SPEED CONTROL ISSUES OF 3D-TUNNEL/PREDICTOR DISPLAYS

G. Sachs and U. Sennes
Technische Universität München
Boltzmannstr. 15, 85747 Garching, Germany

Keywords: *tunnel/predictor display, speed control, 3-dimensional guidance information*

Abstract

Speed control issues are considered for tunnel/predictor displays presenting 3-dimensional guidance information, with reference to a predictor control law for best performance of the pilot-predictor-aircraft system. Possible problems concerning speed control can be removed by proper thrust control. It is shown that the thrust control loop is supported by the predictor control law because of favorable coupling effects. There is another favorable effect related to a minimum number of nonsensitive feedback loops. Furthermore, a command thrust indication in the tunnel/predictor display is introduced to support speed control. Results from pilot-in-the-loop simulation experiments are presented for verification.

1 Introduction

Tunnel/predictor displays presenting guidance information in a 3-dimensional format have attained significant interest and are subject of recent research [1-10]. They provide command information and preview, thus offering an enhancement in the visual information of the pilot.

A primary goal of a tunnel/predictor display is to provide the pilot with 3-dimensional guidance information for precise flight path control. As part of the piloting task, speed control is also of concern. It will be shown that there are specific aspects of tunnel/predictor displays in this respect.

2 Predictor Control Law and Basic Speed Control Characteristics

In a tunnel/predictor display as illustrated in Fig. 1, the command flight path is presented in the form of a tunnel and the future position of the aircraft is indicated using a predictor. The pilot operates on visually sensed inputs and exerts manual control outputs. The resulting loop closure is schematically illustrated in Fig. 2. There are basically two predictor goals:

– Prediction of future aircraft position
– Providing controlled element properties requiring minimum pilot compensation

An appropriate predictor control law reads

$$Y_{PR}(s) = K_{PR} K_q (s + 1/T_1)(s + 1/T_2)/s^2 \qquad (1)$$

where K_q, T_1 and T_2 may be selected as

$$K_q \approx V T_{PR}/\omega_{SP}, \quad T_1 \approx T_{PR}, \quad T_2 \approx 1/\omega_{SP} \qquad (2)$$

With Eq. (1), the open-loop predictor-aircraft system can be described by

$$Y_{PR}(s) Y_C(s) = -\frac{K^*(s + 1/T_1)(s + 1/T_2)(s + 1/T_{h1})}{s(s^2 + 2\zeta_{SP}\omega_{SP}s + \omega_{SP}^2)(s^2 + 2\zeta_P\omega_P s + \omega_P^2)} \qquad (3)$$

where

$$K^* = -K_{PR} Z_\alpha M_{\delta_e} T_{PR}/(M_\alpha \omega_{SP}) \qquad (4)$$

For speed control and stability characteristics, the long-term modes of the closed-loop pilot-predictor-aircraft system are of concern. They can be expressed as

$$\omega_P'^2 \approx \frac{\omega_P^2 + K_P K^*/(T_1 T_2)}{1 + K_P K^*}, \quad 2\zeta_P'\omega_P' \approx \frac{K_P K^*}{1 + K_P K^*}\frac{1}{T_2}$$
$$-\frac{1}{T_{h1}'} \approx -\frac{1}{1 + T_1 T_2 \omega_P^2/(K_P K^*)}\frac{1}{T_{h1}} \qquad (5)$$

The closed-loop path mode denoted by the primed quantities ω_P' and ζ_P' is basically stable. It profits from the predictor related pilot gain K_P which increases its frequency and damping. The closed-loop aperiodic mode denoted by T_{h1}' shows a different behavior: it is stable for

$T'_{h1} > 0$ and unstable for $T'_{h1} < 0$. According to Eq. (5), the stability of the closed-loop aperiodic mode is determined by the zero $-1/T_{h1}$ of the transfer function of the predictor-aircraft system Eq. (3):

$$1/T_{h1} \approx -X_u + (X_\alpha - g)Z_u / Z_\alpha \tag{6}$$

This expression shows that stability of the closed-loop aperiodic mode depends on thrust-drag characteristics, yielding stability for operation on the frontside of the power-required curve $(T_{h1} > 0)$ and instability for operation on its reverse $(T_{h1} < 0)$.

