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CASE STUDY II – AN AIRCRAFT AUTOMATIC LANDING SYSTEM

11

11.1 INTRODUCTION

A fully automatic aircraft landing system provides an interesting example of an engineering system for which simulation techniques offer important advantages at the design stage. Although system evaluation through flight trials is very important in the development of a complex control system of this kind, much useful work can be carried out through simulation. Safety considerations are always of paramount importance in aircraft systems, and simulation experiments are both safer and less costly than flight trials, especially in the initial stages of system testing and evaluation. Simulation techniques can also provide the engineer with valuable insight which is difficult to obtain by other methods.

Maneuvers of a conventional fixed-wing aircraft are normally achieved using control surfaces, such as the elevator, ailerons and rudder, which apply forces and moments to the vehicle and thus generate angular accelerations about the pitch, yaw and roll axes. Figure 11.1 shows these control surfaces and defines the axes. Direct control of translational velocity can be achieved only through variation of engine thrust. Hence, in attempting to follow a chosen trajectory in the sky, as in a landing system, control is achieved indirectly through changes of pitch attitude, roll attitude and heading. Attitude-control systems are therefore of fundamental importance for flight-path control and thus for all forms of automatic landing system.

One form of radio system capable of feeding signals to the aircraft flight-control system is known as the instrument landing system (ILS). Basically this is a short-range navigational aid which provides azimuth (i.e. horizontal) position information and vertical position data relative to a defined glide-slope path. The parts of the ILS system which are on the ground are the 'localizer' transmitter, which provides azimuth approach data, the 'glide-slope' transmitter, which provides vertical approach information, and 'marker' beacons, which provide information on the distance to the runway. The aircraft carries the receiving antennae for the three signals transmitted from the ground and the associated ILS receiver unit. There is also an indicator display device on the aircraft to show the pilot whether or not the aircraft is on the correct approach path.

The localizer transmitter is positioned at the far end of the runway relative to the approaching aircraft. It transmits a radio-frequency signal in a band from 108 MHz to 112 MHz. Two signals are transmitted, one to the left and one to the right of the runway center-line, as shown in Fig. 11.2. The signal transmitted to the left is modulated by a 90-Hz signal, while that on the right is modulated by a signal at 150 Hz. The transmission patterns for the two radio-frequency signals overlap along the runway center-line. When an aircraft is approaching the runway in line with the central axis, the ILS receiver picks up the 90-Hz and 150-Hz signals with equal strength. If the aircraft deviates to the left, the strength of the 90-Hz signal will be greater than that of the 150-Hz signal and, conversely, if there is a deviation to the right, the

