Aerospace Engineering Dept. Faculty of Engineering Cairo University
Giza, 12613, Egypt

قسم هندسة الطيران و الفضاء
كلية الهندسة
جامعة القاهرة
الجيزة – جمهورية مصر العربية

AER408
Aerospace Guidance & Control Systems

Task (6)
Lateral Autopilot Design

Introduction:

The objective in this part of our project is to design ***"The lateral Autopilot"*** for a conventional fixed wing airplane. The rule of the lateral autopilot is to control the motion of the airplane in the lateral-directional plane, shortly ***"it controls the rudder & aileron to achieve a coordinated turn"***, and when added to ***"The longitudinal Autopilot"*** we can achieve the so-called ***"coordinated level turn"***

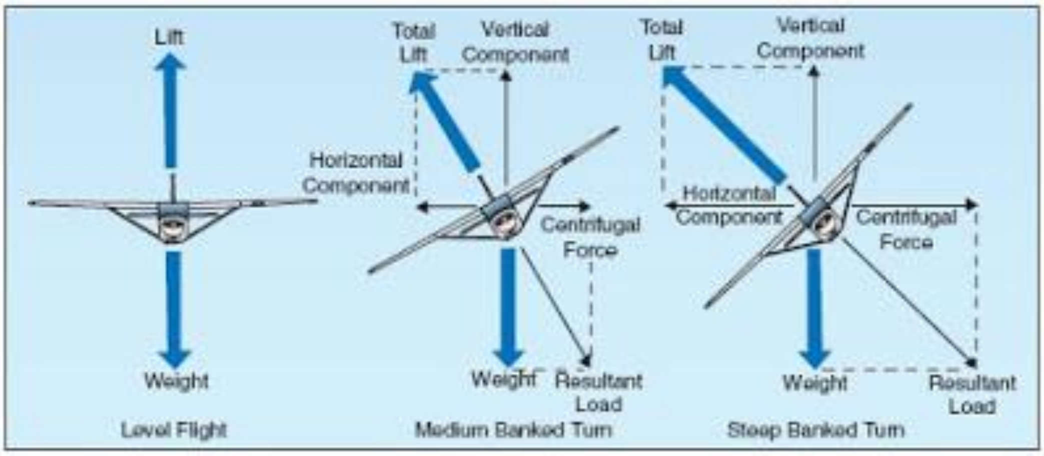
We will use the linearized state space model of the lateral dynamics (5x5) to represent the motion of the airplane in the lateral-direction plane, and the "Successive loop closure" method will be used to design the lateral autopilot

What is the *"coordinated turn"*?

It can be defined in terms of **"mechanics"** and in terms of **"Aerodynamics"** and both conditions are equivalent. If one condition is satisfied, then the other condition is satisfied as well

In terms of mechanics:

The coordinated turn is a maneuver in which the airplane's heading angle is changed (airplane turns) without experiencing any lateral acceleration, i.e. the resultant of the centrifugal acceleration due to turning and the acceleration due to gravity is acting along the **(z-body axis)** of the airplane. We may call it ***"zero-lateral acceleration turn"***

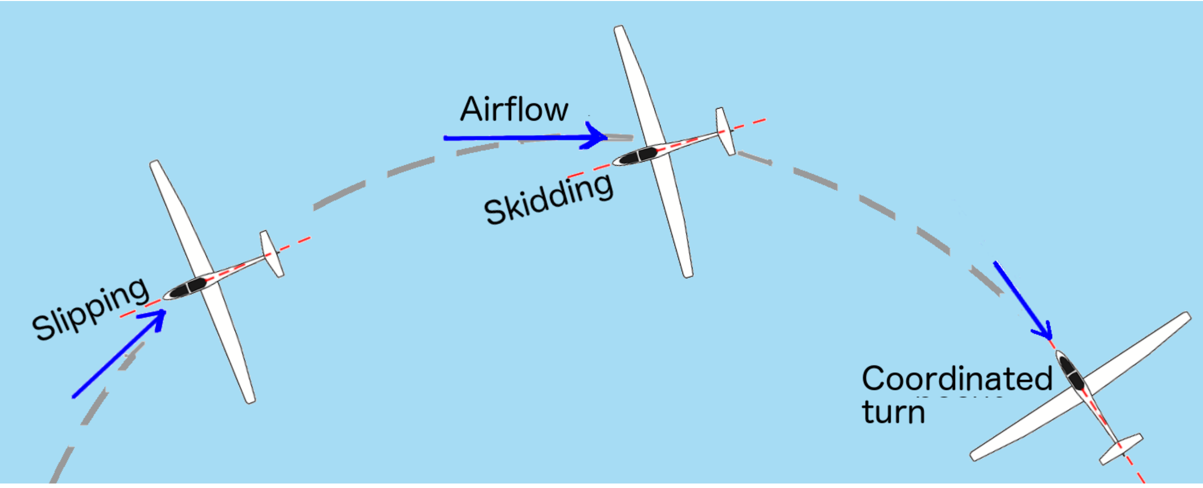


In terms of Aerodynamics:

