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Auto-Pilot
1. Longitudinal auto-pilot
2. Lateral auto-pilot
3. AP basic principles
4. Flight Management System
1. Longitudinal auto-pilot

Introduction
1 Displacement auto-pilot
2 Pitch speed control system
3 Acceleration control system
4 Vertical speed control
5 Mach speed control
6 Altitude control
1. Longitudinal auto-pilot

Introduction

Note: in all block diagrams, all sum blocks are with a feedback as:

![Diagram]

even if + & - symbols do not appear.
1. Longitudinal auto-pilot

Introduction

Control surface actuator:

so far, various Transfer Functions (TF) that represent the aircraft dynamics have been seen, still missing some control systems:

• **Servo actuators** are used to deflect the aerodynamic control surfaces: either electrical, hydraulic, pneumatic or some combination of the 3. Typically their TF is of a 1\(^{st}\) order system.

• Transfer functions for any **sensors** in the control loop: attitude gyro, rate gyro, altimeter or velocity sensor: TF for most sensors can been approximated by a gain K.
1. Longitudinal auto-pilot

Displacement AP

- first auto-pilot was developed by Sperry Corporation
- linked a gyroscopic attitude with a magneto-compass to the rudder, the elevator and the flaps (with hydraulic system)
- allowed the plane to flight straight and leveled without pilot’s attention
- “straight-and-level” AP is the most common and thus the cheapest
- low error due to the use of simple control systems
1. Longitudinal auto-pilot

Displacement AP

- pitch/attitude angle: between horizontal and longitudinal axis

- plane *trimmed* to reference pitch → turned on AP
- if pitch angle varies, voltage $e_g$ is generated → amplified → servo-elevator (hydraulic for ex.), positions the elevator
  → pitch movement so that the aircraft moves with the desired pitch angle
1. Longitudinal auto-pilot

Displacement AP

Transfer function represents aircraft dynamics

Remember: 6 hypothesis:

1. X and Z axis in the plane of symmetry of the aircraft and its gravity center = origin of the system of axis
2. Aircraft has a constant mass
3. Aircraft = rigid solid
4. Earth = inertial reference frame
5. Small perturbations with respect to the equilibrium
6. Leveled, non accelerated, non turbulent flight
1. Longitudinal auto-pilot

Displacement AP

Longitudinal model transfer function

Elevator’s movement:

\[(13.78s + 0.088)u(s) - 0.392\alpha(s) + 0.74\theta(s) = 0\]
\[1.48u(s) + (13.78s + 4.46)\alpha(s) - 13.78s\theta(s) = -0.246\delta_e(s)\]
\[(0.0552s + 0.619)\alpha(s) + (0.514s^2 + 0.192s)\theta(s) = -0.710\delta_e(s)\]
1. Longitudinal auto-pilot

Displacement AP  

Short period oscillation mode

- study of the oscillation frequency and damping factor after the perturbation
- fast damping without effort from the pilot

Angle of attack $\alpha$ in green
Attitude angle $\theta$ in blue
1. Longitudinal auto-pilot

Displacement AP

Short period oscillation mode considered for:

2 examples:

- conventional transport aircraft flying at 150mph at sea level
- jet flying at 600 ft/sec at 40,000 ft
1. Longitudinal auto-pilot

First aircraft

Response to a step entry for a non-corrected TF, in open loop

\[ G(s) = \frac{-(s + 3.1)}{s(s^2 + 2.8s + 3.24)} \]
First aircraft

\[ G(s) = \frac{-(s + 3.1)}{s(s^2 + 2.8s + 3.24)} \]

Aircraft #1 rootlocus (non-corrected)
1. Longitudinal auto-pilot

First aircraft, basic correction

- amplifier: proportional controller: $K$ gain
- servo-elevator: first order system
- vertical gyroscope: sum + sensor (not represented)