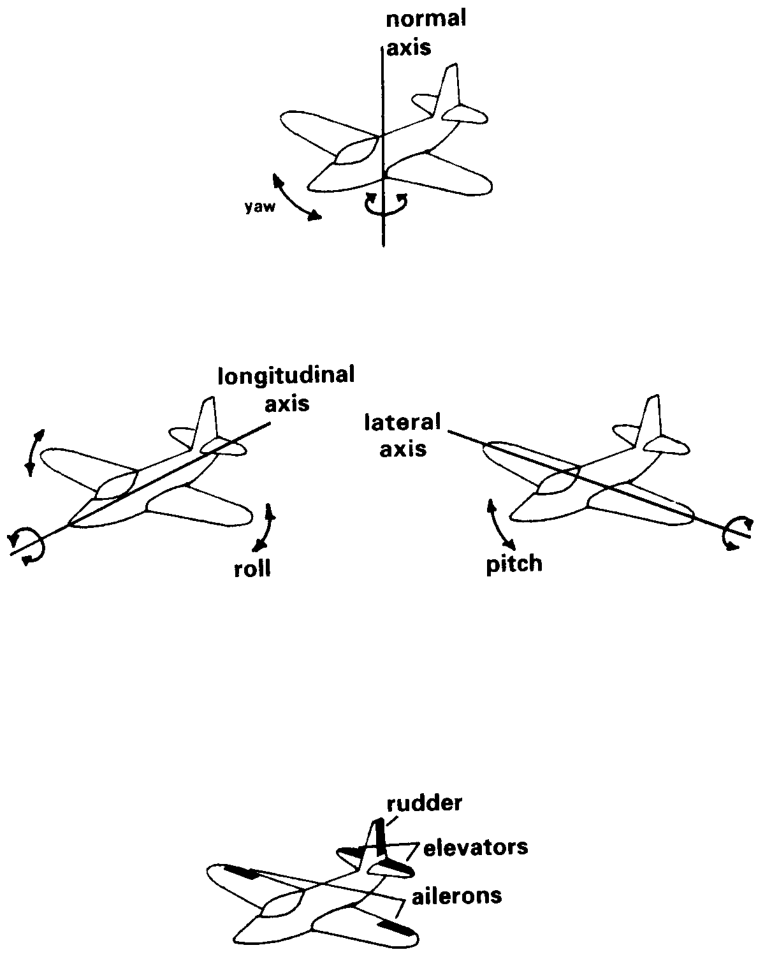

Fig. 11.1 The longitudinal (roll), lateral (pitch) and normal (yaw) axes of a conventional fixed-wing aircraft, together with the control surfaces which are used to apply control forces and moments to the vehicle.

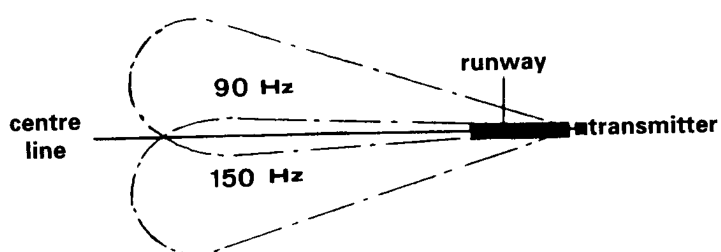

Fig. 11.2 Radio transmission patterns associated with the localizer transmitter within an instrument landing system (ILS).

150-Hz signal will be greater. The received signals provide the input for the indicator display device and can also provide a reference for the directional control system. The linking of the ILS receiver output and the autopilot reference input is carried out using a 'coupler' unit.

The glide-path transmitter is located near the point of touchdown on the runway and transmits on a given frequency in the band 329.3 MHz and 335.0 MHz. The radiated signal pattern is similar to that of the localizer transmitter. When on the correct descent path the aircraft receives the 90-Hz and 150-Hz signals with equal strengths and the horizontal pointer takes up a central position on the ILS display device. In this case the ILS receiver can be linked to the longitudinal attitude-control system of the aircraft and provides information which ensures that the aircraft follows the glide path.

This chapter is concerned with a case study which involves the lateral beam guidance system, which uses the localizer signal to align the aircraft with the runway. The second major component of the landing system, which ensures that the aircraft descends on the correct glide slope, is not considered in this simulation study. The two systems are very similar in terms of their block diagram structures and, since they are essentially independent in their operation, they can be investigated separately. In developing a mathematical model for the lateral guidance system it is necessary first to describe the aircraft's directional control system. Preliminary investigation of this subsystem, which is of central importance for lateral guidance, provides an interesting illustration of simulation methods for control system studies.

Aircraft models are well understood and well documented. Therefore, in this particular study, emphasis has been placed on the process of building up a simulation program to represent a system provided in block diagram form and on the use of the simulation to investigate a nonlinear closed-loop system model which could not be studied using analytical methods alone. No consideration has been given to the question of model validation in this particular study. In an application such as this, in which a simplified model is used for the analysis and design of a flight-control system, validation might well be carried out by comparing the performance of the reduced model with a more versatile and complex model, which had been the subject of separate investigations in terms of model validity. An incremental approach has been adopted in which the simulation model of the lateral beam guidance system is built up from a simpler linear model of a directional-control system. This allows verification to be carried out through comparisons with results from linear systems theory.

11.2 MODELING AND SIMULATION OF AN AIRCRAFT DIRECTIONAL-CONTROL SYSTEM

In general, an uncontrolled aircraft has no inherent tendency to return to its initial heading and roll attitude after some disturbance from equilibrium. Thus, in the absence of any kind of flight-control system, the pilot must make corrections continually in order to maintain a required heading and attitude. Directional-control systems can provide a means of ensuring that a reference heading is maintained without pilot intervention.