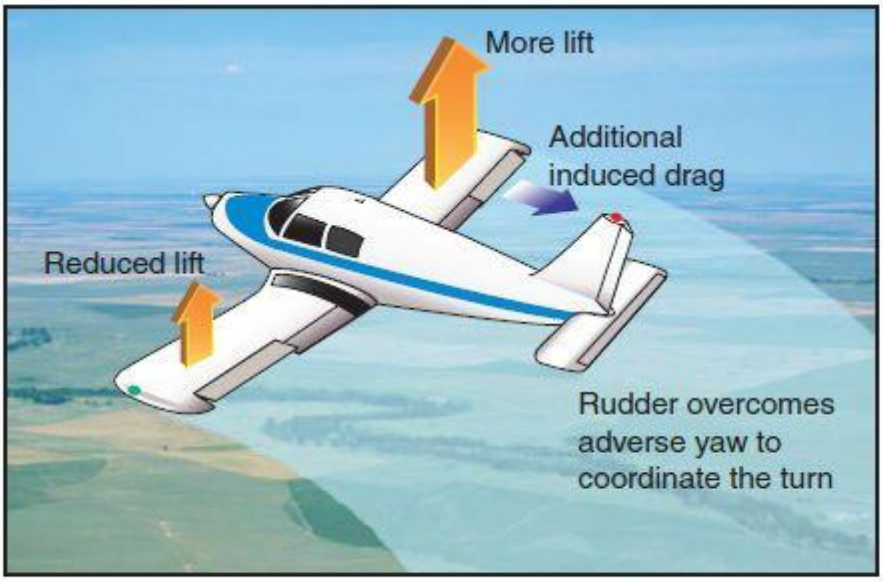
The coordinated turn is a maneuver in which the airplane's heading angle is changed (airplane turns) without "**slipping** or **skidding"**, i.e. the side slip angle **(β = 0)**.

note:

skidding is having +ve sideslip angle **(β>0)** while slipping is having -ve sideslip angel **(β<0)**



By default, any airplane performing a turn will experience slipping, this is due to what is called **"adverse yaw"**. When ailerons are deflected, the lift of one wing increases and the lift of the other wing decreases, the difference in the lift forces generates the rolling moment that banks the airplane. However, the same phenomenon occurs to the drag, it is increased on one side and decreased on the other, generating a yawing moment on the airplane and it is called "adverse yaw"



Why should we perform *"coordinated turn"* while turning?

In terms of mechanics:

For the comfort of passengers, a passenger should not feel any lateral acceleration while the airplane is turning. If a lateral acceleration component presents the passenger will feel a side force pushing him to the right or the left direction, of course such a condition is not acceptable

In terms of mechanics:

flying with a non-zero sideslip angle increases the drag of an airplane, and hence increases the power consumption, so side slipping is not favorable in either manned or unmanned airplanes

How to perform a *"coordinated turn"*?

To perform a coordinated turn the pilot should use both the (aileron & rudder) to produce the required bank angle (Φ) and yawing acceleration (r) to achieve no slip or zero-lateral acceleration while turning

Briefly the pilot does the following:

- deflect the ailerons to bank the airplane in the direction of the turn
- the pilot should observe the slipping of the airplane in order to eliminate it, this is achieved by the "turn coordinator" dial in the cockpit, it contains a glass tube with a free ball inside, if there was a side way acceleration component the ball is moved from the center of the tube

