Analysis of Visual Threshold Effect on Manual Aircraft Control

G. R. Sarma*
National Aeronautical Laboratory, Bangalore, India

and

Y. N. Bapat†
Indian Institute of Technology, Bombay, India

Theme

THE effect of visual display threshold on manual aircraft control is established analytically under the condition when the pilot is adapting himself to obtain the best closed-loop performance of the pilot-vehicle system, by applying recognized pilot adaptation rules and constraints. The effects are discussed in terms of airframe dynamics, handling qualities, and control theory.

Contents

Experimentally, through simulator studies, it has been established that display thresholds can give rise to stable pilot-induced oscillations (PIO).[1] Figure 1a represents a generalized nonlinearity which can be specialized to simulate various threshold phenomena. For example, by letting $K=1$ and $x_2>A$, where A represents the expected maximum amplitude of the displayed quantity, the figure represents a dead-band nonlinearity, characteristic of a pilot indifference threshold. By letting $K \gg 1$, and $x_2-x_1=x_3-x_2=\Delta$, etc., the figure represents a nonlinearity characteristic of discrete element indicators consisting of luminous bars or television-type raster displays of lines. Threshold as used in this paper is a generalized characteristic of input-output relationship, where the output appears only after a set input level is exceeded. The output thereafter is related to input in a linear fashion until another threshold is reached, again followed by a linear range and so on, covering the entire scale, representing the displayed quantity as shown in Fig. 1a. For the two cases where the input amplitude can lie within the threshold level or outside the threshold level, the describing function N for each case is given by Eqs. (1) and (2), K representing the slope as shown

$$N=\frac{2K}{\pi}\left[\frac{\pi}{2}-\sin^{-1}\frac{x_1}{X}+\sin^{-1}\frac{x_2}{X}-\sin^{-1}\frac{x_3}{X}\right.$$
$$-\frac{x_1}{X}\left\{1-\left[\frac{x_1}{X}\right]^2\right\}^{1/2}+\frac{x_2}{X}\left\{1-\left[\frac{x_2}{X}\right]^2\right\}^{1/2}$$
$$\left.-\frac{x_3}{X}\left\{1-\left[\frac{x_3}{X}\right]^2\right\}^{1/2}\right] \text{for } x_3<X<x_4 \tag{1}$$

and

$$N=-\frac{2K}{\pi}\left[\sin^{-1}\frac{x_1}{X}-\sin^{-1}\frac{x_2}{X}+\frac{x_1}{X}\left\{1-\left[\frac{x_1}{X}\right]^2\right\}^{1/2}\right.$$
$$\left.-\frac{x_2}{X}\left\{1-\left[\frac{x_2}{X}\right]^2\right\}^{1/2}\right] \text{for } x_2<X<x_3 \tag{2}$$

For a typical case, when $x_1=\Delta$, $x_2=3\Delta$, and $K=2$, the computed numerical values are plotted in a Nichol's plane as shown in Fig. 1b. It can be seen that the dominant effect is felt only because of the initial portion of the curve which imposes the minimum gain margin requirements.

In most of the PIO situations, the pilot was recognized to have adapted to the pre-PIO situation itself with lead, lag, or lead-lag equalization as the case may be.[2] With nearly sinusoidal motion during PIO, because of threshold effects in display, the visual cues to the pilot will not be purely sinusoidal, but distorted. Hence, the pilot can be expected to sustain the oscillations until he recognizes the oscillatory nature of the airframe motion. Since the pilot will be controlling the vehicle in a closed-loop mode, the compensatory model will give a conservative representation. In the pitch-attitude control in the landing phase of an aircraft, which is considered here, since low natural frequencies are involved, the required pilot equalization would be lead equalization. With a second-order representation for his neuromuscular lag, and with a maximum lead of 1 sec, which he can generate, the pilot model[3] for the task therefore would be, as given by

$$Y_\theta=[K_\theta(1+T_Ls)]/(1+T_Ns)^2 \tag{3}$$

where K_i represents the pilot gain in pitch-attitude control, T_L is the lead time constant (maximum of 1 sec), and T_N is the neuromuscular lag time constant, typically 0.2 sec. The essence of pilot adaptation is that the pilot adapts an equilization which would make the open-loop pilot-vehicle transfer function much greater than unity below the gain crossover frequency. The gain crossover should be between 1 and 2 rad/sec with a positive stability margin.

