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Spatial Disorientation During a Coordinated Turn

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During a banked turn without sufficient visual cues, a pilot can become disoriented and unknowingly enter into a graveyard spiral. This occurs as a consequence of the dynamics of the semicircular canals in the inner ear reacting to the changing attitude angles. This is a well-known phenomenon. However, what is not commonly known is that spatial disorientation (SD) in a turn can also occur due to the linear sensing part of the inner ear, the otolith mechanism. It is demonstrated how, during a steady-state, banked, coordinated turn, that is, no longitudinal or rotational acceleration, a pilot can become disoriented. The pilot will sense a pitch-up angle and then "correct" it by pitching down, thus, entering into a fatal spiral dive. The greater the bank angle, that is, the tighter the turn, the more critical is the disorientation. It is shown how a quantitative understanding of the dynamics of the vestibular otolith can be used to advantage in developing algorithms for SD flight trainers and in defining potentially hazardous flight maneuvers for safe flight-path planning.

Nomenclature

a_x = aircraft translational acceleration component along body x axis
a_y = aircraft translational acceleration component along body y axis
a_z = aircraft translational acceleration component along body z axis
f_x = otolith specific force component along otolith x axis
f_y = otolith specific force component along otolith y axis
n = number of G's due to centripetal (or normal) acceleration during turn
p = aircraft rotational velocity component about body x axis
q = aircraft rotational velocity component about body y axis
R = turn radius
R_x = distance from aircraft c.g. to head c.g. along body x axis
R_y = distance from aircraft c.g. to head c.g. along body y axis
R_z = distance from aircraft c.g. to head c.g. along body z axis
r = aircraft rotational velocity component about body z axis
V = aircraft velocity
α = otolith angle
θ = aircraft pitch angle
θ_L = limit on perceived pitch angle to avoid hazardous flight condition
θ_p = perceived pitch angle
ϕ = aircraft bank angle
ω = turn rate

Introduction

PILOT error has been identified as being the major cause of all aircraft accidents. As much as 65% of all general aviation accidents are attributed to pilot error, followed by 43% for charter aircraft, 35% for commuter aircraft, and 10% of scheduled jet aircraft accidents[1] (Fig. 1). However, pilot error is too general a term to be meaningful if corrective actions are to be taken. Lumped together are such factors as poor judgment, oversight, exhaustion, schedule pressure, negligence, and a host of other causes having negative connotations.

However, not all pilot errors can be considered a fault of the pilot. One significant cause is spatial disorientation (SD), and this is certainly not a fault of the pilot. Rather, SD leads to natural misperceptions to which we are all subject. This is especially true when we are placed into an environment in which we are not adapted to perform.

SD related accidents can be prevented. A description of SD and a methodology for its prevention have been presented in Refs. 2–4. Suffice it to say that SD is a false perception of the actual spatial orientation of the pilot and aircraft with respect to the ground. Attitude, motion, and distances are misperceived. Pilots are especially prone to spatial disorientation because they are operating in an environment completely foreign to their innate sense of perception.

When the senses get conflicting information or information that cannot be interpreted, the pilot is subject to complete disorientation, unable to make any reasonable decision. Worse still is when the input to the senses are misperceived and the pilot is lulled into a false sense of security. Here pilots may believe that they are in control and continue performing "as usual" when, in reality, the aircraft is out of control.

That SD is a real problem for nonmilitary as well as military aircraft can be seen in Figs. 2–4. During the years 1970–1975, 16% of all general aviation accidents were due to SD.[5] For the period from 1976 to 1992, the total number of fatal general aviation accidents involving SD were 1022 (Fig. 2), resulting in 2355 fatalities[6] (Fig. 3). Compared to all fatalities over this period, the total fatalities[6] due to SD was 13% (Fig. 4).