1 block
First aircraft, basic correction

\[ K_{se} = 77.5 \]

\[ G_C = \frac{-K_{se}}{s + 12.5} \cdot \frac{-(s + 3.1)}{s(s^2 + 2.8s + 3.24)} \]

rootlocus, corrected
1. Longitudinal auto-pilot

First aircraft, basic correction

Closed loop response to a step entry,

for $\xi=0.6 \rightarrow K_{se}=8.8$
1. Longitudinal auto-pilot

Second aircraft

\[ G(s) = \frac{-1.39(s + 0.306)}{s(s^2 + 0.805s + 1.325)} \]

Step response for a non-corrected TF, in open loop
1. Longitudinal auto-pilot

Second aircraft

\[ G(s) = \frac{-1.39(s + 0.306)}{s(s^2 + 0.805s + 1.325)} \]

root locus (non-corrected)
1. Longitudinal auto-pilot

Second aircraft, basic correction

\[
\frac{-K_se}{s+10}\quad \text{Transfer Fcn} \quad \frac{-1.39s-0.425}{s^3+0.805s^2+1.325s}\quad \text{Transfer Fcn1}
\]
1. Longitudinal auto-pilot

Second Plane, Basic correction

\[ G_C(s) = -\frac{K_{se}}{s + 10} \cdot \frac{-1.39(s + 0.306)}{s(s^2 + 0.805s + 1.325)} \]

Corrected root locus

\[ K_{se} = 38.4 \]
1. Longitudinal auto-pilot

Second aircraft, Basic correction

Closed loop response to a step input with $K_{se}=9 \rightarrow \xi=0.17$

→ unacceptable response, airplane has very little natural damping and AP is not efficient enough
1. Longitudinal auto-pilot

Displacement AP

Pitch rate feedback

Need to increase damping of the short oscillation mode by adding an inner feedback loop

→ feedback is added affecting pitch rate
1. Longitudinal auto-pilot

Displacement AP

Pitch rate feedback

for this problem we now have 2 parameters to select, using root locus method and trial and error procedure
1. Longitudinal auto-pilot

Pitch rate feedback

$K_{va} = 1.82$

$K_{va} = 1.21$

Aircraft 2, root locus of the inner loop
Pitch rate feedback

Aircraft 2 rootlocus in the outer loop for $K_{va}=1.21$

$K_{amp}=14$

$K_{ampCR}=138$
1. Longitudinal auto-pilot

Pitch rate feedback

![Step response for $K_{amp}=14$](image)

Step response for $K_{amp}=14$
1. Longitudinal auto-pilot

Pitch rate feedback

Aircraft 2 rootlocus in the outer loop for $K_{va} = 1.82$

$K_{amp} = 30$

$K_{ampcr} = 190$
1. Longitudinal auto-pilot

Pitch rate feedback

Step response for $K_{\text{amp}}=30$
1. Longitudinal auto-pilot

Displacement AP

• no rule to select $K_{va}$ but, for a bigger $K_{va}$ value, bigger stability margin and faster response is obtained

• pitch rate feedback controls the jet well enough, but is always better to have a Type I system (here we had it already) to cancel the position error in steady state
1. Longitudinal auto-pilot

**Speed AP**

Input: desired pitch rate; to obtain a type I system a integrator gyro is added through a direct loop

![Block diagram of Speed AP](image)

*Control stick steering* used to position the elevator, and keeping pressure on the stick, pitch rate is maintained
1. Longitudinal auto-pilot

**Speed AP**

Used in aircraft with bad longitudinal stability

→ *pitch up* occurs, which causes stall for great angles of attack

→ either you use a limiter of angle of attack

→ or a automatic control system is used, which would allow the aircraft to fly with angles of attack higher than the critical one
1. Longitudinal auto-pilot

Speed AP

Study case: *high performance combat fighter:*

\[
G_1(s) = \frac{\dot{\theta}}{\delta_e} = \frac{-15(s + 0.4)}{s^2 + 0.9s + 8}
\]

For low angles of attack (stable condition)

\[
G_2(s) = \frac{\dot{\theta}}{\delta_e} = \frac{-9(s + 0.3)}{(s + 3.8)(s - 2.9)}
\]