With values of T_L and T_N as stated, the pilot adjusts his gain K_θ to obtain best possible closed-loop performance. Short period characteristics of F106B, as a typical case, are natural frequency $\omega_n=0.87$ rad/sec, damping ratio $\zeta=0.69$, normalized lift force derivative $L_\alpha=0.79$, and forward velocity $U_0=223$ fps. With $K_\theta=1$, $T_L=1.0$ sec, and $T_N=0.2$ sec, the gain-phase plot of the pilot-vehicle system is drawn as in Fig. 2, corresponding to curve *a*. The inverse describing function also is plotted in the same figure. Under the preceding conditions, the crossover frequency can be seen to be 1.4 rad/sec with a phase margin of 22° and corresponding gain margin of 7 dB. With crossover frequency at 1.4 rad/sec (i.e., lying between 1 and 2 rad/sec), and with maximum lead time constant of 1 sec, the curve represents typical pilot-vehicle organization under the given representation of the system, prior to the occurence of any PIO. The important point in looking at this plot is the gain change required to go from compensatory tracking to the oscillatory control situation. In this case, an increase by a factor of about 1.8 is required. This is not a large change with regard to pilot adaptability, provided the stick forces are not excessive. Thus for sufficiently reasonable stick forces PIO is likely.

Conversely, as the force gradient increases, the physical effort required to increase gain by a factor of about 2 prevents the pilot from reaching the PIO region. Of course, neither

Received Sept. 11, 1973; synoptic received Sept. 11, 1975; revision received Dec. 22, 1975. Full paper available from National Technical Information Service, Springfield, Va. 22151, as N76-14140 at the standard price (available upon request).

Index category: Aircraft Handling, Stability, and Control.

*Scientist.

†Professor.

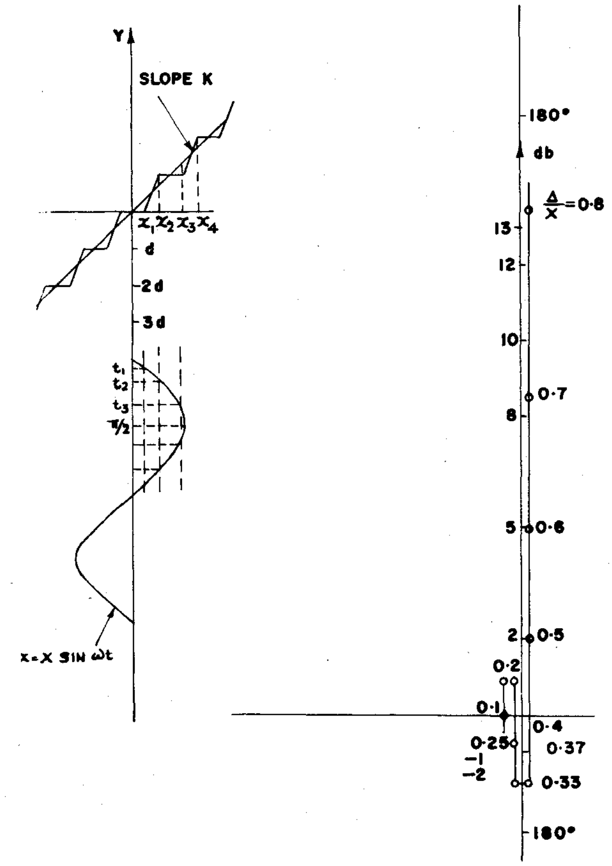

Fig. 1 Display threshold and its inverse describing function.

