Aerospace Systems

- **Newtonian Mechanics:**
  - Main assumptions/definitions
  - Reference Systems, Rigid Body Motion
- **Atmospheric Flight Dynamics:**
  - Reference systems
  - A/C Nonlinear Equations of Motion
  - Applied forces and moments
  - Geometry, Flight Envelope, Equilibrium Conditions
  - Linearization, Natural Modes, Stability Derivatives
- **A/C Control**
  - Primary Control Loops
  - Stability Augmentation, Autopilots
  - Sensors, Actuators, Quadcopter D/C
- **Orbital Mechanics:**
  - Law of Gravitation, 2-Body Problem
  - Keplerian Orbits, Kepler Equation
  - Orbit Transfer, Patched Conics
  - Lambert theorem, Restricted 3-Body Problem
- **S/C Control**
  - Stability, Open Loop/Closed Loop
  - Attitude Control
  - Sensors, Actuators, Power Limitations
- **Proximity Operations:**
  - Euler-Hill Equations
  - Rendez Vous and Docking, Formation Flight
- **Basic Human Operator in - the - Loop**
  - Operator in the Control Loop, Classical Models
  - MMI, Haptics

Aircraft Control

Aircraft Desired State
- Position
- Velocity
- Orientation
- Mission Requirements
- Safety
- Stability
- Performance (speed, ceiling, endurance, fuel consumption, comfort, maneuverability,…)

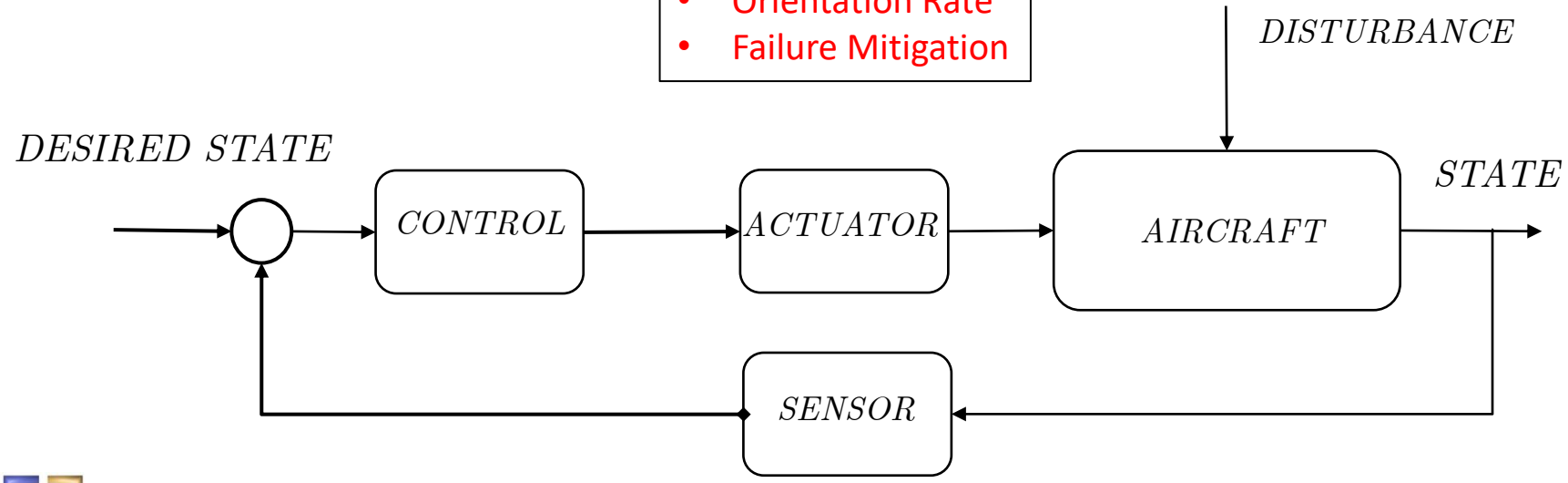
Control
- Pilot
- Stability
- Regulation
- Guidance
- Navigation

Intervention
- Elevator
- Rudder
- Ailerons
- Spoilers
- Engine

Disturbances
- Turbulence
- Wind
- Failures

Performance Verification
- Monitoring
- Continuous Action
- Discontinuous Action

Aircraft Actual State
- Position
- Velocity
- Orientation
- Orientation Rate
- Failure Mitigation



Aircraft Control

Longitudinal States/Variables available for feedback

- Pitch Rate
- Attitude (Pitch) Angle
- Angle of Attack (direct or from accelerometer)
- Forward, Vertical velocities
- Altitude, Flight Path Angle
- Normal Acceleration (at CG or other location)

Lateral-Directional States/Variables available for feedback

- Yaw Rate
- Heading Angle
- Roll Rate
- Bank Angle
- Sideslip Angle (direct or from accelerometer)
- Lateral velocity
- Lateral Acceleration