For high angles of attack (unstable condition)
1. Longitudinal auto-pilot

Stable condition, internal loop

- $K_{va} = 0.67$
- $K_{va} = 0.25$

Root locus of the inner loop for low angles of attack
1. Longitudinal auto-pilot

Stable condition, external loop

Outer loop root locus, for $K_{va}=0.25$

- $K_{amp}=0.57$
- $K_{ampcr}=3.16$
1. Longitudinal auto-pilot

Stable condition, step response

Step response for $K_{va}=0.25$ and $K_{amp}=0.57$
1. Longitudinal auto-pilot

Stable condition, external loop

Outer loop root locus, for $K_{va} = 0.67$

- $K_{amp} = 2.5$
- $K_{ampcr} = 7.5$
1. Longitudinal auto-pilot

Stable condition, step response

Step response for $K_{va} = 0.67$ and $K_{amp} = 2.5$
1. Longitudinal auto-pilot

Unstable condition, internal loop

Inner loop root locus for high angle of attack

- $K_{va} = 0.61$
- $K_{va} = 0.26$
1. Longitudinal auto-pilot

Unstable condition, external loop

Outer loop root locus for $K_{va} = 0.26$

$K_{amp} = 1.7$

$K_{amp} = 1.4$

$K_{amp} = 3$
1. Longitudinal auto-pilot

Unstable condition, step response

Step response for $K_{va}=0.26$ and $K_{amp}=1.7$
1. Longitudinal auto-pilot

Unstable condition, external loop

Outer loop root locus for $K_{va} = 0.61$

- $K_{ampcr} = 7.2$
- $K_{ampcr} = 1.2$
- $K_{amp} = 2.1$
1. Longitudinal auto-pilot

Unstable condition, step response

Step response for $K_{va}=0.61$ and $K_{amp}=2.1$
1. Longitudinal auto-pilot

Acceleration control system

\[ a_{ref} \rightarrow \text{Integrator Acc} \rightarrow e_g \rightarrow \text{amplifier} \rightarrow e_{\delta e} \rightarrow \text{elevator servo} \rightarrow \delta_e \rightarrow \text{aircraft dynamics} \rightarrow a \]

\[ e_g = a_{ref} - a \]

\[ \delta_e = \text{amplifier}(e_g) \]

\[ \dot{\theta} \]
1. Longitudinal auto-pilot

Acceleration control system

\[ K_{\text{amp}} = 2.85 \]

Outer loop root locus
1. Longitudinal auto-pilot

Acceleration control system

Response for $K_{amp} = 2.85$
1. Longitudinal auto-pilot

Acceleration control system

Control is done through an *accelerometer*: correction is good but:

- acceleration control system can’t distinguish between the acceleration of gravity and the acceleration due to the movement of the aircraft → it has to be insensitive to small accelerations

- non desired turbulence acceleration → noise, has to be filtered

These problems + there are not so many requirements needing the aircraft to fly at constant acceleration → acceleration AP scarcely used

Sometimes used for tactical maneuvers and missile control
1. Longitudinal auto-pilot

AP basic configurations

- maintain pitch angle constant
- maintain pitch rate constant
- maintain pitch acceleration constant

+ used for fight aircrafts (bad stability, good maneuverability)

Both cases: add an inner loop over pitch rate increases
damping of short period oscillations

Basic modes: when pilot turns on AP, are activated by default
1. Longitudinal auto-pilot

Vertical Speed AP

Another basic mode: maintain constant vertical speed

\[
\begin{align*}
V_{Z_{\text{ref}}} & \rightarrow K_{V_Z} & \theta_{\text{ref}} & \rightarrow K_{\theta} & \delta_e \\
\text{aircraft dynamics + elevator} & \rightarrow \theta & \dot{\theta} & \rightarrow \dot{\theta} \\
\theta & \rightarrow \dot{\theta} & \rightarrow \dot{\theta} \\
\text{Sensor 1} & & \text{Sensor 2} & \rightarrow V_Z
\end{align*}
\]
1. Longitudinal auto-pilot

Vertical speed AP

2 loops:

• outer loop: sends $\theta$ associated to piloting functions
  
  $\rightarrow$ input control

• greater loop: controls trajectory parameters
  
  $\rightarrow$ guidance function (maintains pitch desired for the aircraft based on flight info: instrumentation, vision…)
  
  $\rightarrow$ stabilizing function

• inner loop corresponds to servo (stabilizer)

**Sensors:**

Vertical gyro measures pitch angle

Variometer measures vertical speed

**Control laws:** (choice of $K_{Vz}$ based on FL (flight level))
1. Longitudinal auto-pilot

Superior modes

Selected in AP command: Flight Control Unit (FCU)

3 phases:

• turn on the mode

• identify the reference value

• maintain it
1. Longitudinal auto-pilot

**Speed AP (Mach)**

Used during cruise flight

In *Mach hold* mode, aircraft flies at constant Mach speed through automatic control of pitch angle by the elevator

Aircraft flies → fuel is burned → weight decreases → speed tends to increase

Speed increase detected by control system → corrected by elevator → aircraft rises

Making plane rise slowly due to burned fuel (constant Mach #), beneficial effect in long term flights (fuel consumption lowers with altitude)
1. Longitudinal auto-pilot

Speed AP (Mach)

\[ V_{\text{ref}} \xrightarrow{K_v} \theta_{\text{ref}} \xrightarrow{K_{\theta}} \delta_e \xrightarrow{\text{aircraft dynamics} + \text{elevator}} \theta \]

AP Calculator

sensor 1: Vertical gyro, sensor 2: Anemometer

control laws (integrator can be added)
Altitude control AP

Constant altitude is needed due to:

- terrain topography
- vertical distance between planes in flight

Maintain altitude during cruise flight: manual piloting is a monotone and tedious job → interesting to use AP

Mach number is being controlled, manual or automatically by thrust

Visual and noise alarm: warns the crew that aircraft’s trajectory is closer or further from the selected one
1. Longitudinal auto-pilot

Altitude control AP

\[ Z_{\text{ref}} \xrightarrow{K_Z} \theta_{\text{ref}} \xrightarrow{K_\theta} \delta_e \rightarrow \text{aerial dynamics + elevator} \]

Outer loop: piloting

Stabilization

Greater loop: trajectory, guidance

AP Calculator


Control laws (+ integrator over \( Z_{\text{ref}} - Z \), to reduce position error)
2 Lateral AP

1 Roll attitude AP
2 Heading AP
3 VOR Mode
4 Navigation mode
2 Lateral auto-pilot

Roll attitude AP

- basic mode: bank angle AP ON when AP is turned ON
- + integral correction (accuracy) + bank angle and bank rate limitation
- AP designed to maintain straight and leveled flight path
- control laws
2. Lateral auto-pilot

Heading AP

AP Calculator

- basic mode
- sensor 1: vertical gyro
- sensor 2: directional gyro
2. Lateral auto-pilot

Heading AP

- control laws
- position and speed limitations
- limited roll movements even though the difference between actual and selected heading is big
- → ensure passenger’s comfort + limit lateral and longitudinal coupling

\[
\begin{align*}
\Phi_{\text{max}} &= 30^\circ \\
\dot{\Phi}_{\text{max}} &= 5^\circ / \text{s}
\end{align*}
\]

A310
2. Lateral auto-pilot

VOR Mode

• superior modes: select and maintain magnetic heading

![Diagram of VOR Mode](image-url)
2. Lateral auto-pilot

VOR Mode

- superior modes: select and maintain magnetic heading
VOR Mode

- If there is wind, when the plane is following its determined airways, $\Psi - \Psi_{\text{ref}}$ won’t be cancelled.
- In order to maintain the airways, an integral factor is added.
2. Lateral auto-pilot

Navigation Mode

- This mode allows to follow a route described by the flight plan: composed of a series of *waypoints*.

- The crew introduces route in the flight calculator or in the *Flight Management System*.

- An inertial central gives the actual aircraft position information.