One particular form of directional-control system will be examined in detail. In this case the system being controlled is the coordinated aircraft, which incorporates coupling between the aileron and rudder. Such coupling allows coordinated maneuvers to be made, and only the overall transfer function between the aileron input and the roll angle need be considered. A block diagram for the control of heading is shown in Fig. 11.3. It may be seen from this that the system involves three feedback loops. The outermost loop involves the feedback of the

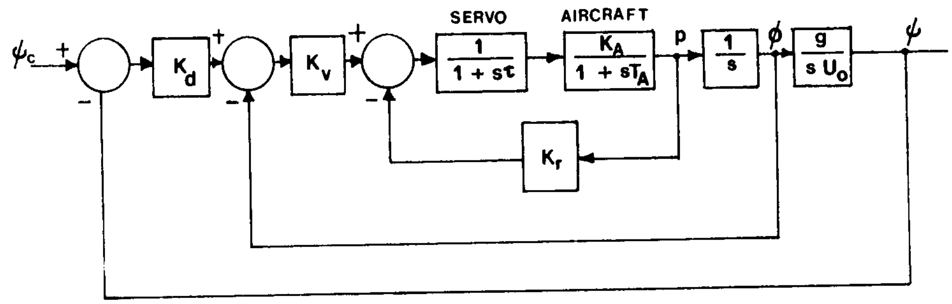

Fig. 11.3 Block diagram of an aircraft directional-control system.

variable of primary concern, which is the heading angle. This feedback is provided through the action of a directional gyroscope. The other two loops provide secondary feedback signals which are needed to ensure that the overall system has an acceptable dynamic response. The block diagram shows that the second pathway involves roll angle feedback, via the vertical gyroscope, while the innermost loop has roll rate feedback. It should be noted that the aircraft description adopted here is a highly simplified one, and that a detailed description of a practical flight-control system would involve a significantly more complex block diagram. Further details of aircraft flight mechanics modeling and of flight-control systems may be found, for example, in the texts by Blakelock [1] and McLean [2]. The reference quantity is the heading angle commanded by the pilot or provided as an electronic signal from some other system within the aircraft. The various gain constants associated with the feedback pathways in this system (K_d, K_v and K_r) are chosen at the design stage to ensure that steady-state and dynamic performance specifications are met.

The transfer function of the coordinated aircraft, relating the roll rate, p, to the aileron deflection angle, δ_a, has the form

$$\frac{K_A}{1+sT_A} \tag{11.1}$$

where K_A is a gain factor and T_A is a time constant associated with this highly simplified description of aircraft lateral dynamics.

Similarly, in terms of the roll angle, ϕ, for an aileron deflection angle, δ_a, we have a relationship of the form

$$\frac{K_A}{s(1+sT_A)} \tag{11.2}$$

The control-surface actuation system can be described approximately by a transfer function

$$\frac{1}{1+s\tau} \tag{11.3}$$

where τ is a time constant.

The three transfer functions given above, and which appear in the block diagram, may be converted readily to a state-space form of model using the methods discussed in Chapter 3. This state-space description has the form shown in equations (11.4), (11.5) and (11.6).

$$\frac{dp}{dt} = -\frac{1}{T_A}p + \frac{K_A}{T_A}\delta_a \tag{11.4}$$

$$\frac{d\phi}{dt} = p \tag{11.5}$$

$$\frac{d\delta_a}{dt} = -\frac{1}{\tau}\delta_a + \frac{1}{\tau}e_s \tag{11.6}$$

An additional relationship is needed to allow the heading angle to be related to the roll attitude. For small angles of roll, ϕ, it may

```
        DYNAMIC
            DERIVATIVE
              PSID=PHI*G/U0
              PSI=INTEG(PSID,PSI0)
              PHIC=(PSIC-PSI)*AKD
              EV=PHIC-PHI
              ES=EV*AKV-PHID*AKR
              DAD=(ES-DA)/TAW
              DA=INTEG(DAD,0.0)
              Q=(AKA*DA-PHID)/TA
              PHID=INTEG(Q,PHID0)
              PHI=INTEG(PHID,PHI0)
            DERIVATIVE END
            TYPE T,PSIC,PHID,PHI,PSI
            IF(T-15.0)10,10,12
10      DYNAMIC END
12      STOP
        END
```

Fig. 11.4 Listing of the DYNAMIC and TERMINAL segments of the SLIM program ALASH.SLI for simulation of an aircraft directional-control system. Variable names in the program are, in most cases, very similar to the corresponding variables of the mathematical model. The complete source program may be found on the diskette.