Main Sensors for Dynamic Control

- Inertial Navigation Unit (gyroscopes, accelerometers)
- Inclinometer (vertical gyro)
- GPS
- Airspeed Sensor
- Altimeter, Radar-Altimeter
- Magnetic Compass
- Pressure sensors (speed, angle of attack, sideslip angle)
- Engine status

$$u$$

$$w \leftrightarrow \alpha \approx w / U_0$$

$$q$$

$$\theta \approx \int q dt$$

$$\gamma = \theta - \alpha$$

$$n_{z_{CG}} = \frac{a_{z_{CG}}}{g} = \frac{(\dot{w} - U_0 q)}{g}$$

$$\ddot{h}_{CG} = -a_{z_{CG}}$$

$$\dot{h}_{CG} = -w + U_0 \theta$$

$$h_{CG} = U_0 \int \gamma dt$$

$$v \leftrightarrow \beta \approx v / U_0$$

$$\chi = \psi + \beta$$

$$p$$

$$r$$

$$\phi \approx \int p dt$$

$$\psi = \int r dt$$

$$n_{y_{CG}} = \frac{\dot{v} - g\phi + U_0 r}{g}$$

Desirable Dynamic Properties of Aerospace Vehicles:

- Satisfactory static stability within the flight envelope
- Damping and natural frequency of critical natural modes appropriate to certification requirements
- Capability of providing commands proportional to specified states
- Capability of maintaining equilibrium conditions (desired speed, desired altitude, desired angular rate, …), in the absence or presence of disturbances
- Capability of following specified trajectories with accuracy and fast enough response

- **Static stability:**

1. Static stability in the longitudinal plane is dominated by the pitching moment curve slope with respect to angle of attack (i.e. $C_{m\alpha} < 0$ or $M_\alpha < 0$, and $C_{m0} > 0$).

$$\begin{cases} (1 - Z_{\dot{w}})\dot{w} = Z_w w + (U_0 + Z_q)q + Z_\delta \delta_E \\ -M_{\dot{w}}\dot{w} + \dot{q} = M_w w + M_q q + M_\delta \delta_E \\ w = U_0 \alpha \end{cases}$$

$$M_w = \frac{\rho S U_0 \bar{c}}{2 I_{yy}} C_{m\alpha}$$

$$C_{m\alpha} = C_{L\alpha w}\left(\frac{X_{CG}}{\bar{c}} - \frac{X_{AC}}{\bar{c}}\right) - \eta V_H C_{L\alpha t}\left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

- Change location of center of mass
- Feedback of the angle of attack by the elevator in the pitching moment equation (as an alternative use normal acceleration)

$$\delta_E = -K_\alpha \alpha = -K_{ss}\frac{w}{U_0} = -K_w w$$

2. Static stability in the lateral – directional plane is dominated by the weathercock derivative (i.e. $C_{n\beta} > 0$ or $N_\beta > 0$), and dihedral derivative (i.e. $C_{l\beta} < 0$ or $L_\beta < 0$)

$$\begin{cases} \dot{v} = Y_v v + U_0 r - g\cos\gamma_0\ \phi + Y_{\delta_R}\delta_R \\ \dot{p} = L'_v v + L'_p p + L'_r r + L'_{\delta_A}\delta_A + L'_{\delta_R}\delta_R \\ \dot{r} = N'_v v + N'_p p + N'_r r + N'_{\delta_A}\delta_A + N'_{\delta_R}\delta_R \end{cases}$$

- Change size of Vertical Tail, Dihedral angle, Wing Sweep
- Feedback of sideslip angle to the rudder in the yawing moment equation (in alternative use lateral acceleration)

$$N'_v = \frac{1}{U_0}N'_\beta = \frac{1}{U_0}\left[N_\beta + \frac{I_{xz}}{I_{xx}}L_\beta\right] \qquad N'_v = \left[N_v + \frac{I_{xz}}{I_{xx}}L_v\right]$$

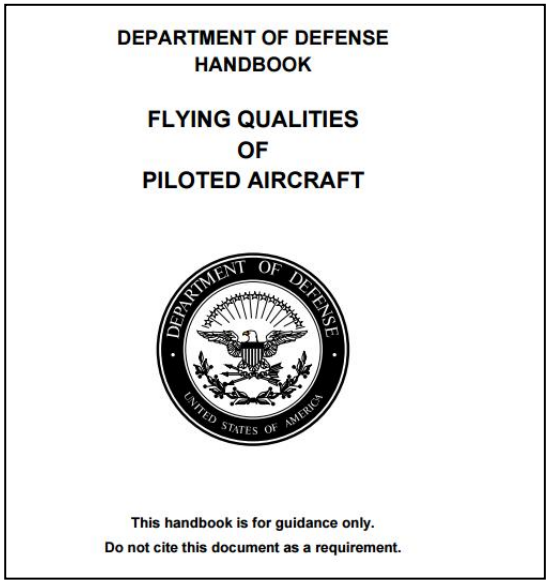
$$L_v = \frac{QSb}{I_{xx}U_0}C_{l\beta};\ N_v = \frac{QSb}{I_{zz}U_0}C_{n\beta} \qquad \delta_R = -K_R\beta = -K_R\frac{v}{U_0} = -K_v v$$

