11.3 SPEED CONTROL SYSTEMS

Although speed is not truly a path variable, its exact control is essential for many tasks related to the control of an aircraft's flight path. Consequently, speed control systems are treated in this present chapter. If speed can be controlled, the position of an aircraft, in relation to some reference point, can also be controlled.

A block diagram representing a typical airspeed control system is shown in Figure 11.9. Speed is controlled by changing the thrust, δ_{th}, of the engines; such a change in thrust is obtained by altering the quantity of the fuel flowing to the engines by means of the throttle actuator. Typical values for the time constant, T_E, of a jet engine lie in the range 0.3–1.5 s, depending on the thrust setting and the flight condition. For the purposes of illustration, T_E will be assigned a value of 0.5 s. Although the thrust/throttle angle relationship is not linear, in practice, it will be assumed to be so here. The system depends upon a feedback signal based on sensed airspeed and sensed longitudinal acceleration. However, the dynamics of the accelerometer are such that its bandwidth is much greater than that of the aircraft system so that its response in this application can be assumed to be instantaneous. Since the airspeed sensor is usually a barometric device, it has been represented by a first order transfer function, with a time constant of T_p. The controller is a proportional plus integral type; the integral term has been added to remove, if required, any steady state error in the response of the airspeed system to constant airspeed command. If it is assumed, in the first place, that the aircraft is to be maintained at its equilibrium airspeed, U_0, then no significant changes in airspeed, u, should persist, Hence u_{ref} if taken to be zero. The dynamic response of the system of Figure 11.9 to an initial airspeed error of $+ 10\,m\,s^{-1}$ in the equilibrium (approach) airspeed of $75\,m\,s^{-1}$, for CHARLIE-1, is shown in Figure 11.10. The time constant of the airspeed sensor was taken to be 0.1 s, and the controller gain K_c was chosen to be 2.0. The sensitivity of the accelerometer $K_{\dot{u}}$, was $2.0\,V\,m^{-1}\,s^{-2}$. The integral term was omitted. Note the small error at values of time greater than 12 s. In Figure 11.10 the longitudinal acceleration, $\dot{u}$, is also shown. The key factor in the response of this speed control system is the authority allowed over the engines' thrust. However, if 10 per cent authority is allowed, say, then it is possible to evaluate K_E by knowing that for steady flight:

$$T = W(D/L) \tag{11.4}$$

For the approach flight condition, the weight and lift/drag ratio of CHARLIE are known to be:

$$W = 2\,450\,000\,\text{N} \tag{11.5}$$

$$L/D = 8.9 \tag{11.6}$$

$$T_{max} = 800\,\text{kN} \tag{11.7}$$

Hence the available excess thrust on approach is 525 000 N. Only 10 per cent of that excess thrust can be changed by the actuator (since the control authority is

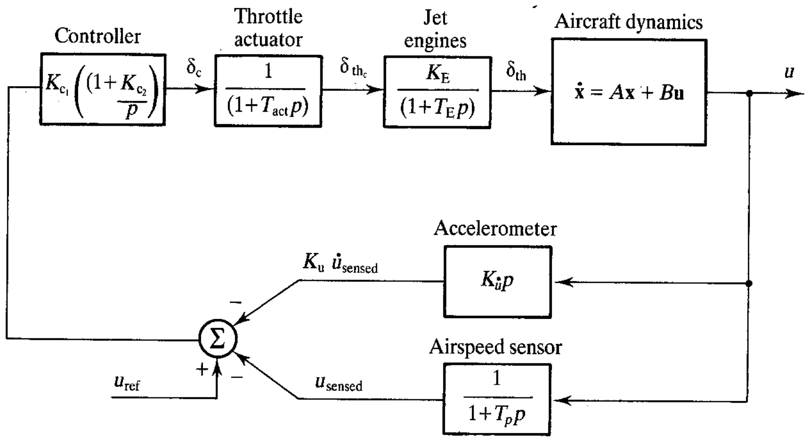

Figure 11.9 Airspeed control system.

only 10 per cent). It is assumed that the maximum throttle deflection is 86° (1.5 rad). Hence:

$$K_E = 35\,000\,\text{N rad}^{-1}$$

The dynamic performance of this system is very greatly affected by the actuator dynamics. In Figure 11.11 are shown the speed responses which result for the same conditions and values of parameters that were used for the response shown in Figure 11.10, except that, in case A, the time constant of the actuator has been