be shown (e.g. ref. 2) that the angular velocity of the aircraft in terms of heading, $d\psi/dt$, can be related to the forward velocity, U_0, and the roll angle, ϕ, by the equation

$$\frac{d\psi}{dt} = \frac{g}{U_0}\phi \qquad (11.7)$$

where g is the gravitational constant

Three additional algebraic equations are necessary to define the structure of the feedback system. These are as follows:

$$e_s = K_v e_v - K_r p \qquad (11.8)$$

$$e_v = K_d e_d - \phi \qquad (11.9)$$

$$e_d = \psi_c - \psi \qquad (11.10)$$

Typical parameter values for this system are as follows:

$T_A = 2.0$ s; $K_A = 1.0$; $\tau = 0.1$ s; $g = 9.81$ m s^{-2}; $U_0 = 60$ m s^{-1}; $K_r = 2.5$, $K_v = 2.5$; and $K_d = 2.0$.

Figure 11.4 shows part of a simple SLIM program for simulation of this system. The complete source program (ALAS-.SLI) may be found on the diskette. The parameter values describing the aircraft itself are assigned in the initial region of the program, while the additional gain constants involved in the feedback loops are read in by means of an ACCEPT statement. The program has been written in this way because interest is focused particularly on the flight-control system and the effect of the gain in each of the three feedback loops on the overall performance. Using an ACCEPT statement for the parameters of particular interest simplifies experimentation. Initial conditions are also established from data provided by the user through ACCEPT statements, as is information concerning the magnitude of the reference heading. The SLIM source program would need to be edited to perform other simulation experiments for different values of the aircraft parameters such as K_A or τ. The choice of communication interval, CINTERVAL, of 0.1 allows graphical output to be provided having sufficient resolution in terms of the time axis to show all transient events of interest. It should be noted that, although the program includes MINTERVAL, MERROR and XERROR statements, the values used are all default values and the program would give identical results if these lines of code were omitted. An experiment duration time of 15 s has been defined in the program. This could easily be made a variable and could be defined by the user at runtime through an additional ACCEPT statement in the initial region of the program.

Sample results, in terms of time histories of heading angle (ψ) and roll angle (ϕ) following a step change of heading reference (ψ_c), of magnitude 0.15 rad, are shown for three values of the directional gyroscope gain (K_d) in Figs 11.5, 11.6 and 11.7. The results in Fig. 11.5 show that, for the nominal value of directional gyroscope gain factor ($K_d = 2.0$), the response of the system to the step input is stable, rapid and shows no tendency to oscillate in terms of the heading variable. As could be expected, there is a marked transient in roll angle but this variable returns to zero as the aircraft attains the desired heading. A reduced value of the directional

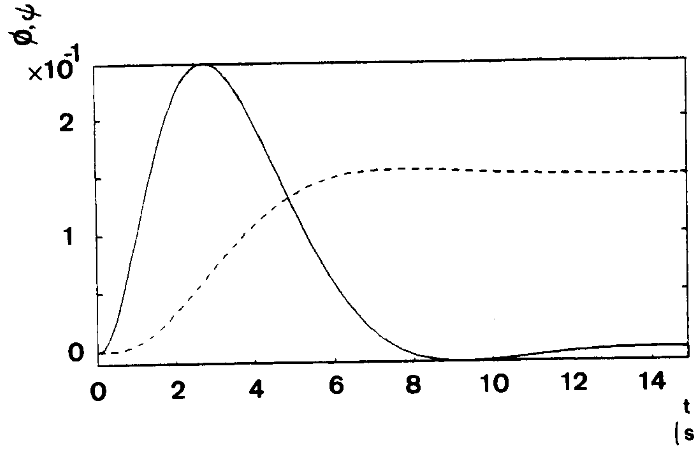

Fig. 11.5 Results from a simulation experiment on the aircraft directional-control system showing time histories of the heading angle (dashed line) and the roll angle (continuous line) in response to a demanded step change of heading of 0.15 rad. The value of the directional gyroscope gain factor (K_d) in this case was 2.0, while the parameters K_r and K_v were both 2.5.