Summing up the basic speed control characteristics, the pilot-predictor-aircraft system is stable provided the closed-loop aperiodic mode is stable. In case of instability, the response shows a divergent characteristic particularly related to speed. A proposal is presented to remove this divergence problem and, for a slow stable aperiodic mode, to achieve a faster convergent response.

3 Improvement of Speed Control

The proposal for improving speed control comprises two successive loop closures, as illustrated in Fig. 3. The first closure relates to the above predictor-aircraft system as the inner loop, yielding the single prime poles described by Eq. (5). The second closure shows feedback of speed to thrust as the outer loop, modifying the single prime to the double prime characteristics described below. An essential element of this proposal is that speed control is supported by the predictor control law.

With regard to the loop $u \to \delta_T$ shown in Fig. 3, it is assumed that the representation of pilot behavior does not imply linearity on a point-by-point sense, but rather on the average. Thus, for example, the presence of a threshold in the perception of e_V and a consequent discrete manipulation of the throttle are considered to be representable with the applied modeling.

For dealing with the speed control issue in mind, the speed to thrust transfer function concerning the path and aperiodic modes is used

$$\frac{u(s)}{\delta_T(s)} = \frac{X_{\delta_T}}{1 - K_P K^*} \frac{s^2 + 2\zeta'_u \omega'_u s + \omega'^2_u}{(s + 1/T'_{h1})(s^2 + 2\zeta'_P \omega'_P s + \omega'^2_P)} \tag{7}$$

Evaluation of the effect of the predictor related pilot gain on the zeros (ω'_u, ζ'_u) shows that

$$\omega'_u \approx \omega'_P, \quad \zeta'_u \approx \zeta'_P \tag{8}$$

Closure of the outer loop $(u \to \delta_T)$ with gain K_u yields for the path and aperiodic mode roots denoted by the double prime

$$\begin{aligned} \omega''_P &\approx \omega'_P, \quad \zeta''_P \approx \zeta'_P \\ -1/T''_{h1} &\approx -1/T'_{h1} - (1 + K_P K^*) X_{\delta_T} K_u \end{aligned} \tag{9}$$

These relations show that there are several effects which can be considered as favorable for speed control:

1) Effect of Thrust Related Gain K_u on Path and Aperiodic Modes

There is an effect of K_u solely on the aperiodic mode and not on the path mode. Thus, the aperiodic mode which is the mode having deficiencies can be purposively influenced. The favorable properties of the path mode for trajectory control are preserved. This result is due to the predictor control law.

2) Effect of Predictor Related Pilot Gain K_P on Aperiodic Mode

From Eq. (9) it follows that the predictor related pilot gain, K_P, supports the stabilization of the aperiodic mode. The shift of the closed-loop aperiodic mode root, $-1/T''_{h1}$, to more negative values indicating an improved stability and a faster speed response behavior profits from K_P. This is a further effect of the predictor control law in support of speed control.

3) Modal Properties

The path and aperiodic modes have differences as regards their modal properties. The path mode involves both altitude and speed components, similar to the phugoid. Speed is the dominant modal component of the aperiodic mode, yielding

$$|u/\Delta h|_{\text{aperiodic mode}} >> |u/\Delta h|_{\text{path mode}}$$

Accordingly, there is a decoupling concerning speed and altitude. This is considered to also contribute to path (altitude) and speed control.

4) Bandwidth Ordering

For K_u gains providing an adequate stability level of the aperiodic mode, the following relation holds

$$\omega_P'' >> 1/T_{h1}''$$

As a consequence, the path mode is significantly faster than the aperiodic mode. Thus, the h-loop has a faster response than the u-loop, indicating that there is an adequate bandwidth separation between the two loops. This can be regarded as a desirable property for path and speed control.

Furthermore, manual speed control is considered to be supported by an appropriate command thrust indication, integrated in the tunnel/predictor display (Fig. 1). Thus, the pilot can be assisted in performing his control task.

The speed control issues considered in the previous sections were subject of an experimental investigation in a simulation test program. A fixed base simulator was used which was equipped with the tunnel/predictor display shown in Fig. 1. The non-linear 6-degree-of-freedom aircraft model applied in the simulation experiments can be regarded as representative of small twin jet engine aircraft.

