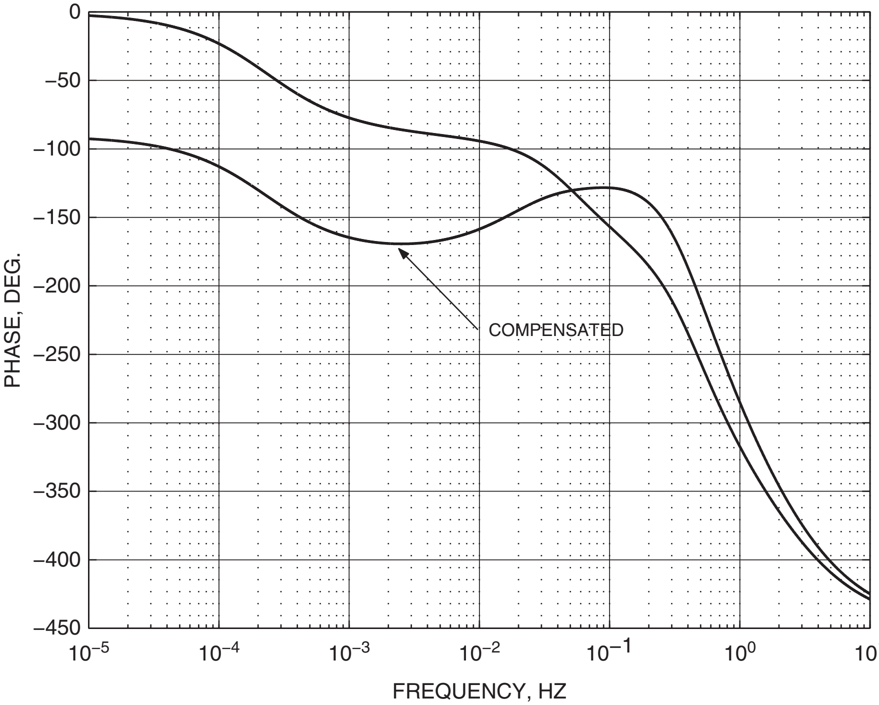

Figure 4.6-11*b* Bode phase plot for the automatic-landing *d*-loop.

causes the low-frequency phase lag to approach -180° (like a type-2 system) before the lead compensation begins to take effect.

When some close poles and zeros are canceled, the principal closed-loop transfer functions are

$$\frac{v_T}{v_c} \approx \frac{20.20(s+1)}{(s+7.627)(s+1.280 \pm j0.9480)} \tag{5}$$

$$\frac{d}{d_c} \approx \frac{677.0(s+1.40)(s+0.50)(s+0.20)(s+0.180)}{(s+16.2)(s+5.16 \pm j1.65)(s+1.38 \pm j1.69)(s+0.292 \pm j0.348)(s+0.179 \pm j0.0764)} \tag{6}$$

Note that in the d transfer function the slowest pair of complex poles is close to terminating on the zeros at $s = -0.18$ and $s = -0.20$. The step responses could be evaluated by a linear simulation using the closed-loop state equations. Instead a nonlinear simulation of the glide-path descent will be illustrated in Section 4.7. ■

Roll-Angle-Hold Autopilots

In its simplest form, as a wing leveler, the roll angle autopilot has a history going back to the experiments of Elmer Sperry (see Section Introduction). A sensor incorporating

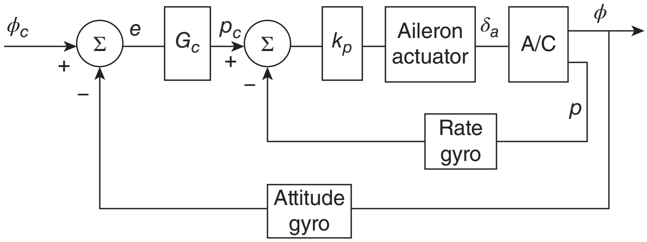

Figure 4.6-12 A roll angle control system.

an attitude reference, such as a gyroscope, is used to sense deviations from the vertical. Feedback of the deviation signal in the aircraft y-z plane to the ailerons can then be used to control the roll angle of the aircraft. The autopilot will hold the wings level and thus provide a pilot relief function for long flights and eliminate the danger of the pilot being caught unaware in a coordinated spiral motion toward the ground.