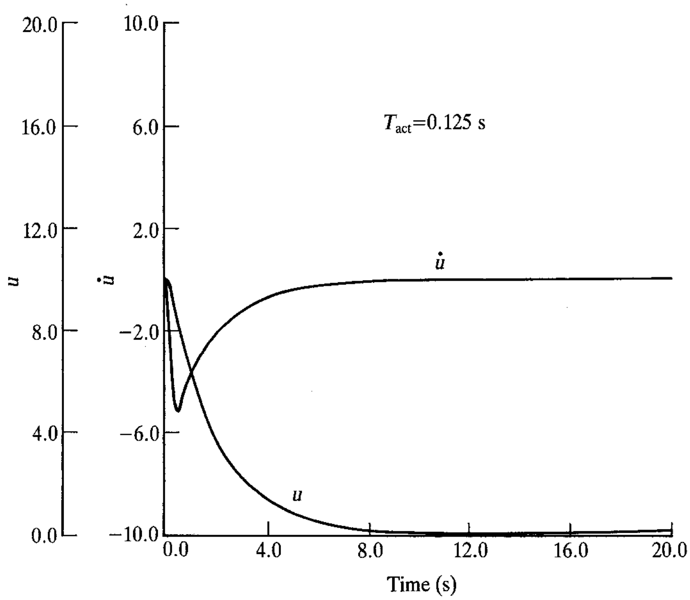

Figure 11.10. Response to initial airspeed error.

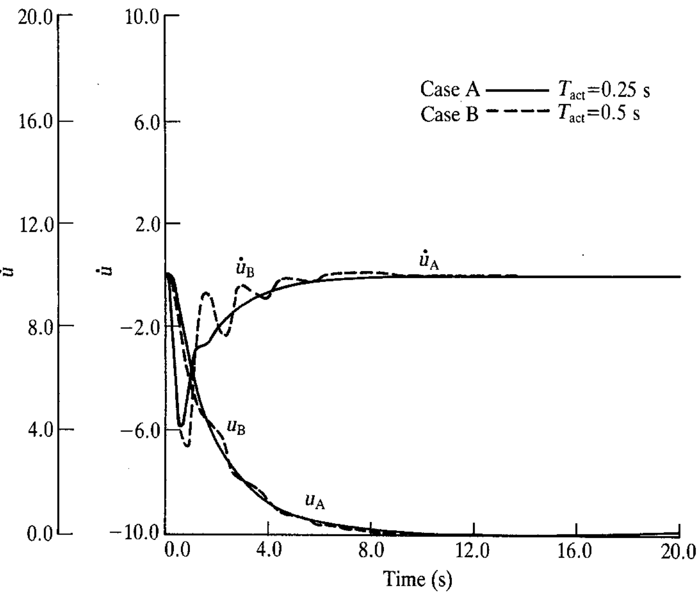

Figure 11.11 Response to initial $u(0)$ – effects of actuator time constant.

doubled ($T_{act} = 0.25$ s) and, in case B, the actuator's response is four times slower than the standard case, when $T_{act} = 0.125$ s. It can be seen how the response is beginning to be oscillatory. Further increases in the time constant of the actuator will lead to instability of the speed control system. Similarly, the dynamics of the airspeed sensor are crucial.

Figure 11.12 shows the dynamic responses to the same initial airspeed error, with the same flight condition and control parameters (the value of the time constant of the actuator being restored to 0.125 s). Case A represents the response when the value of time constant of the airspeed sensor was increased to 0.4 s and case B when its value was increased further, by a factor of 10. With the value of the proportional gain of the controller set at 25.0, and the sensitivity of the accelerometer reduced to 1 V m^{-1} s^{-2}, the response of the system to a reference speed command, which is a linear change of airspeed from 75.0 m s^{-1} to 70.0 m s^{-1} in 20 s, is shown in Figure 11.13. The resulting steady state speed error of approximately 0.3 m s^{-1} can be reduced by increasing K_{c_1} but the dynamic response will be destabilized by such an increase.