Coordinated Turn Skid Slip

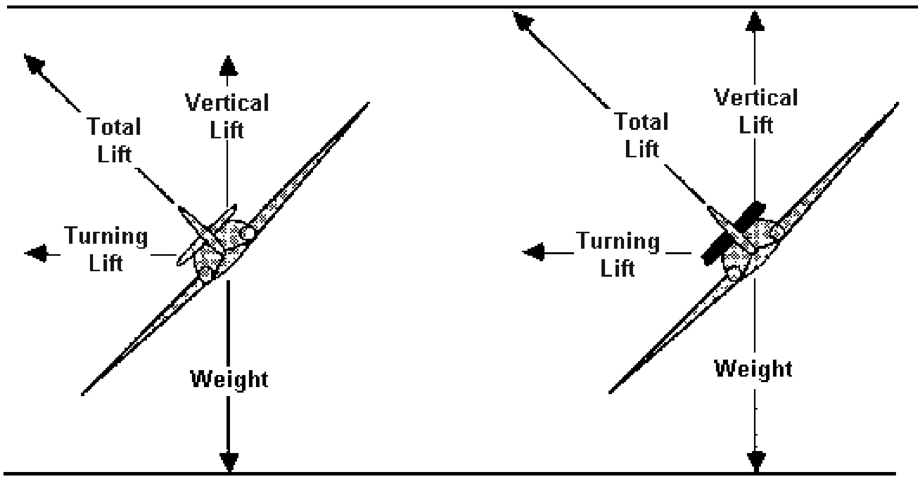
- the pilot observes the position of the ball, and start to deflect the rudder in the direction that will vanish the lateral acceleration component, i.e. the ball is returned to the center of the tube

Watch this video for clearer explanation https://www.youtube.com/watch?v=DqA2o9dq_vg

Now having understood the “coordinated flight” maneuver, what is meant by “coordinated level turn”?

During cruise the lift is vertical and is equal to weight, but when the airplane is banked, the lift vector with the same magnitude is inclined and its vertical component is less than the weight and is in the opposing direction, so the airplane starts to lose altitude

To keep the altitude constant, the total lift of the airplane should be increased. This is achieved by deflecting the elevator to increase the lift of the tail and thus the total lift of the airplane in order to make the vertical component of the lift equal to the weight as shown in the figure.



Bank angle, Turning component of lift, and Weight are equal in both cases

In manned flight, the pilot should control the (aileron, rudder & elevator) in order to perform “coordinated level turn”, in case of autopilot operation a lateral autopilot is designed to control the (aileron & rudder) to achieve “coordination” and the ***“Altitude hold controller”*** designed previously will control the (elevator) to keep the altitude constant, and thus we can achieve “coordinated level turn”

Remarks:

- The loops design proposed in this task are not obligatory, you are totally free to use any control architecture you want to control your airplane with and the total response will judge your design

- The following loops are based on "Micro pilot autopilot manual" + the reference "Automatic control of Aircraft and missiles" + Autopilot course from “MIT open courseware”

Task Statement:

a) Design a "Yaw damper" for the Dutch roll mode

Block diagram: the block diagram designed is shown in the figure. It includes the transfer function of the pitch rate (r) w.r.t the elevator deflection (δ_r) i.e. (r/δ_r). Also we can see the transfer function representing the servo dynamics which is the actuator that deflects the elevator

The rule of the "Yaw damper" is to modify the damping of the (Dutch roll mode) which is lightly damped. For lateral dynamics there is no table for the desired damping ratio like the "Cooper-Harper flying qualities" table

There is a nice example in MATLAB control toolbox which represents the design of a yaw damper for Boeing 747 airplane, you can follow the example to design your controller. In this example a desired value of 0.35 for damping ratio is used, use this value for your design

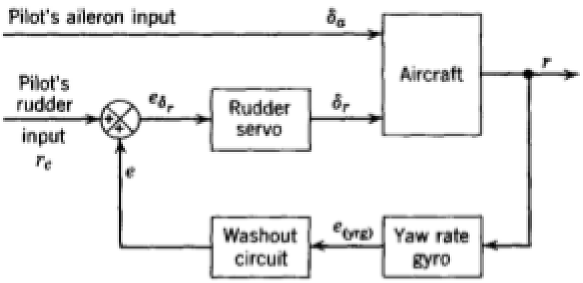


Figure 4-2 Block diagram of Dutch roll damper.