One aspect of SD is a direct consequence of the motion and tilt sensing function of the inner ear; in particular, the semicircular canals and the utricular otolith. This is especially true under limited visibility flight conditions such as fog, haze, clouds, and night. Briefly, the inner ear has two motion detecting sensors: the otoliths and the semicircular canals. (For more detail, see Refs. 2–4 and 7–10.) The otoliths sense linear acceleration and tilt. The semicircular canals sense rotational acceleration. It is the otolith that gives rise to the G-excess and elevator illusions. These illusions are major contributors to SD. The semicircular canals also contribute to SD, for example, the graveyard spin.[11]

The otolith is a calcified platform within the inner ear. It is sensitive to tilt and linear acceleration of the body. However, it can only be displaced parallel to its own surface. Therefore, it cannot sense any gravitational force or acceleration normal to its surface. This means that it transmits two-dimensional information from three-dimensional inputs (Fig. 5). Thus, many different inputs can result in the same perceived sensation. In practical terms, an acceleration can be confused for a pitch up. The consequence is SD.

If the acceleration is in the longitudinal direction, for example, at takeoff or landing, then the misperception is called the G-excess illusion (Fig. 6). If the acceleration is vertical, for example, coordinated turn or pullout, then it is referred to as the elevator illusion

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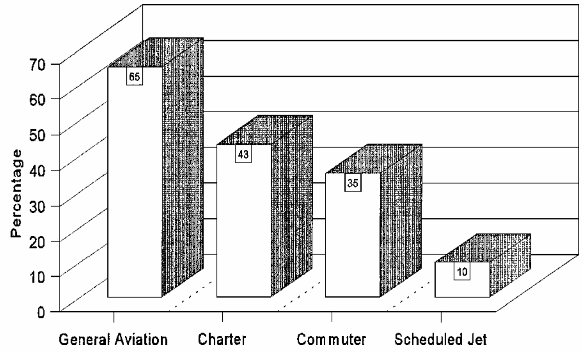

Fig. 1 U.S. accidents initiated by pilot error.

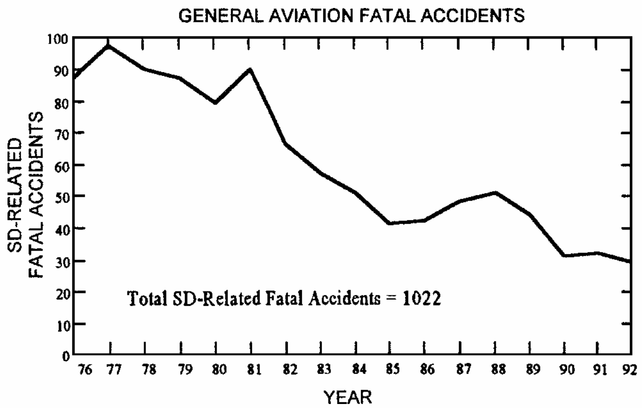

Fig. 2 Fatal accidents due to SD.

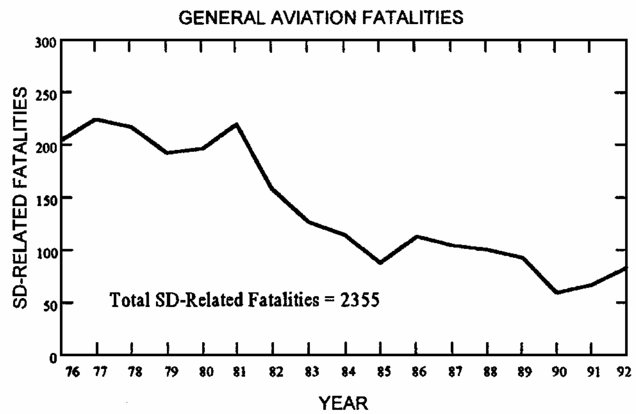

Fig. 3 Fatalities due to SD.

