitch in simulator θ_{s_p}, deg
0.25	0	16	14
0.50	−10	21	18
0.50	0	38	27
0.75	−10	49	30

comparable to that in the aircraft. However, there are many other conditions for which false cues ($\theta_{s_p} \neq \theta_{a_p}$) are significant. The psychophysical significance of these false cues has to be determined separately and will depend on such factors as student tasks being performed, visual cueing, g-seat cueing, and other information (pertinent and extraneous) received by the student.

Modified Gravity Vector Alignment Method

In Ref. 6, it is shown how to use Eqs. (6) and (7) to simulate sustained motion without introducing false motion cues. In addition, the limits on the aircraft maneuvers and motion platform excursions are evaluated for real and false cue regimes.[6] The basis for quantitatively defining real cues is that the value of the otolith components (f_x, f_y) in the aircraft [Eqs. (6) and (7)] must be the same as that in the simulator.[6] This assures that the perceived sustained motion in the simulator is the same as that in the aircraft.

The method developed in Ref. 6 should be used for all sustained motion simulation. In that reference, several different degree-of-freedom motion platforms are evaluated. For a platform tilted in pitch, the simulator tilt angle required to provide real cues for simulating an aircraft undergoing climb maneuvers is given by[6]

$$\theta_s = \sin^{-1}[\sin(\theta_a + \alpha) + n\cos\alpha] - \alpha \qquad (19)$$

[Note that this equation is the same as Eq. (17) since $\theta_{s_p} = \theta_s$ and it is required to have $\theta_{s_p} = \theta_{a_p}$.]

This equation represents a modified gravity vector alignment method as contrasted to Eq. (13) used in the conventional approach.

The general tilt orientation in both roll and pitch corresponding to real cues for simulating combined aircraft tilt and acceleration is presented in Ref. 6. It is this new method which should be used in lieu of or as a modified form of the gravity vector alignment method.

Conclusions

The gravity vector alignment method provides a simple, direct approach to simulating sustained motion cues. However, as demonstrated in this paper, this approach can still lead to false cues. Based on a new theory of tilt perception, the gravity vector alignment method should be replaced by the method of Ref. 6.

In this new approach,[6] the real cue regime is increased considerably, constrained only by the physical excursion limits and by the 1 g limit of a tilted platform simulating sustained motion.

The question naturally arises, "Do the transient aspects of perceived motion mask the effects of sustained acceleration?" To answer this question, further experimentation is required. The best test, of course, is to experimentally evaluate the conventional gravity vector alignment method with the modified version presented here using pilots as subjects. This comment also applies to the influence of the nonvestibular sensors as well, since they are generally rapidly adapting sensors. If the sustained cues are of sufficient duration, then the transient specific forces will probably have little effect on sustained force perception. However, that is a separate issue. The premise of this paper is that if the gravity vector alignment method is to be used to provide sustained cues, independent of the influence of transient conditions, then it must be modified within the realm of sustained cueing.

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