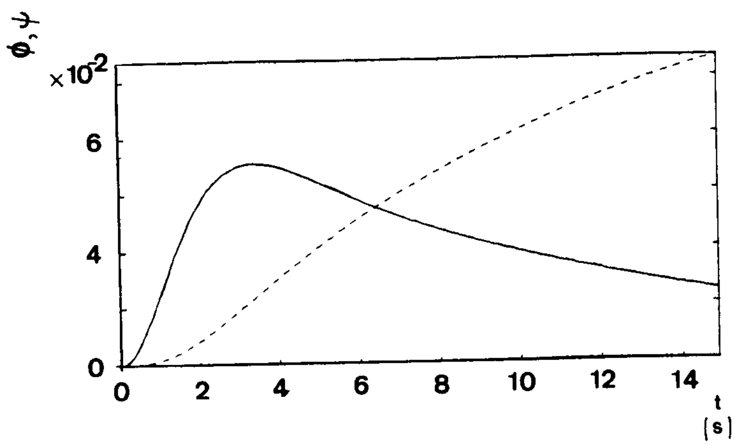

Fig. 11.6 Results obtained from simulation of step test on directional-control system for a directional gyro gain factor of 0.5. Values of the other parameters read in from the input data file were the same as for the case given in Fig. 11.5.

gyroscope gain factor (0.5) produces a very sluggish response (Fig. 11.6) in which the required heading is not attained within the 15-s duration of the simulation experiment. The performance, in this case, is clearly inferior to that of the system with the higher value of gain. However, increasing the gain factor can produce other problems, as shown in Fig. 11.7, where a value of K_d of 8.0 gives a highly oscillatory response, which is again unsatisfactory for a system of this kind. Although the mathematical tools of linear systems analysis could be applied very readily to a linear system such as this, the use of a simulation can provide opportunities for additional understanding, particularly in

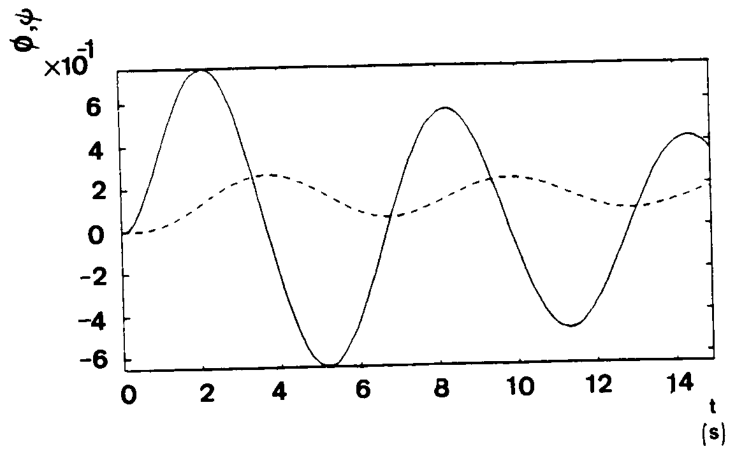

Fig. 11.7 Results similar to those of Figs 11.5 and 11.6 for a directional gyro gain factor of 8.0.

terms of parameter sensitivity analysis of the kind illustrated by these results. Linear theory also provides opportunities to verify the simulation program. In this case, for example, the simulation could be used very readily to establish stability limits in the directional-control system and selected sets of results from the simulation could be compared with results obtained by applying standard stability tests from control theory, such as Nyquist's criterion.

11.3 MODELING AND SIMULATION OF A LATERAL BEAM GUIDANCE SYSTEM

The lateral beam guidance system is based upon the directional-control system described in section 11.2. In the lateral guidance application the directional reference input, ψ_c, is derived from the ILS receiver output.

Figure 11.8 is a block diagram of the lateral beam guidance system which must be interpreted in conjunction with Fig. 11.9. This shows the geometry of the situation and defines some of the variables used in the block diagram.

The variable ψ_{ref}, which represents the heading to be followed, would be set by the pilot and, for simplicity, this reference value is taken to be zero in the equations which follow. An error angle, λ, is related to the lateral displacement, y, and the range, R, by the equation

$$\sin\lambda = \frac{y}{R} \qquad (11.11)$$

Hence, for small angles

$$\lambda \simeq \frac{y}{R} \qquad (11.12)$$

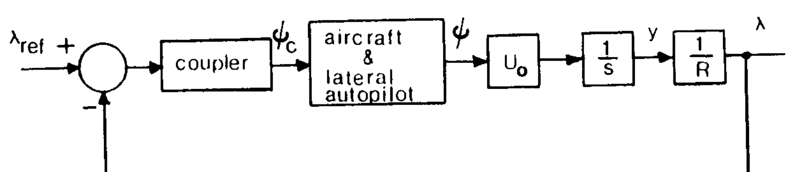

Fig. 11.8 Block diagram of the lateral beam guidance system.