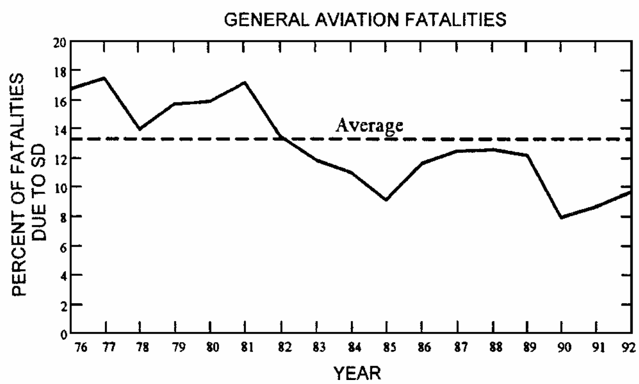

Fig. 4 Percent fatalities due to SD.

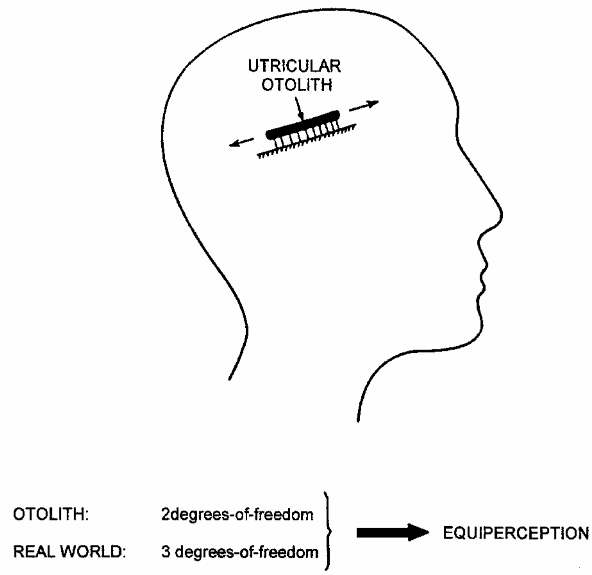

Fig. 5 Otolith mechanism.

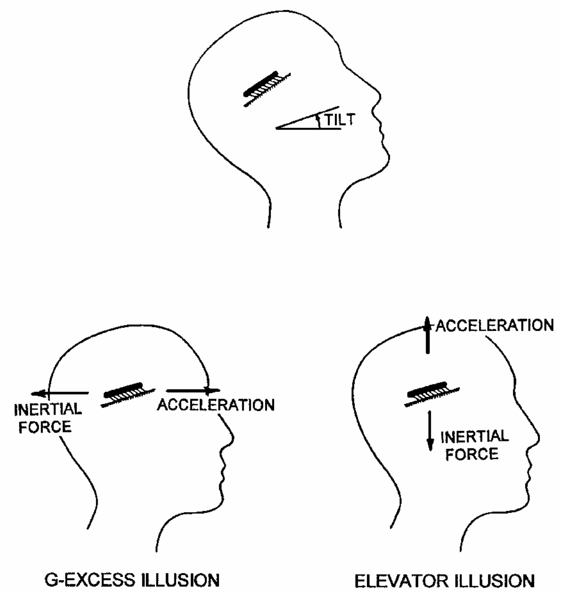

Fig. 6 Tilt/motion equiperception.

(Fig. 6), similar to that experienced in an elevator. Understanding the physical mechanism is the basis for quantifying these illusions.[3] A working model for this mechanism has been developed in Refs. 7–10. There, a quantitative model for calculating the actual SD state was developed. Note that it is not the resultant force due to gravity and acceleration that determines the misperceived attitude (a common mistake in current algorithms used for motion simulation[10]), but rather it is the component of this resultant force that lies in the plane of the otolith that is the key to defining the perceived attitude.

Accelerations during each of the following maneuvers can result in SD and cause the pilot to make erroneous "corrections": takeoff (g-excess illusion), landing (g-excess illusion), climb (g-excess illusion), coordinated turn (elevator illusion), and pullout (elevator illusion).