- Flight calculator calculates differences and track:
  - Position guidance of the route (XTK)
  - Ground speed (*GS*) of the route.
  - Angle and attitude of the route (TAE- Track Angle Error)
2. Lateral auto-pilot

Navigation Mode

\[
\text{TAE} = \Psi - \Psi_{\text{ref}}
\]

\[
\text{XTK} = \text{AC} = \text{AB} \tan(\Psi - \Psi_{\text{ref}}) \approx \text{AB} \cdot \text{TAE}
\]

for small TAE : \( \text{XTK} = \text{GS} \cdot \text{TAE} \)
2. Lateral auto-pilot

**Navigation Mode**

- $XTK_{ref}$
- Navigation calculator
- Lateral AP calculator
- $\delta_a$
- Aircraft dynamic+ ailerons
- Inertial central
- $\dot{\Phi}$
- $\Phi$
- $\Psi$
- $\dot{XTK}$
- $XTK$
- Control laws + limits
3 AP basic principles
3. AP basic principles

- Auto Pilot mission: make the aircraft evolve from a static equilibrium position to another
- 1st principle: separate the small movements of the aircraft around an equilibrium point in longitudinal and lateral planes
- Longitudinal modes affect the aircraft in its vertical plane
- Lateral modes affect the aircraft in its horizontal plane
3. AP basic principles

- Interesting to decouple the automatic command chains
  → thus making easier the PA tasks

- For basic modes:
  - *longitudinal*: attitude commands
    speed control
  - *lateral*: bank angle control
    yaw control
3. AP basic principles

- A lot of couplings exist between longitudinal and lateral movements of the aircraft (ex.: turning), within longitudinal mode (maintaining a constant descent rate and decreasing speed) and within lateral modes (stabilized turn)

→ Command laws should include these couplings

  either with more correcting terms

  or with introduction of limitation to ensure only small movements
3. AP basic principles

- 2nd principle: in automatics, system signals are classified in function of their speed or frequency (their bandwidth).

→ They are processed separately

For aircrafts:

- Aircraft’s structure vibration modes (fast >10Hz)
- Normal modes associated to flight quality: short term oscillations, phugoid, spiral divergence, Dutch roll (slower <2Hz, + damped)
3. AP basic principles

- There should be no frequency coupling between these 2 types of modes.
- Auto Pilot system creates its own modes (due to feedback loop) making flight quality modes faster and with the possibility of exciting the vibration modes of the aircraft’s structure.
- The control engineer should ensure frequency decoupling.
3. AP basic principles

- 1st Autopilot: principal limitation: systems 1 input, 1 output
- Aircraft is a complex system: 1 input (aileron or elevator deflection) → various outputs
- Example: **input**: elevator deflection
  **output**: variation of: attitude, pitch velocity, attack angle, climbing angle, vertical speed, altitude
- Solution: order signals to be sent in function of its variation speed:
  → Superposition principle
3. AP basic principles

Fast signal $s_1$ affects $s_2$ (which is slower).

$s_2$ affects output $s_3$ (which is the slowest signal).
3. AP basic principles

Control laws act in cascade taking into account speed of subsystems

Commanded systems

Command system

Captors

Fast signal $s_1$ affects $s_2$ (which is slower). $s_2$ affects output $s_3$ (which is the slowest signal).
3. AP basic principles

**Improvements:**

- Feedback correction (improves stability)
- Integration correction (improves accuracy)
- Position or speed limiters for input signals
- Readjustment of $K_1$, $K_2$ and $K_3$ (controllers)

**AP Organization in 2 loops:**

- Inner loop: servo actuator
- Outer loop: sends $\theta$ and $\Phi$: *piloting function*
- Greater loop: controls trajectory parameters: *guidance*
3. AP basic principles

- These solutions were created in the analog calculator era, but they have been later applied to AP with digital calculators.