Results on speed control are shown in Figs. 4 and 5. Basically, speed is effectively controlled in both cases (Fig. 4). There is some increase of the speed deviations when operating on the reverse of the power-required curve. A corresponding behavior shows the control behavior of the pilot (Fig. 5). There is practically no control activity for operation on the frontside of the power-required curve, in accordance with speed stability of the pilot-predictor-aircraft system in this case.

4 Conclusions

Speed control issues are considered for tunnel/predictor displays presenting guidance information in a 3-dimensional format. As a basis, a predictor control law for minimum compensatory effort by the pilot and maximum system performance is used. Conditions for stability and instability of the closed-loop pilot-predictor-aircraft system are considered. It is shown that possible speed instability problems can be removed by an appropriate thrust control. Furthermore, it is shown that the thrust control loop is supported by the predictor control law because of favorable coupling effects between the two loops involved. Another favorable effect is due to the control economy possible with a tunnel/predictor display, yielding a minimum number of nonsensitive feedback loops. This result corresponds with the desire of the pilot to use as simple a control technique as possible. Furthermore, a command thrust indication in the tunnel/predictor display is considered to support the pilot. The theoretical findings are supported by results from pilot-in-the-loop simulation experiments.

References

[1] Theunissen, E., "Integrated Design of a Man-Machine Interface for 4-D Navigation," PhD Dissertation, TU Delft, The Netherlands, 1997.

[2] Grunwald, A.J., "Improved Tunnel Display for Curved Trajectory Following: Control Considerations," *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, 1996, pp. 370-377.

[3] Grunwald, A.J., "Improved Tunnel Display for Curved Trajectory Following: Experimental Evaluation," *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, 1996, pp. 378-384.

[4] Wickens, C.D., Fadden, S., Merwin, D., Ververs, P.M., "Cognitive Factors in Aviation Display Design," *Proceedings of the 17th AIAA/IEEE/SAE Digital Avionics Systems Conference*, Bellevue WA, 31 October - 6 November 1998.

[5] Funabiki, K., Muraoka, K., Terui, Y., Harigae, M., Ono, T., "In-Flight Evaluation of Tunnel-in-the Sky Display and Curved Approach Pattern," *AIAA Guidance, Navigation, and Control Conference Proceedings*, 1999, pp. 108-114.

[6] Mulder, M., "Cybernetics of Tunnel-in-the-Sky Displays," Delft University Press, Delft, The Netherlands, 1999.

[7] Sachs, G.; Moeller, H., "Synthetic Vision Flight Tests for Precision Approach and Landing," *AIAA Guidance, Navigation and Control Conference Proceedings*, 1995, pp. 1459-1466.

[8] Lenhart, P.M., Purpus, M., von Viehbahn, H.: Flugerprobung von Cockpitdisplays mit synthetischer Außensichtdarstellung. DGLR-JT98-060, 1998.

[9] Sachs, G., Dobler, K., Theunissen, E., "Pilot-Vehicle Control Issues for Predictive Flightpath Displays," *AIAA Guidance, Navigation, and Control Conference Proceedings*, 1999, pp. 574-582.

[10] Sachs, G., Dobler, K., "Predictor/Flight-Path Display for Manual Longitudinal Control Improvement," *Journal of Guidance, Control, and Dynamics*, 2002, Vol. 25, No. 3, pp. 494-501.