This paper will concentrate on the quantitative evaluation of spatial disorientation during a coordinated turn. (The others have been evaluated in Refs. 3 and 8.) The perceived pitch-up angle during a level turn is derived and its influence on inducing the pilot to correct by pitching down is evaluated. It will be shown that the greater the bank angle, that is, the tighter the turn, the more critical is the disorientation.

Basic Equations

The key to quantitatively evaluate the effects of any aircraft maneuver is to resolve the inertial and gravitational forces acting on the otolith into the two components acting on the otolith surface because any force acting normal to the surface is not sensed. To this end, the equations for the x and y otolith specific force components, that is, normalized with respect to gravitational acceleration, in their most general form[8] are given by (Fig. 7)

$$\begin{aligned} f_x = &-[\cos\alpha\sin\theta + \sin\alpha\cos\theta\cos\phi] - [a_x\cos\alpha - a_z\sin\alpha] \\ &- [(\dot{q}R_z - \dot{r}R_y)\cos\alpha - (\dot{p}R_y - \dot{q}R_x)\sin\alpha] \\ &- \left[\left\{p(qR_y + rR_z) - R_x(q^2 + r^2)\right\}\cos\alpha\right. \\ &\left. - \left\{r(pR_x + qR_y) - R_z(p^2 + q^2)\right\}\sin\alpha\right] \qquad (1) \end{aligned}$$

$$\begin{aligned} f_y = &\cos\theta\sin\phi - a_y - [\dot{r}R_x - \dot{p}R_z] \\ &- \left[q(pR_x + rR_z) - R_y(p^2 + r^2)\right] \qquad (2) \end{aligned}$$

For a coordinated turn, the resultant force (combined centrifugal and gravitational) is normal to the seat (Fig. 8). This is to provide comfort to the passengers, ease of control for the pilot, and symmetric structural loading to the aircraft. This resulting vertical force will give rise to the elevator illusion and will be perceived as a pitch-up sensation. During a coordinated turn, the aircraft conditions are

$$\theta = 0 \qquad (3)$$

$$a_z = -n\sin\phi \qquad (4)$$

$$a_y = n\cos\phi \qquad (5)$$

Note also that

$$a_x = p = q = \dot{p} = \dot{q} = \dot{r} = 0$$

For this analysis, it is assumed that $R_x \approx 0$ and $R_y \approx 0$ so that the yaw velocity terms in Eqs. (1) and (2) are negligible. For specific aircraft, Eqs. (1) and (2) can be used in their more general form as shown. However, for the current analysis, it suffices to neglect these terms.

Under these steady-state conditions, Eqs. (1) and (2) reduce to

$$f_x = -(\cos\phi + n\sin\phi)\sin\alpha \qquad (6)$$

$$f_y = \sin\phi - n\cos\phi \qquad (7)$$

For a coordinated turn, $f_y = 0$, that is, no roll or side force sensation.

$$\therefore \quad \tan\phi = n \qquad (8)$$

When Eq. (8) is substituted into Eq. (6), there results

$$f_x = -\sin\alpha\sec\phi \qquad (9)$$

To find the pitch perceived during this maneuver, the specific force f_x in Eq. (9) is equated to that experienced by a body tilt in a normal 1-g environment.[7] That is, because the only force acting on the otolith is f_x, then the coordinated turn and the normal body tilt, each having the same input f_x, must necessarily experience the same sensation (Fig. 8). This approach has been amply verified in Ref. 7.

Thus, for tilt in a normal 1-g environment, Eq. (1) reduces to

$$f_x = -\sin(\theta_p + \alpha) \qquad (10)$$

where θ_p is now the perceived tilt (or pitch) angle.