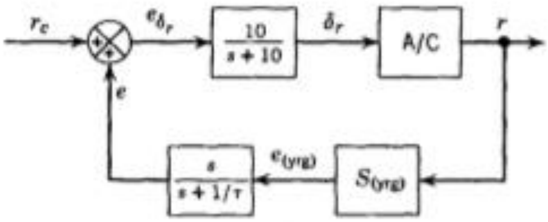


Figure 4-3 Block diagram of the Dutch roll damper for the root locus study;

b) Test the "Yaw damper" on the full state space model

Test your controller with an aileron command as used in Blakelock and show your results

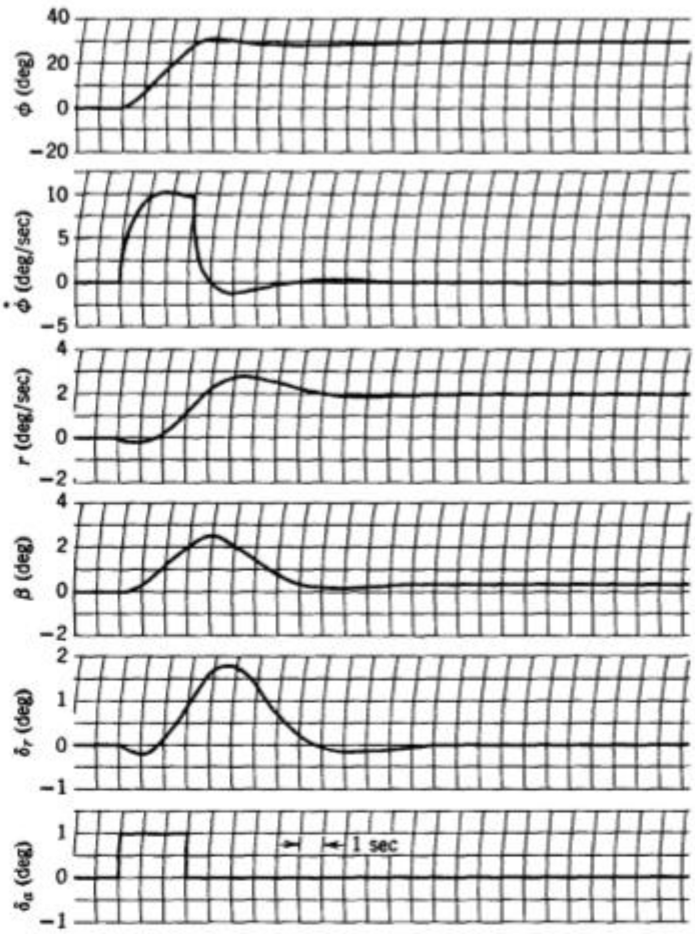


***Figure 4-6** Response of the aircraft with Dutch roll damping for $S_{(yrg)}$ = 1.04 volt / (deg / sec) for a pulse aileron deflection (sea level at 440 ft / sec).*

c) Design "Roll Controller"

Block diagram: the block diagram designed is shown in the figure. It includes the transfer function of the roll angle (Φ) w.r.t aileron (δ_a) i.e. (Φ / δ_a) but for the "coordinated airplane. Also, we can see the transfer function representing the "servo" dynamics

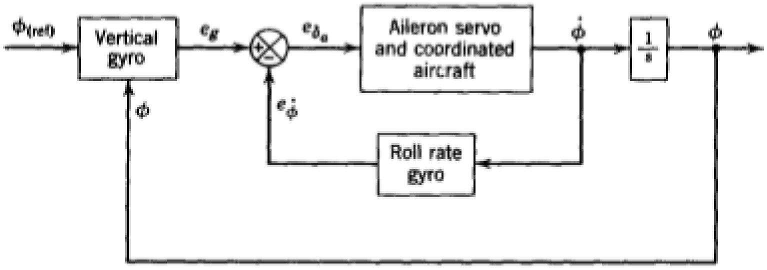
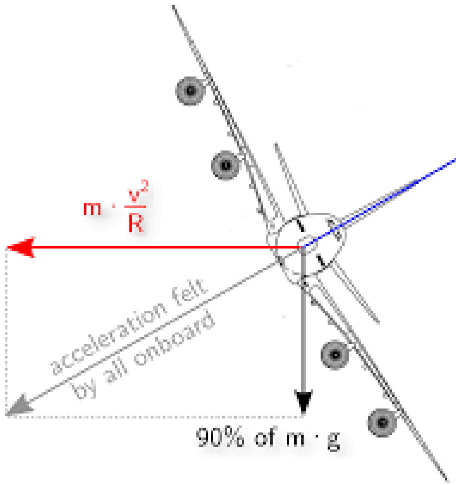