- Progress (capacity, calculation speed)
  - multidimensional piloting laws (considers multiple input / output, MIMO systems)
  - allows delicate maneuvers with strong coupling between command chains or non-linear phenomenon, and performs unstable maneuvers thanks to correction speed
3. AP basic principles

Autopilot composition

AP composed by the following elements:

1. A pilot-machine interface composed by:

   • AP activation handle
   • Flight Control Unit: to choose the AP active modes and show the instructions.
3. AP basic principles

FCU

FCU A320
3. AP basic principles

FCU: Selection of the altitude reference

1. Visualization of the current altitude reference (1013mb) and the selected mode (QNH or STD)

2. Selection button: (PULL: STD mode, PUSH: QNH mode)

3. Flight Director ON/OFF

4. Landing System ON/OFF
3. AP basic principles

FCU: Navigation Display control case

1: Selection of the database elements to be visualized (VOR, ...)

2: ND Mode selector: (ILS, VOR, NAV, ARC, PLAN)

3: ND scale selector (from 10 to 320Nm)

4: NAV1/NAV2 Selector (VOR or ADF: Automatic Direction Finder)
3. AP basic principles

FCU: Speed selection

1: Visualization of the selected speed

2: Selection button (PULL: Selected Mode, PUSH: Managed Mode)

3: Speed/Mach selection button

4: Timer
FCU: Heading/Track window

1: Selected heading or track

2: HDG/TRK Selection button (PULL: Selected Mode, PUSH: Managed Mode)

3: Localizer mode ON/OFF
3. AP basic principles

FCU: AP/ATHR Heading/Track window

1: HDG-VS or TRK-FPA (Flight Path Angle) modes selection

2: Visualization of the selected mode (HDG-VS or TRK-FPA)

3: AP 1 On/Off

4: AP 2 On/Off

5: Auto-Thrust On/Off (A/THR)
3. AP basic principles

FCU: Altitude management window

1: Selected altitude

2: Altitude selector (PULL: Selected Mode, PUSH: Managed Mode)

3: Increasing step selector (100ft or 1000ft)

4: Expedite function: It selects between the ascend or descend parameters the more efficient to reach a level depending on the instantaneous airplane configuration.
3. AP basic principles

FCU: Vertical/Slope speed window

1: Selected VS/FPA

2: VS/FPA selector

3: Approach mode ON/OFF (Localizer+Glide path)
FCU Reproduction

Key features:
• C167CR-LM Siemens microcontroller (18.432 MHz)
• RAM: 8 Ko
• EEPROM: 32 Ko
• RS232 asynchronous serial interface (from 19.2 to 115.2 Kbauds)
• Synchronous serial interface (1 MHz)
3. AP basic principles

- A mode indicator: Flight Mode Annunciator-FMA: informs the pilot of the AP operation (operating modes, waiting or “armed”)

![AP basic principles diagram](image)
3. AP basic principles

Autopilot composition

2. **Measure chains** (aerodynamic, inertial, radio navigation data) → system calculation elements and flight parameter values to be watched (=sensors)

3. **Electronic calculators** that receive the pilot instructions (selected modes) or the flight management ones (managed modes), and the values of the measure chains → to apply corresponding control signals

4. **Transmission chains** of the control signals to the servo-actuators that act on the control surfaces and the fuel arrival to the engines (=control systems)
3. AP basic principles

Aircraft flight control systems

Devices that transform the movements done by the pilot on the airplane controls into deflections in the control surfaces

1 Mechanic control systems

The pilot, by the actions made on the stick and the pedals through classic mechanic systems (wires…), moves the elevators, rudders, ailerons.

COMMANDES DE VOL MECANIQUES
3. AP basic principles

Aircraft flight control systems

2 Power-boosted control systems

The pilot supplies only a part of the control force: there is a parallel power system (pneumatic or hydraulical).