Therefore, when each f_x is equated [Eqs. (9) and (10)], the perceived pitch during a coordinated turn is

$$\theta_p = \sin^{-1}(\sin\alpha\sec\phi) - \alpha \qquad (11)$$

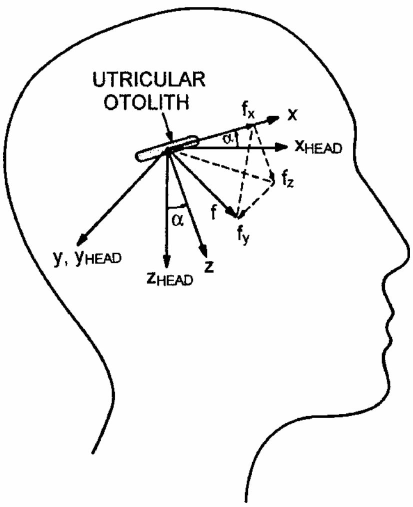

Fig. 7 Head and otolith coordinate systems.

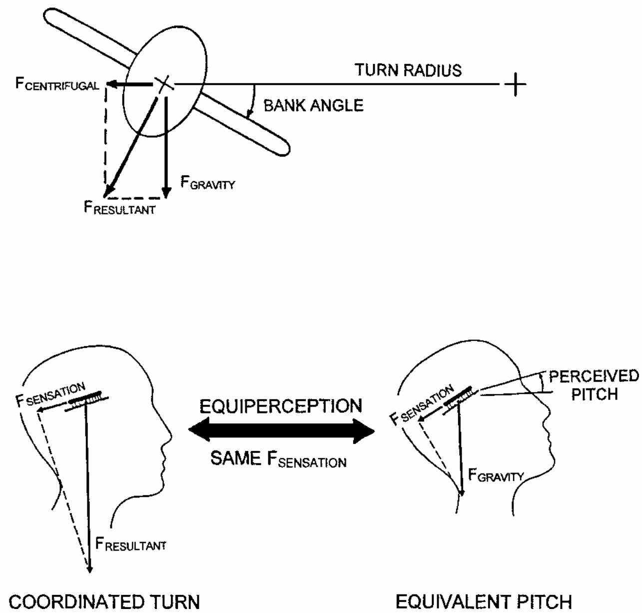

Fig. 8 Coordinated turn.

This equation quantitatively defines the perceived pitch as a function of bank angle during a coordinated turn. The bank angle ϕ is also expressed as a function of the number of G's pulled in a coordinated turn [see Eq. (8)]. Therefore, Eq. (11) may also be rewritten as

$$\theta_p = \sin^{-1}\left(\sqrt{1 + n^2}\sin\alpha\right) - \alpha \qquad (12)$$

Alternatively, the number of G's can also be expressed as a function of the turn radius, aircraft speed, and turn rate by using any of the following forms:

$$n = \omega^2 R/g = V^2/gR = \omega V/g \qquad (13)$$

Results

When Eqs. (11–13) are used, the perceived pitch for different coordinated turns is presented in Figs. 9–11 as functions of bank angle (Fig. 9), normal (or centripetal) acceleration (Fig. 10), and turn radius with aircraft velocity (Fig. 11). (The value of the otolith angle α is taken to be 28.7 deg. Although α can vary from individual to individual, the literature generally refers to it as being approximately 30 deg. The value of 28.7 deg comes from Ref. 7, where it was found to be the best fit to the data.)

Thus, knowing the flight condition for a coordinated turn, the perceived pitch can readily be calculated. For example, in Fig. 9 it can be seen that, for a coordinated turn at a 30-deg bank angle,

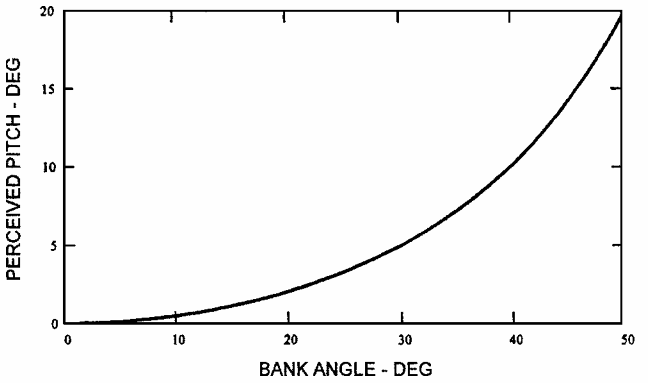

Fig. 9 Perceived pitch in a coordinated turn, function of bank angle.