The improved dynamic response of the system can be clearly seen in Figure 11.14 which shows the responses to the same initial speed error of + 10 m s^{-1} but, in case A, with $K_{c_1} = 10.0$, and $K_{\dot{u}} = 2.0$, and, in case B, with $K_{c_1} = 25.0$, and $K_{\dot{u}} = 1.0$. Case B is the case used to obtain the ramp response shown in Figure 11.13. In Figure 11.14 the incipient oscillatory response with increased values of K_{c_1} can be seen in the acceleration ($\dot{u}$) responses.

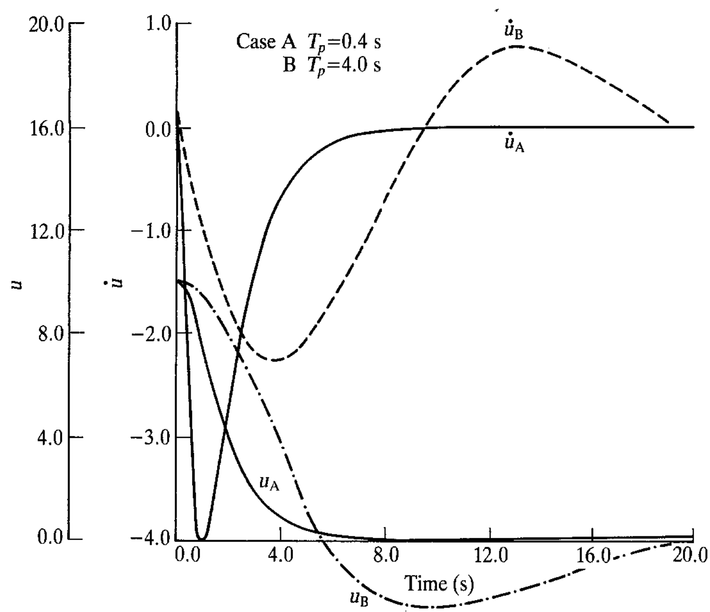

Figure 11.12 Response to $u(0)$ – effects of sensor time constant.

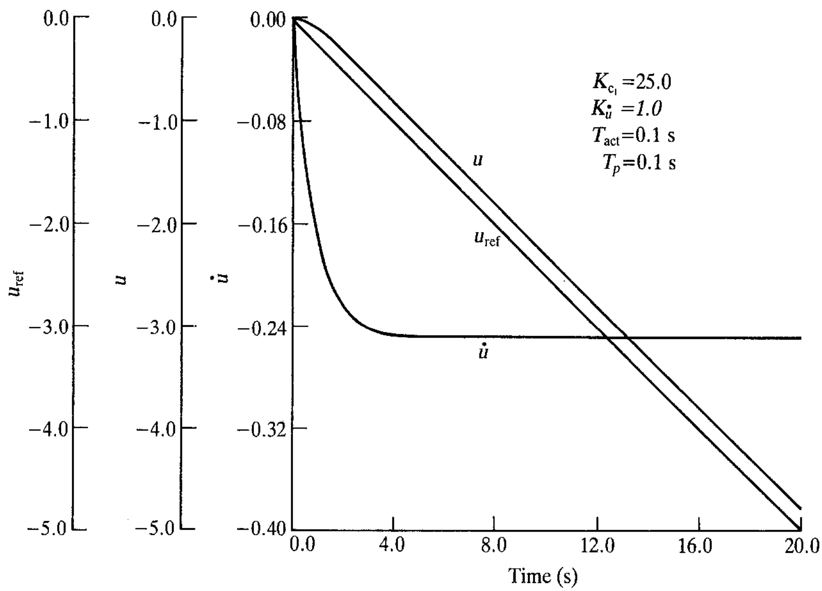

Figure 11.13 Ramp response of airspeed system.