Example: Boeing 707
3. AP basic principles

Aircraft flight control systems

3 Control systems completely operated with power (hydromechanical)

When the pilot moves a control, he activates an electronic or hydraulic device that moves the control surface

→ irreversible system

→ need of artificial sensation: pilot feels forces proportional to the surface deflection

→ big airplanes of first generation: Boeing 747, 767, A300, A310

and fighter jets of the 60s: Mirage III, Mirage F1, F15

→ triple hydraulic system requisite: redundancy in case of failure
3. AP basic principles

Aircraft flight control systems

4 Fly-By-Wire

The pilot controls the airplane movement by electric signals

→ it saves weight + possibility of flight control laws creation
including artificial stability (adjustment speed)

→ redundant system (quadruple: 4 computers, or similar, A320 or A340 case: 3 primary comp. + 2 secondary)

3. AP basic principles

Aircraft flight control systems

COMMANDES DE VOL ELECTRIQUES (FLY BY WIRE)
3. AP basic principles

Aircraft flight control systems

4 Fly-By-Wire: analog signals

Fly-by-wire flight control systems eliminate the complexity, fragility and weight of the mechanical circuits of the hydraulic/mechanical control systems and they replace them with an electric circuit.

Cockpit sends orders to the control surfaces using electric signals processed by an analogical controller (Autopilot)

Analogical computers allow the selection of flight control characteristics like the artificial stability.
3. AP basic principles

Aircraft flight control systems

4 Fly-By-Wire

Concorde: one of the first airline airplanes using analogue fly-by-wire
3. AP basic principles

Aircraft flight control systems

4 Fly-By-Wire: digital

“Digital fly-by-wire” control system is similar to the analogical one but the signal is processed by digital calculators. Increases the flexibility, because the calculator can receive inputs of any airplane sensor.

Calculator
1. it reads the positions and forces from
   • cockpit (where it receives the pilot orders)
   • airplane sensors
2. it computes differential equations to act on the control surfaces in order to carry out the pilot intentions
3. AP basic principles

Aircraft flight control systems

4. Fly-By-Wire: digital

Thanks to the computers that continuously fly the airplane, the work load of the crew is reduced.

1. For very unstable airplanes → advantage for the maneuverability of the military airplanes (+ FBW avoids leaks in the hydraulic system that can produce the airplane loss)

Examples:
- Lockheed Martin F-117 Nighthawk
- Airbus A320: first airline airplane with digital FBW
3. AP basic principles

Aircraft flight control systems

4. Fly-By-Wire

Note that Boeing and Airbus differ in their FBW philosophy:

• In Airbus aircraft, the computer always retains ultimate control and will not permit the pilot to fly outside the normal flight envelope.

• In a Boeing 777, the pilot can override the system, allowing the aircraft to be flown outside this envelope in emergencies.
3. AP basic principles

Example: Auto-thrust

FADEC: Full Authority Digital Engine Control.
digital computer to control all aspects of aircraft engine performance.

FADECs for both piston engines and jet engines: difference in the different ways of controlling the engines.
Electronics' superior accuracy led to early generation analogue electronic control
1: First used in Concorde's Rolls-Royce Olympus 593 in the 1960s.

2: Later the Pratt & Whitney PW4000 as the first commercial "Dual FADEC" engine
3. AP basic principles

Auto-thrust

Operation modes

The auto-thrust has 2 different operation modes:

- Thrust mode (THR): system maintains the pre-calculated power.
- SPD/MACH mode: auto-thrust adjusts the power to maintain a certain airspeed or Mach number.
3. AP basic principles

Present achievements of the autopilot

From the initial ascension to the landing and the final stop

1. **Longitudinal modes:**
   - Pitch angle control, $\theta = \theta_{\text{ref}}$
   - Vertical speed control, $V_z = V_{z\text{ref}}$
   - Altitude control, $Z = Z_{\text{ref}}$
   - Vertical path tracking (ascension, cruise, descent) → FMS connection
   - Speed / Mach control → auto-thrust connection
   - Slope control
3. AP basic principles

Present achievements of the autopilot

2. **Lateral modes:**

   - bank angle control
   - Heading control
   - VOR radial or magnetic route tracking
   - Inertial route tracking (horizontal navigation)
     \[ \rightarrow \text{FMS connection} \]
3. AP basic principles

Present achievements of the autopilot

3. Common modes:

• Automatic landing
• Taking off → Flight Director

It implies a simultaneous action around the pitch, roll and/or yaw axes
4. Flight Management System

1 Objectives and functions
2 Flight Management System composition
3 Use of the Flight Management System
4. Flight Management System