If the aircraft is held at some attitude other than wings level, additional control systems must be used to control sideslip and pitch rate, so that a coordinated turning motion is produced. Depending on the commanded pitch rate, the aircraft may gain or lose altitude in a turn. If a means of varying the roll reference is provided, the aircraft can be steered in any direction by a single control. These control systems can provide the inner loops for other autopilots that allow an aircraft to fly on a fixed compass heading or follow a radio navigational beam in the presence of cross-winds. Such systems will be described later.

Figure 4.6-12 shows a block diagram of a roll-angle-hold autopilot. High-performance aircraft virtually always have available a roll-rate gyro for use by a SAS or CAS, and this can be used to provide inner-loop rate damping for the autopilot. If the roll-rate gyro is not available, then for good performance, a compensator is needed in the roll angle error path. There is usually no requirement for precise tracking of roll angle commands, so type-0 roll angle control can be used. By the same token, the *velocity error* due to straight roll-rate feedback (i.e., no washout) is not important, particularly since the roll rate is not usually sustained for very long.

If the aircraft has strong roll-yaw coupling, the roll-angle-to-aileron feedback must be considered as part of a multivariable design, as in Sections 4.4 and 4.5. This is often not the case, and in the lateral transfer function, the poles associated with the directional controls are approximately canceled by zeros. The transfer function for the roll angle loop is then determined by the roll subsidence pole, the spiral pole, and the actuator and compensator (if any) poles. If roll-rate feedback is used, in conjunction with the roll angle feedback, there is good control over the position of the closed-loop poles and quite large amounts of feedback can be used. A roll angle autopilot design will now be illustrated.

Example 4.6-5: A Roll Angle-Hold Autopilot This example will use the controller subroutine from the lateral-directional CAS in Example 4.5-3 and with the same flight conditions. In Figure 4.6-12 the dynamics of the gyros will be neglected. With

$k_p = 0.2$, the closed-loop transfer function from the roll-rate command, p_c, to the roll angle in Figure 4.6-12 is found to be

$$\frac{\phi}{p_C} = \frac{182.7(s + 13.09)(s + 2.429 \pm j2.241)(s + 1.540)}{(s + 13.42)(s + 2.386 \pm j2.231)(s + 1.575)(s + 0.002116)(s + 11.78 \pm j10.96)} \quad (1)$$

or, approximately,

$$\frac{\phi}{P_c} = \frac{182.7}{(s + 11.78 \pm j10.96)(s + 0.002116)} \quad (2)$$

In this transfer function the complex pole pair arose from the actuator pole and the roll subsidence pole, and the real pole is the spiral pole. The spiral pole is close to the origin and approximates an integration between the roll rate and the roll angle. When the roll angle feedback loop is closed, the spiral pole moves to the left and the complex poles move to the right. The root-locus plot is shown in Figure 4.6-13.

A proportional gain (for G_c) of $k_\phi = 5.0$ gave the complex poles a damping ratio of $\zeta = 0.71$ (at $s = -8.88 \pm j8.93$), and the real pole was at $s = -5.4$. The roll angle control loop is well damped but unrealistically fast. The commanded attitude will be more tightly controlled in the steady state, but the aileron actuators may be driven