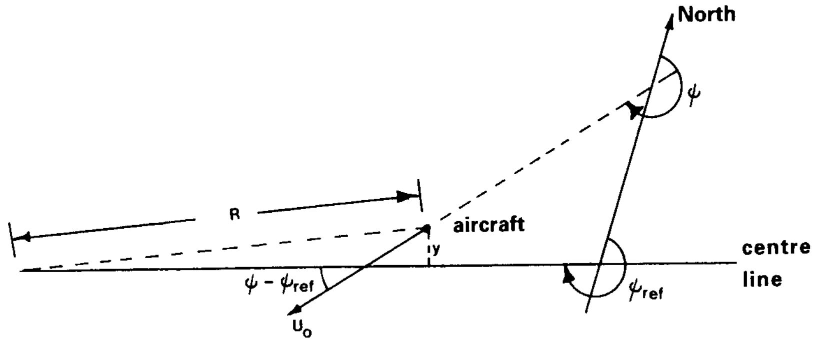

Fig. 11.9 Geometry of lateral beam guidance.

Also, it follows from the geometry of Fig. 11.9 that the rate of change of displacement, dy/dt, is related to the aircraft velocity, U_0, by the equation

$$\frac{dy}{dt} = U_0 \sin(\psi - \psi_{ref}) \tag{11.13}$$

Thus, for a small angle ψ and for a zero value of reference heading (ψ_{ref}), it follows that

$$\frac{dy}{dt} \simeq U_0\psi \tag{11.14}$$

The signal from the localizer course correction receiver is approximately proportional in magnitude to the angle λ and, for the case where λ_{ref} is zero (see Fig. 11.8), the output of the coupler is given by

$$\psi_c \simeq G_c \frac{y}{R} \tag{11.15}$$

where G_c is the gain of the coupler. Combining the block diagram of Fig. 11.8 with the block diagram of the directional flight-control system gives the complete structure of the lateral beam guidance system, as shown in Fig. 11.10.

The parameter set for the lateral beam guidance system includes all of the parameters of the directional flight-control system of section 11.2 and, in addition, the coupler gain parameter values for the outer loop of $G_c = 8.0$. In some cases the coupler involves a transfer function of a more complex form, incorporating proportional plus integral control in a transfer function of the form

$$G_c(s) = G_c\left(1 + \frac{K_I}{s}\right) \tag{11.16}$$

This coupler transfer function provides a controller that has a form which is very common

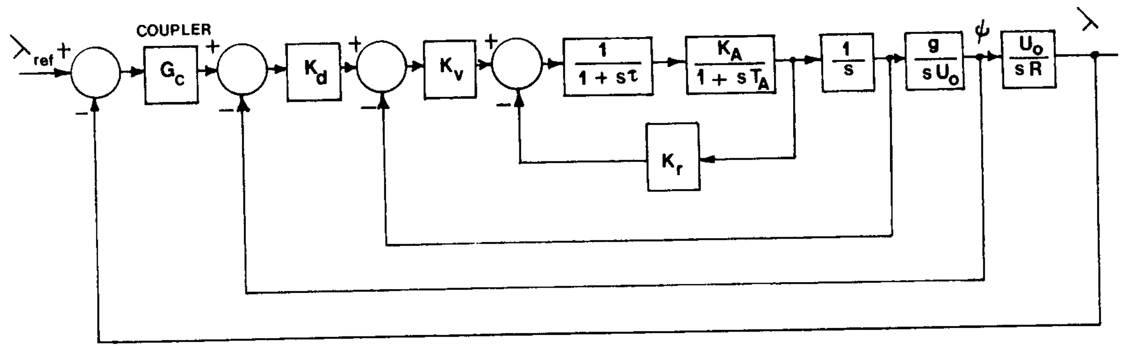

Fig. 11.10 Block diagram showing the detailed structure of the lateral beam guidance system.

in many other control system applications. It is known as a proportional plus integral controller and can ensure zero steady-state errors in the presence of a steady external disturbance, such as a cross-wind in this instance. The parameter K_I is taken as zero in the examples considered here.