FMS: Objectives

Important economical factor in the air transport

→ look for maximum efficiency of the aircraft

→ try to reduce costs

1. At the end of the 70s: piloting assistance (safety + regularity)

2. Very soon, technology applied to flight management problems (1984: 1st certified FMS)

2 advantages:

1. Decrease the crew’s workload (otherwise more and more complex management tasks)

2. Minimization of the exploitation costs: to help the pilot in every flight stage to minimize the fuel consumption and the flight time
4. Flight Management System

**FMS: Objectives**

Example: Iberia: January 2008-September 2008:

- Iberia: 1,201.4 million euros in fuel (29% of total operating expenses)
- 50 millions L of kerosene per week
- Fuel: second cost in relevance (after staff)
- 1% of saving in fuel $\rightarrow$ 12 millions euros

$\rightarrow$ How can you avoid 1% increase in fuel consumption?
$\rightarrow$ Flight Management System optimizes
4. Flight Management System

**FMS: Objectives**

How can you reduce the consumption of 1%?

- choosing for a 500 nm route a more direct path of only 6 or 7 nm
- choosing a lower Flight Level if the wind is lower there

How can the consumption be increased of 1%?

- beginning the descent one minute too early
- flying one Mach point (0.01) too fast at the optimum altitude
- flying 1000 feet too low at cruise speed
- transporting 1 additional fuel tone in the A320
4. Flight Management System

FMS: Functions

- Flight plan design
- Flight plan sequence
- Development of forecasts and performance optimization
- Initialization of the inertial centrals
- Selection of the RNAV environment
- Emission of information for the crew
- Emission of piloting order and guidance to the autopilot
The Flight Management Computer (FMC), interacts with:

- A **database** (inside the system)
- The **crew** through the “Control Display Unit” - CDU, the “Navigation Display” - ND, and the “Primary Flight Display” - PFD
- The **navigation assistance systems** (VOR, DME, ILS, GPS…)
- The **measurements of the fuel consumed by the engines**
- The **AP and thrust calculators**
4. Flight Management System

Control and Display Unit
4. Flight Management System

Control and Display Unit

- Cost Index
- Route management
- Transition
- Approximation
- Management of the temporary flight plan
- Access to all vertical and lateral revision pages
- Instructions insertion
4. Flight Management System

Control and Display Unit

Route change management

Radio Nav page:
Management of the radio navigation systems
4. Flight Management System

N.D: Navigation Display

Next to the PFD.

Visualization of the navigation information: horizontal or vertical flight plan.

Visualization of the images from the meteo radar, the TCAS (traffic collision avoidance system) information with the position of the other airplanes, and the navigation instruments.
4. Flight Management System

N.D: Navigation Display
4. Flight Management System

PFD: Primary Flight Display

On-board principal instrument used to pilot the airplane
4. Flight Management System

PFD: Artificial horizon

1. Roll (11° left turn)
2. Attitude (5°)
3. Ball
4. Airplane model
5. Horizon line
6. Flight director
7. Radar altimeter (2000ft)
4. Flight Management System

**PFD: Anemometer**

1. Indicated speed (154 kts)
2. Speed tendency in 10 sec (150 kts)
3. Objective speed (145 kts)
4. Alpha Floor speed
5. Alpha Protection speed
6. Stall speed
7. Max speed
4. Flight Management System

PFD: Compass

1. Heading (315°)
2. Route (315°)
3. Heading or route objective
4. ILS course

PFD: Altimeter

1. Altitude (1360ft)
2. Objective altitude (2000ft)
3. Variometer (-700 ft/mn)
4. Altitude reference
4. Flight Management System

PFD: Localizer and Glide indicator

1. Localizer
2. Glide
4. Flight Management System

PFD: Flight Mode Annunciator

1. Mach hold mode (speed holding)
2. Longitudinal mode (altitude holding)
3. Lateral mode (LOC*: Localizer interception)
4. Approximation capacity
5. AP, FD, and A/THR state
4. Flight Management System
REFERENCES