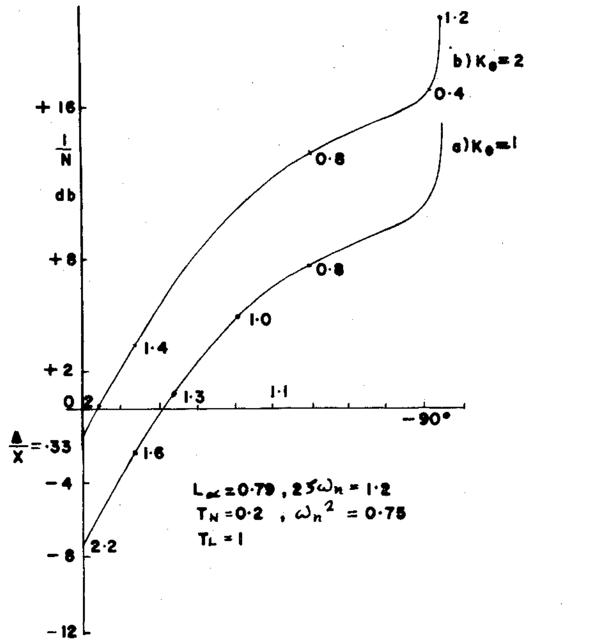

Fig. 2 Response of the original dynamics with inverse describing function.

large stick forces nor small stick forces are desirable from criteria for handling qualities. With desirable stick forces, the fact that a pilot can change his gain by a factor of 2 has been established by studies of handling qualities. Thus, in the foregoing situation (curve *a* in Fig. 2), a sustained pilot-induced oscillation is possible, and the frequency of oscillation would be 2.2 rad/sec, which is higher than the crossover frequency. The amplitude of oscillation would be about 3Δ. Furthermore, reduction of pilot lead T_L, i.e., smaller equalization by the pilot, resulting from insufficient time or training with the given situation, will increase the PIO tendencies (gain margin further reduced).

Another point also can be noticed from Fig. 2. Curve *b* represents a situation where the pilot gain is adjusted (with other parameters reamining the same) to obtain a higher crossover frequency at 2.0 rad/sec, which is higher limit of the desired range as stipulated. This is within the critical limits introduced by the nonlinearity. Thus if larger crossover is desired, the pilot will be compelled to generate larger lead than he normally could to avoid PIO in the presence of the threshold, thus degrading the pilot opinion rating. Therefore, it can be said that the presence of the threshold in visual display imposes a restriction on the gain margin and requires a larger than normal T_L to be generated by the pilot in order to get the required bandwidth.

Conventionally, longitudinal handling qualities data of an aircraft always are expressed in terms of short-period natural frequency, short-period damping ratio, and the reciprocal of the normalized lift-force derivative. Extension of the analysis to investigate the effect of these parameters shows that, for the same pilot-adapted configuration, a higher natural frequency was found to reduce the chances of PIO, as can be expected. In this case, the pilot has to generate a lead term which would be smaller than what originally is required with lower natural frequency. Similar effects would be observed in the other two parameters as well, in agreement with the existing handling qualities data. The frequency of the pilot-induced oscillation is dependent upon the open-loop crossover frequency of the pilot-vehicle system, and the amplitude depends upon the gain and threshold levels. With recognized crossover frequencies between 1 and 2 rad/sec, in a developed PIO phase, the oscillation frequency would be a little more than the actual crossover frequency, other things remaining the same. To the extent that the pilot-describing function does not differ in form for fixed-base (which, by definition, involves visual inputs only) or airborne tasks with similar controlled element dynamics and configurations with separated displays, the results of the analysis should prove useful in discerning the effects of threshold in pilot-vehicle systems.

References

[1] Barnes, A.G., "Effect of Visual Threshold on Aircraft Control," *Journal of Aircraft,* Vol. 8, June 1971, pp. 450-456.

[2] Ashkenas, I.L., et al., "Pilot Induced Oscillations: Their Cause and Analysis," Systems Technology, Inc., Hawthorne, Calif., Rept. ATI-TR 239-2, June 1964.

[3] Adams, J.J. et al., "Determination of Critical Tracking Tasks for Human Pilot," NASA TN D3242, 1966.