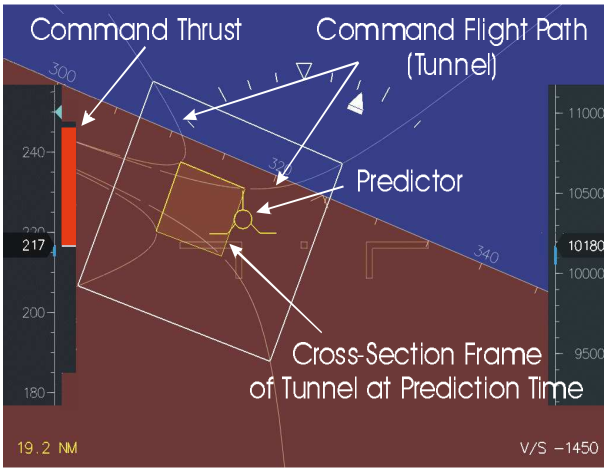

Fig. 1 Predictor/flight-path display with thrust command indicator

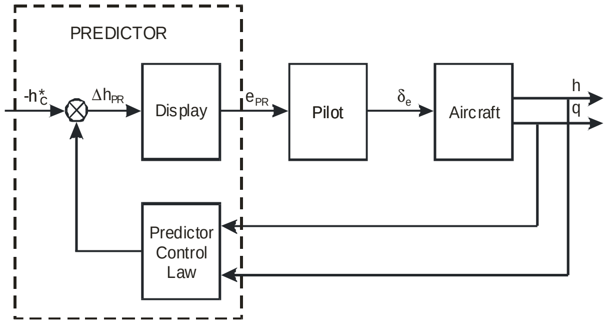

Fig. 2 Block diagram of pilot-predictor-aircraft system

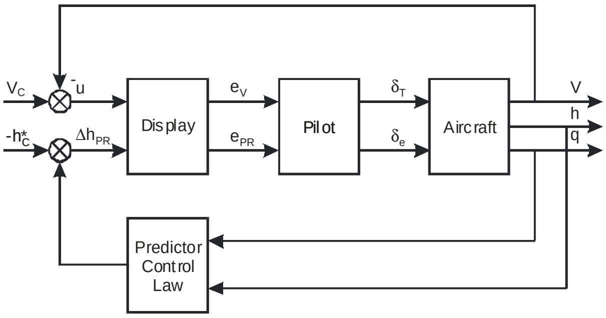

Fig. 3 Model for predictor related flight path control and thrust-speed control

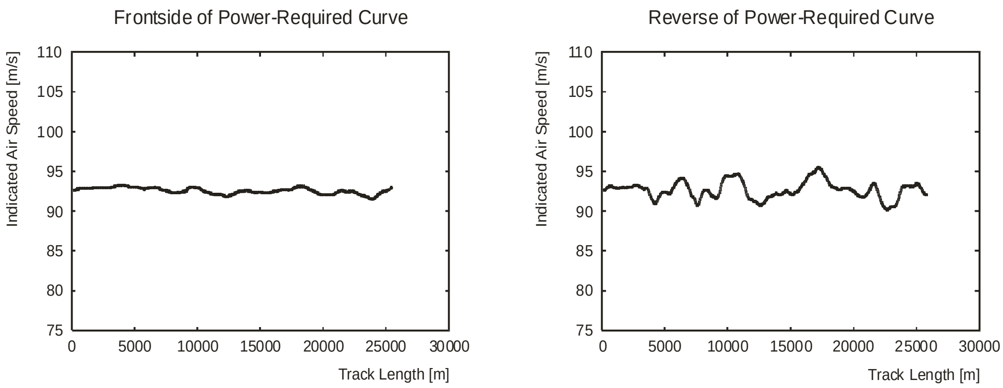

Fig. 4 Speed control in simulation experiment

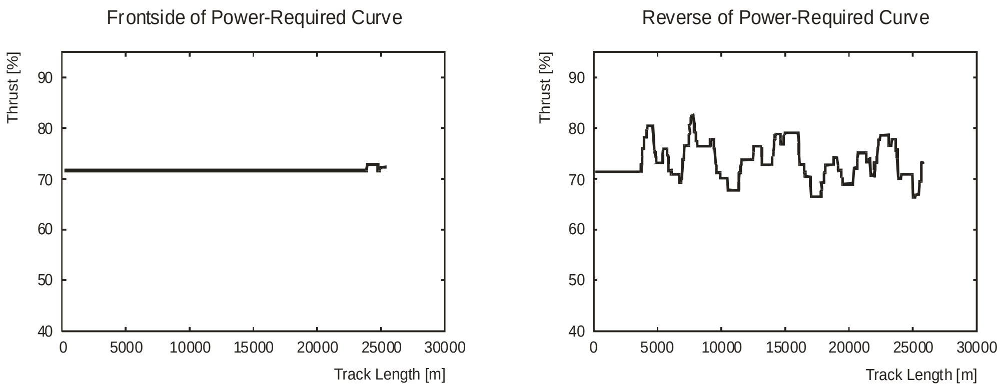

Fig. 5 Thrust input activity in simulation experiment