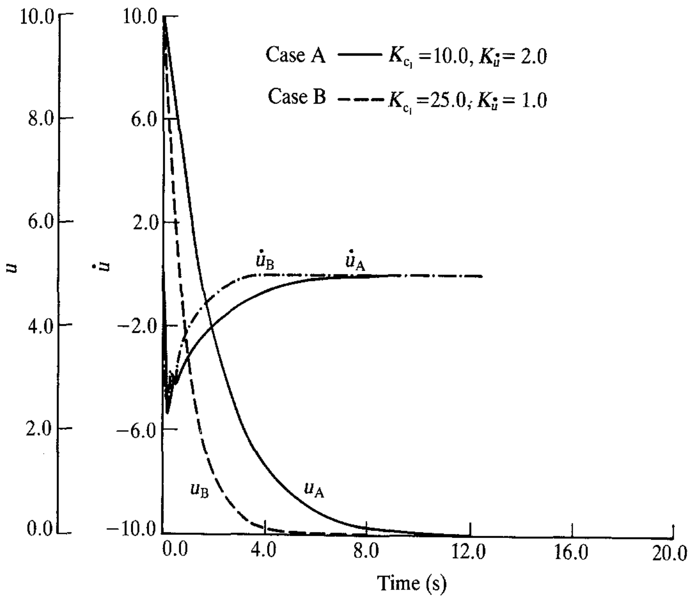

Figure 11.14 Response to $u(0)$ of modified airspeed system.

Further discussion of speed control systems can be found in McRuer *et al.* (1973) and Blakelock (1965).

11.4 MACH HOLD SYSTEM

Modern jet aircraft are often fitted with such a control system; its purpose is to hold the set Mach number in the presence of disturbances, provided that the change in height is not very great. Variations in Mach number can be represented by variations in velocity since:

$$M = V/a = (U_0 + u)/a \tag{11.8}$$

A block diagram of a typical system is shown in Figure 11.15. Note that speed is being controlled in this system by using elevator deflection. Since the elevator is being used, and the aircraft will be flying at large subsonic, or even supersonic, Mach numbers, the basic short period dynamics usually have to be augmented. A pitch rate SAS has been used as an inner loop in the system represented by Figure 11.15. For BRAVO-4, of Appendix B, the aircraft has a Mach number of 0.8. To illustrate how effective the system is, Figure 11.16 shows the results of a digital simulation of the system of Figure 11.15, with $T = 7.0$, $K_q = 5.0$ and $K_{c_1} = 10.0$, and being subjected to a horizontal wind shear, u_g, defined by:

$$u_g = -t \tag{11.9}$$

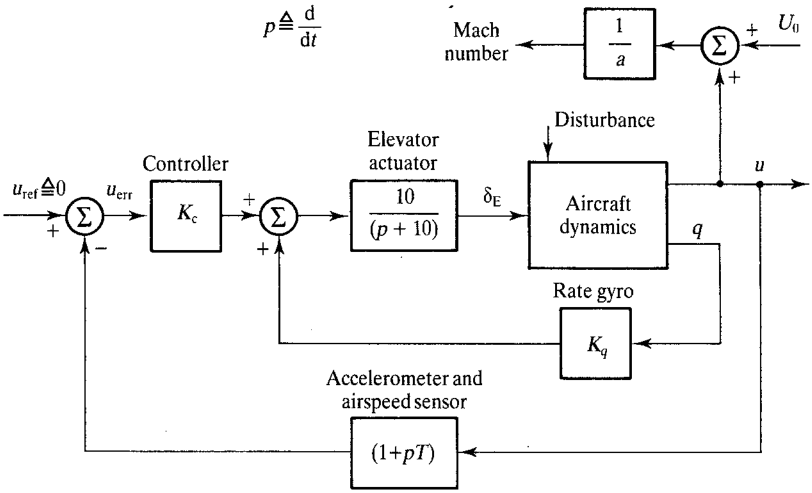

Figure 11.15 Mach hold system.

(i.e. u_g changes from 0 to $-$ 20 m s^{-1} in 20 s). It is evident from Figure 11.16 how effectively the speed and Mach number have been held nearly constant.