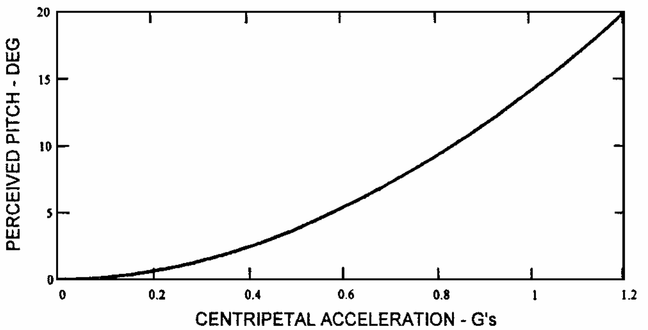

Fig. 10 Perceived pitch in a coordinated turn, function of normal acceleration.

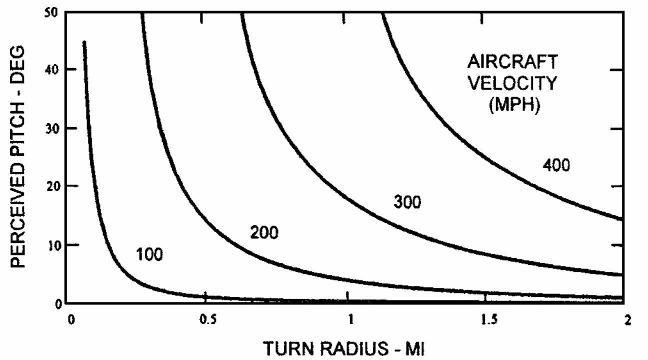

Fig. 11 Perceived pitch in a coordinated turn, function of turn radius.

the perceived pitch is 5 deg and at a bank angle of 40 deg, the perceived pitch is 10 deg. If the bank angle were as high as 50 deg, then the perceived pitch is 20 deg. At any of these perceived pitch angles, if the pilot were to attempt to "correct" the apparent pitch up by pitching down, the aircraft would enter into a spiral dive with potentially fatal consequences.

The situation is not as severe for an aircraft executing a standard rate turn of 3 deg/s. For this case, Eqs. (12) and (13) are used to calculate the perceived pitch for $\omega = 3$ deg/s. The results are presented in Figs. 12 and 13 for aircraft velocity and turn radius, respectively. Note that in Fig. 11 it can be seen that, for a given aircraft velocity, the tighter the turn is the greater is the perceived pitch. In fact, Eq. (13) shows that the number of G's is inversely proportional to the turn radius for a given aircraft velocity. However, for a given turn rate, as in the standard turn rate of 3 deg/s, the perceived pitch increases with increasing turn radius. This can be seen in Fig. 13 and in Eq. (13) where, for a given turn rate, the number of G's is proportional to the turn radius.

A pilot experiencing a perceived pitch up during a coordinated turn under limited visibility (fog, clouds, night) will tend to pitch the aircraft down by approximately the perceived pitch. This action will result in a spiral dive with potentially fatal consequences.