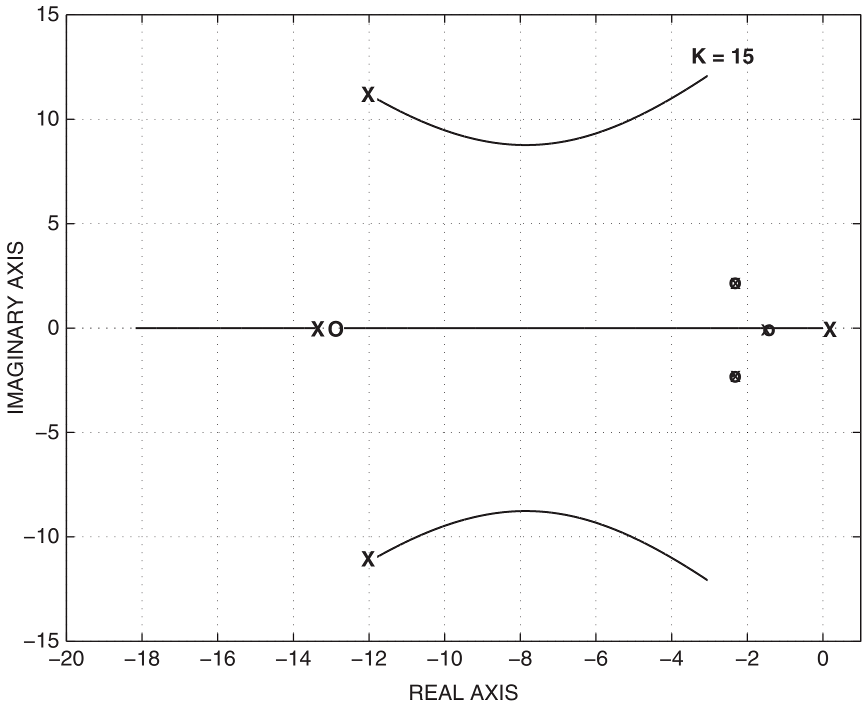

Figure 4.6-13 Root-locus plot for roll-angle-hold controller.

into rate limiting if abrupt roll angle commands are applied. This control system will be used in the next subsection in a nonlinear simulation. ■

Turn Coordination and Turn Compensation

A coordinated turn is defined as zero lateral acceleration of the aircraft cg (i.e., zero component of inertial acceleration on the body y-axis). In a symmetrical aircraft the components of acceleration in the plane of symmetry need not be zero, and so the coordinated turn need not be a steady-state condition. In an asymmetrical aircraft the sideslip angle may not be exactly zero in a coordinated turn because of, for example, asymmetric thrust or the effects of the angular momentum of spinning rotors. Turn coordination is desirable for passenger comfort and, in a fighter aircraft, it allows the pilot to function more effectively. In addition, by minimizing sideslip, it maintains maximum aerodynamic efficiency and also minimizes undesirable aerodynamic loading of the structure. Automatic turn coordination is also useful for a remotely piloted vehicle performing video surveillance or targeting.

In a coordinated turn, level or otherwise, the aircraft maintains the same pitch and roll attitude with respect to the reference coordinate system, but its heading changes continuously at a constant rate. Therefore, the Euler angle rates $\dot{\phi}$ and $\dot{\theta}$ are identically zero, and $\dot{\psi}$ is the turn rate. The Euler kinematical equations (1.3-21) show that, under these conditions, the body-axes components of the angular velocity are

$$\begin{aligned} P &= -\dot{\psi} \sin \theta \\ Q &= \dot{\psi} \sin \phi \cos \theta \\ R &= \dot{\psi} \cos \phi \cos \theta \end{aligned} \tag{4.6-3}$$

If the aircraft is equipped with angular rate control systems on each axis these rates can be computed, and then they can be used as the controller commands to produce a coordinated turn. In level flight, with small sideslip, the turn coordination constraint is given by Equation (3.6-7):

$$\tan \phi = \frac{\dot{\psi}}{g_D} \frac{V_T}{\cos \theta} \tag{4.6-4}$$

If $\cos \theta \approx 1.0$, then, for a specified turn rate $\dot{\psi}$, the required pitch and yaw rates can be calculated and the roll rate can be neglected. This produces a quite satisfactory level turn.

Alternative coordination schemes include feedback of sideslip or lateral acceleration to the rudder or computing just a yaw-rate command as a function of measured roll angle [see Blakelock (1965) for details]. If, in addition, a pitch-rate command is calculated from the above equations as a function of roll angle, the turn can be held level. This is referred to as "turn compensation" (Blakelock, 1965); it can also be achieved by using altitude feedback to the elevator. An example of turn coordination is given in Example 4.7-5.