This splendid regulatory performance is not achieved, however, without adjustment of other motion variables of the aircraft. It can be seen, for example, from Figure 11.17, that the aircraft climbs by approximately 1 800 m to a new

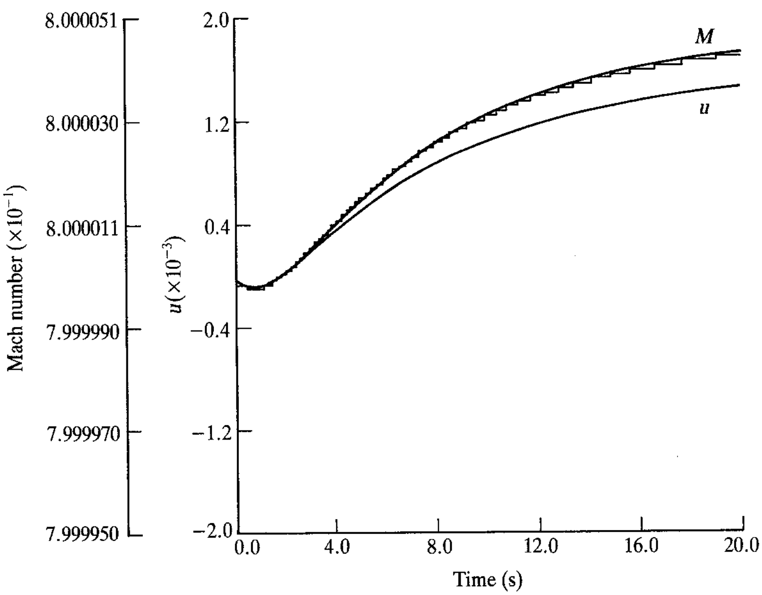

Figure 11.16 Response of Mach hold to horizontal shear.

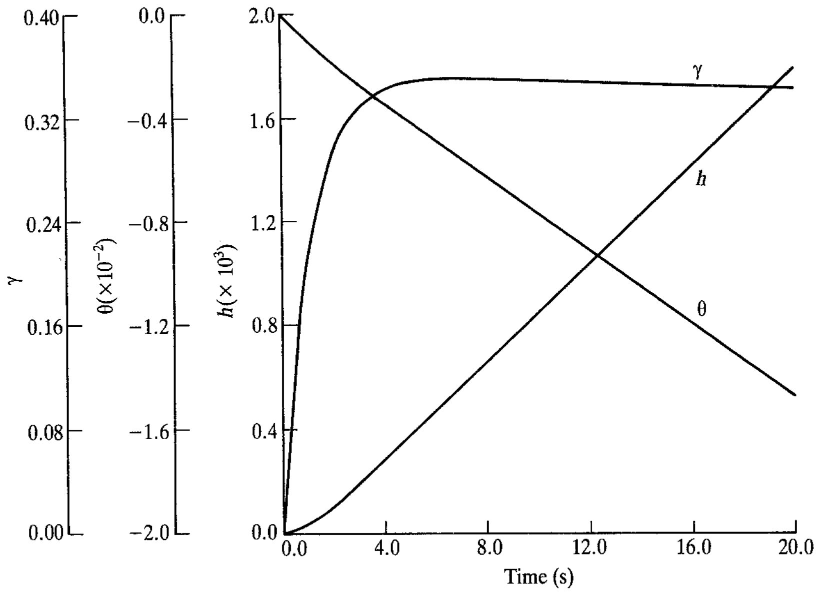

Figure 11.17 Response of motion variables to Mach hold shear.

height of 11 000 m. This dramatic climb occurs because the aircraft being studied is a very high performance fighter.

11.5 DIRECTION CONTROL SYSTEM

The purpose of such a system is to allow an aircraft to be steered automatically along some set direction. A block diagram representation of a typical system is shown in Figure 11.18. The heading of the aircraft is taken as its yaw angle, since it is assumed that any turn the aircraft makes under automatic control will be co-ordinated. Hence, any sideslip angle, β, is zero. It is shown in Section 10.5 of Chapter 10 that for small bank angles:

$$r = (g/U_0)\phi = \dot{\psi} \tag{11.10}$$

This equation is represented in Figure 11.18 by the blocks which have been labelled 'aircraft kinematics'. The aircraft heading is assumed to be sensed by a gyrocompass of sensitivity 1 V deg^{-1}, hence providing a unity feedback path. The control law for this direction control system is simply:

$$\phi_{comm} = K_{\Psi}(\psi_{ref} - \psi) \tag{11.11}$$

where the value of the controller gain, K_{Ψ}, can be determined by any of the appropriate design methods discussed in Chapter 7. The system shown relates to CHARLIE-2 and the bank angle control system being used is that derived as system B