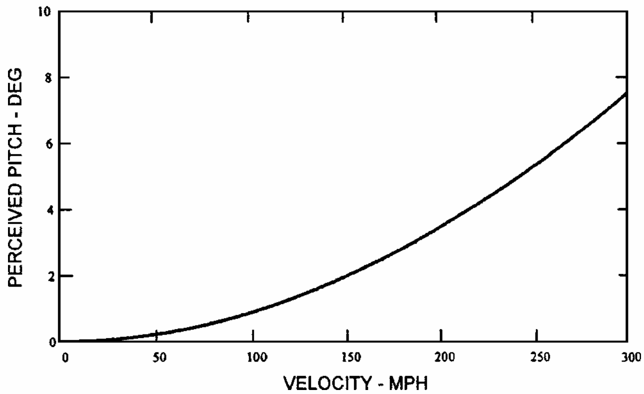

Fig. 12 Perceived pitch for a standard turn rate, function of aircraft velocity.

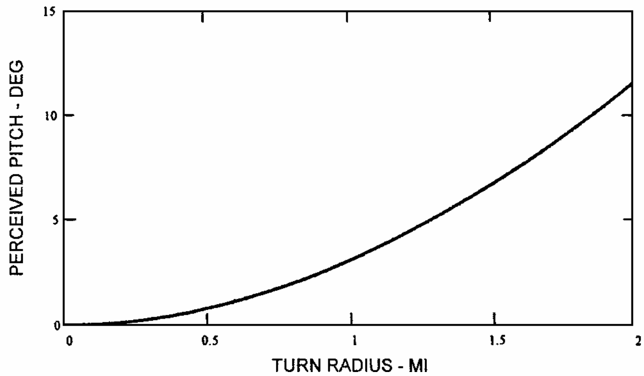

Fig. 13 Perceived pitch for a standard turn rate, function of turn radius.

However, how severe the spiral dive is will depend on the aircraft's altitude and velocity at the start of the dive and the pitch-down angle imposed by the pilot. An analysis of the dynamics and the ability to recover from the dive will determine the acceptable range of pitch-down angles from which a recovery can be made. This dive analysis will not be performed in this paper. Rather, Eqs. (11–13) can be used to complement such an analysis and aid in safe flight-path planning. To this end, Eqs. (11–13) are rewritten in the following form where limits are imposed on the pilot-induced pitch-down angle (or, equivalently, perceived pitch), that is, $\theta_p < \theta_L$. The value of θ_L comes from the dive dynamic analysis.

Bank angle constraint:

$$\phi < \cos^{-1}\left[\frac{\sin\alpha}{\sin(\theta_L + \alpha)}\right] \tag{14}$$

Velocity and turn radius constraint:

$$\frac{V^2}{R} < g\sqrt{\left[\frac{\sin(\theta_L + \alpha)}{\sin\alpha}\right]^2 - 1} \tag{15}$$

Conclusions

It has been shown that, during a coordinated turn under limited visibility conditions, the elevator illusion will be experienced giving rise to a perceived pitch. From an analysis of the physical mechanism of the utricular otolith in the inner ear, equations were derived providing the engineer with the ability to quantitatively evaluate this perceived pitch as a function of bank angle, number of G's, velocity, and turn radius.

A very important result of this paper imposes constraints on coordinated turns to avoid hazardous maneuvers. This provides the aviation community with an added tool for safe flight-path planning.

Some may assume that, under limited visibility conditions, the pilot would rely on the instrument panel and thus not react to his innate perceived sense of pitch. However, as Gillingham and Previc have noted. "That pilots can realize being disoriented, see accurate orientation information displayed on the attitude indicator, and still fly into the ground always strains the credulity of non-aviators. Pilots who have had spatial disorientation, who have experienced fighting oneself for control of an aircraft, are less skeptical."

That at least 13% of all general aviation accidents were due to SD substantiates Gillingham and Previc's[11] observation and reinforces the need to incorporate quantitative spatial disorientation analyses into flight safety planning and flight training. This paper and Refs. 2–4 and 8–10 show how the quantitative analysis of the utricular otolith can be used to develop algorithms for SD flight trainers and to define flight safety constraints.

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