Figure 11.11 shows the DYNAMIC segment of a SLIM program for simulation of the lateral beam guidance system. The complete program (AILS.SLI) is provided on the diskette. The parameter values for the aircraft and directional-control system are assigned in the initial region together with the coupler gain parameter which is input through an ACCEPT statement along with the aircraft velocity. Once again, initial conditions, in terms of the initial range, initial deviation from the runway center-line, initial heading and aircraft velocity, are also input through ACCEPT statements in the initial region. Initial conditions for other variables of the directional flight-control system are all set to zero. The range is scaled to provide values in kilometers instead of meters. This is done mainly to make the labeling of the range axis more convenient. The structure of the derivative region is essentially the same as that for the directional flight-control system simulation

```
         DYNAMIC
            DERIVATIVE
               YD=U0*PSI
               Y=INTEG(-YD,Y0)
               R=INTEG(-U0,R0)
               ALAMB=Y/R
               PSIC=GC*ALAMB
               PSID=PHI*G/U0
               PSI=INTEG(PSID,PSI0)
               PHIC=(PSIC-PSI)*AKD
               EV=PHIC-PHI
               ES=EV*AKV-PHID*AKR
               DAD=(ES-DA)/TAW
               DA=INTEG(DAD,0.0)
               Q=(AKA*DA-PHID)/TA
               PHID=INTEG(Q,PHID0)
               PHI=INTEG(PHID,PHI0)
            DERIVATIVE END
            RP=R/1000.0
            TYPE T,PHI,PSI,Y,RP
            IF(T-90.0)10,10,12
10       DYNAMIC END
12       STOP
         END
```

Fig. 11.11 Listing of the DYNAMIC and TERMINAL segments of a SLIM program (AILS.SLI) for simulation of the lateral beam guidance system. Variable names in the program are, in most cases, similar to the corresponding variables of the mathematical model. The complete program may be found on the diskette.

program with additional statements to allow for the presence of the outer feedback loop involving the coupler.

Figures 11.12, 11.13 and 11.14 show the response of the system in terms of plots of the lateral deviation, y, versus time for three

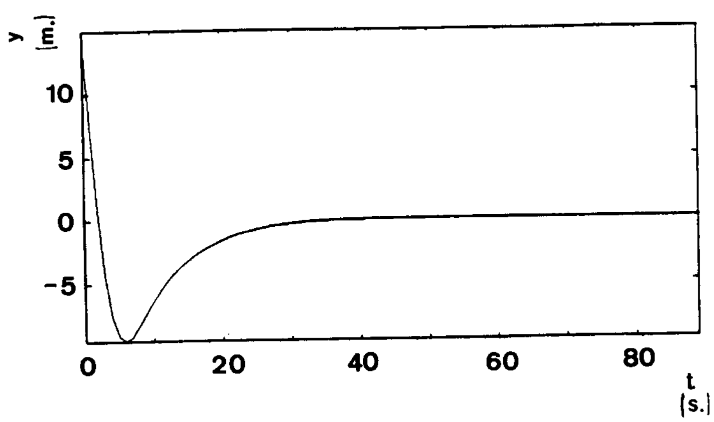

Fig. 11.12 Simulation results from AILS.SLI showing response of the lateral beam guidance system in terms of the deviation, y, versus time for a coupler gain factor G_c of 8.

different values of the coupler gain (G_c = 8.0, G_c = 16.0 and G_c = 32.0). In each case the initial position of the aircraft is 6000 m from the point of touchdown on the runway and 15 m from the center-line in terms of lateral error. For the two lower values of coupler gain the trajectory is clearly of a satisfactory form and the final lateral error is zero or has a very small value. With the largest of the three gain factors the results show a trajectory which is clearly unstable. More detailed examination of this case (Fig. 11.14) shows that the initial part of the trajectory involves a damped oscillation and only the later part of the response shows a diverging oscillations characteristic of a truly unstable system. This behavior is a result of the nonlinear nature of the lateral beam guidance system. Examination of Fig. 11.9 suggests that the system becomes steadily more sensitive as the aircraft approaches the transmitter because the angle λ increases for a given lateral error, y, as the range, R, becomes smaller. This is reflected in Fig. 11.8 by the presence of a block involving a gain factor inversely proportional to R. The loop gain in the outer loop of the feedback system therefore increases as the range becomes smaller, and this explains the type of behavior shown in Fig. 11.14. Although stable for large values