***Figure 4-39** Block diagram of roll angle control system.*

You need first to get the closed loop dynamics of the airplane after adding the "yaw damper" then start the design of the "Roll controller"

d) Coordination

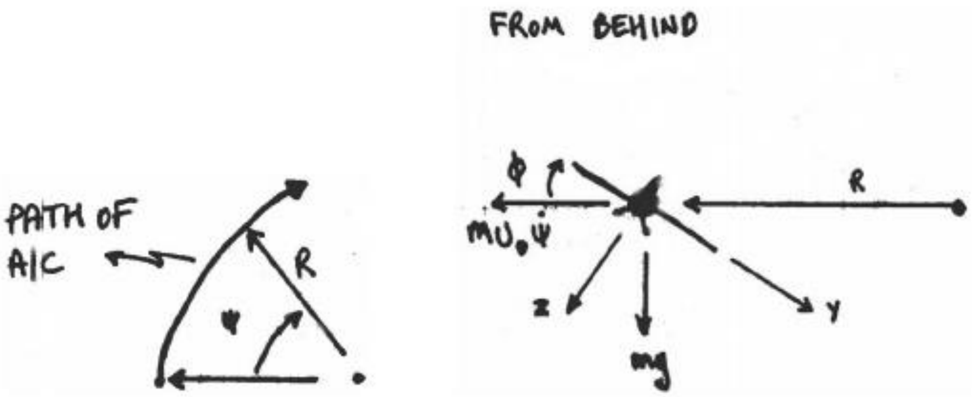
As stated previously, coordination can be achieved when total lateral acceleration is equal to zero, this can be achieved at a certain bank angle (Φ) for a given speed (Uo) and turning rate (Ψ^o), this value of (Φ) can be found from the free body diagram of the airplane during turn



Note: Tangential velocity is (Uo)

$$U_0 = R\dot{\Psi}$$

Where R is the Raduis of turn



Aircraft banked to angle φ so that vector sum of (mg) and ($mU_0\dot{\psi}$) is along the body z-axis

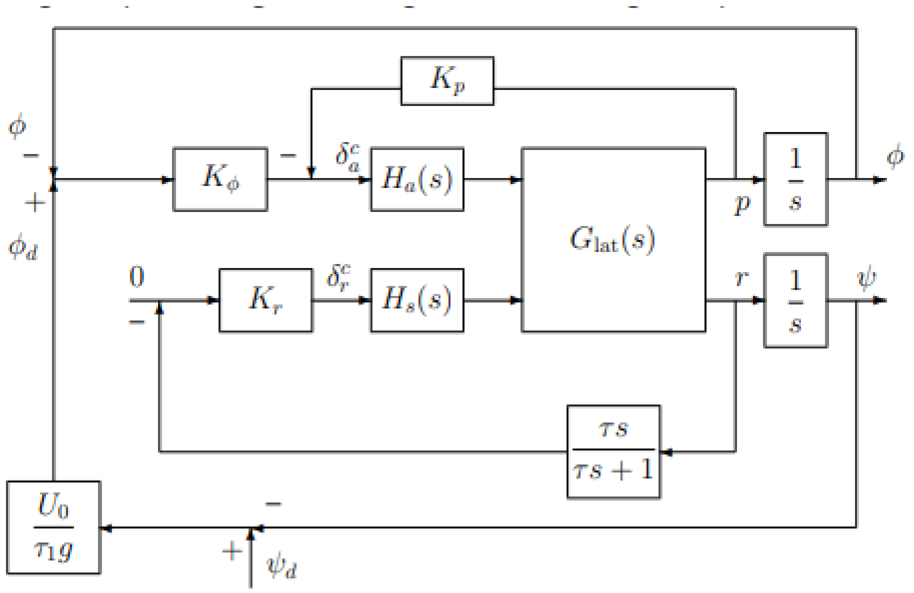
Summing in the body yaxis direction gives

$$mU_o\dot{\Psi}\cos\emptyset = mg\sin\emptyset$$

$$\therefore \tan\emptyset = \frac{U_o\dot{\Psi}}{g}$$

$$\therefore \emptyset \approx \frac{U_o \dot{\Psi}}{g}$$

This gives the desired bank angle for specified velocity and turn rate, please review the notes from the “MIT course” to understand how to close the outer loop



e) Test the designed controllers on the full state space model

Now you can add your controllers together to work simultaneously on the airplane using the simulink model

Note: put a limit on the “Φcom” to be ±30°, and on the rudder deflection “δ_r” to be ±15°, and on the aileron deflection “δ_a” to be ±50°as the δ_a is the sum of both left and right aileron deflections

Test the response for a stwp input of 360° in heading, and check the settling time and check if the coordination is achieved or not by viewing the slip angle (β)