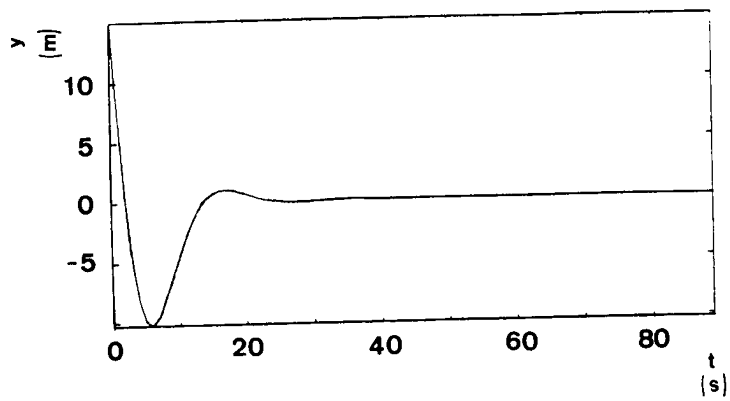

Fig. 11.13 Simulation results for the lateral beam guidance system model for G_c = 16.

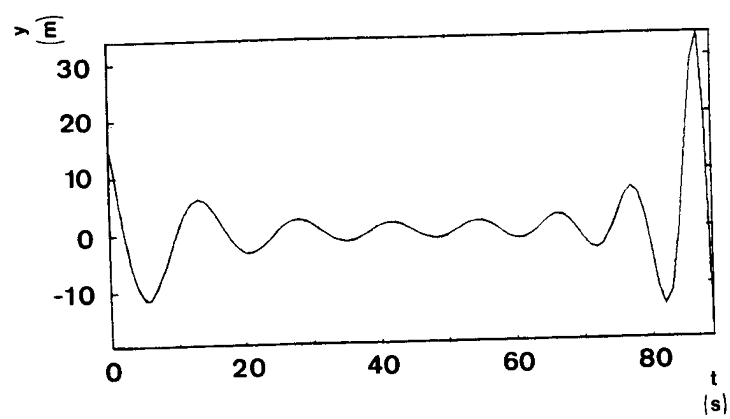

Fig. 11.14 Simulation results for the lateral beam guidance system model for G_c = 32.

of R, the system becomes unstable as R decreases. In this case, linear theory would provide relatively little information about the complex nature of the system and could not be used to predict the form of the response for the situation considered in this investigation, which involves a large change in R.

Another fact of considerable importance is that the performance of both the directional flight-control system and the lateral beam guidance system depend upon the approach velocity U_0. The performance is influenced considerably by this quantity and also by the initial conditions. Unlike a linear system in which the nature of the system response is the same for different initial states, the lateral beam guidance system model has a behavior which depends to a considerable extent on the initial lateral deviation, aircraft velocity and initial range. Investigation of the model behavior for different sets of initial conditions is left to the reader as an exercise using the lateral beam guidance model file provided on the accompanying diskette.

In a practical system of this kind extensive use is made of gain-scheduling techniques, with the coupler gain factor being adjusted according to range information. This gain-scheduling feature of the real system overcomes the major variations of performance with range. This has not, of course, been included in the simple model being considered here. However, the simulation does provide opportunities to investigate the very interesting nonlinear dynamics of the system with constant coupler gain and could easily be extended by the reader to include some form of scheduled coupler gain. Similarly, the introduction of integral control in the coupler is an exercise which could be carried out without difficulty by any reader interested in assessing the performance of the model when subjected to external heading disturbances. The modifications to the SLIM program provided are relatively minor for both these cases [3].

11.4 DISCUSSION

This case study involves the modeling and simulation of a relatively complicated nonlinear multiloop feedback control system. Mathematical models of fixed-wing aircraft are well established and their limitations are well understood and documented. Little consideration is therefore given in this example to questions of model validity. Emphasis is given instead to the control systems aspects of the simulation model and to the use of simulation experiments to reveal the complex and highly nonlinear nature of the system behavior. Similar insight could not be obtained from analytical studies based on linearized models. As with the system in Chapter 10, a nonlinear computer simulation model provides a basis for very valuable testing of the control system prior to any practical implementation in terms of real hardware. This is particularly important in a safety-critical application such as aircraft flight control.

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