$$\dot{r} = (N'_v - N'_{\delta_R}K_v)v + N'_p p + N'_r r + N'_{\delta_A}\delta_A$$

$$\delta_A = -K_A p = -K_A\dot{\phi}$$

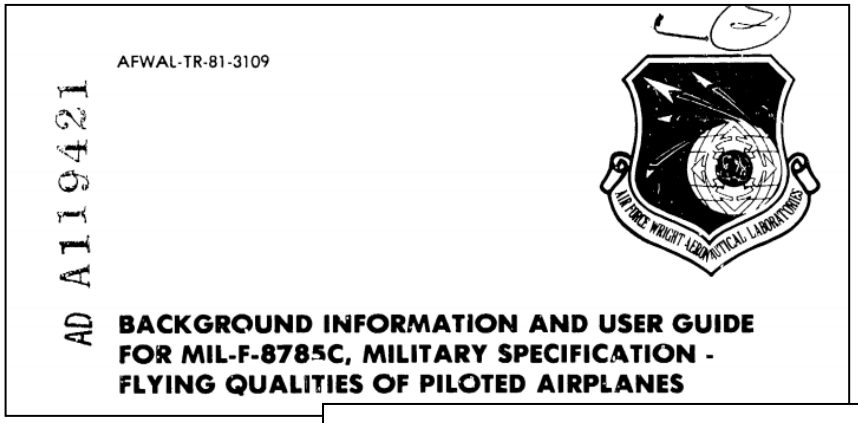
Aircraft Control

- **Damping and natural frequency of critical natural modes appropriate to certification requirements**
- **Handling (Flying) Qualities:** Set of regulatory requirements provided as guidelines to the flight control system designer (MIL Specification: Guidelines and Regulatory).
  - Requirements given in terms of natural modes and satisfactory frequency and time responses
  - Testing with pilot-in-the-loop, ground and flight simulation


DEPARTMENT OF DEFENSE
HANDBOOK

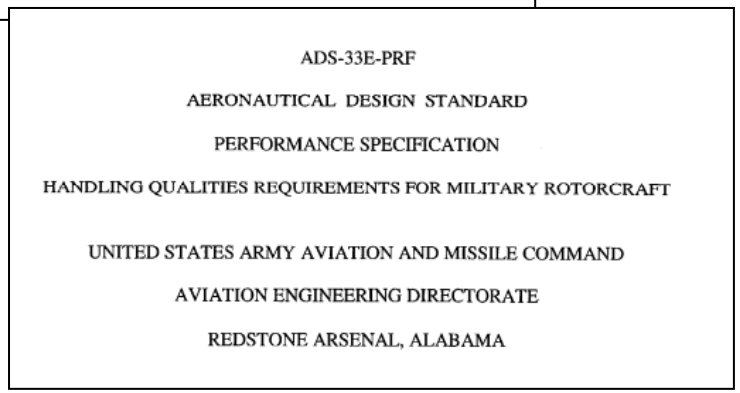
FLYING QUALITIES
OF
PILOTED AIRCRAFT

This handbook is for guidance only.
Do not cite this document as a requirement.


AD A119421

AFWAL-TR-81-3109

BACKGROUND INFORMATION AND USER GUIDE
FOR MIL-F-8785C, MILITARY SPECIFICATION -
FLYING QUALITIES OF PILOTED AIRPLANES


ADS-33E-PRF

AERONAUTICAL DESIGN STANDARD

PERFORMANCE SPECIFICATION

HANDLING QUALITIES REQUIREMENTS FOR MILITARY ROTORCRAFT

UNITED STATES ARMY AVIATION AND MISSILE COMMAND

AVIATION ENGINEERING DIRECTORATE

REDSTONE ARSENAL, ALABAMA

❑ Flying Qualities

MIL-F-8785C Flight Phase

A. Non-terminal flight requiring rapid maneuvering precise tracking, or precise flight path control
   - air-to-air combat
   - ground attack
   - in-flight refueling (receiver)
   - close reconnaissance
   - terrain following
   - close formation flying

B. Non-terminal flight requiring gradual maneuvering
   - climb, cruise
   - in-flight refueling (tanker)
   - descent

C. Terminal flight
   - takeoff (normal and catapult)
   - approach
   - wave-off/go-around
   - landing

8

MIL-F-8785C Levels of Performance

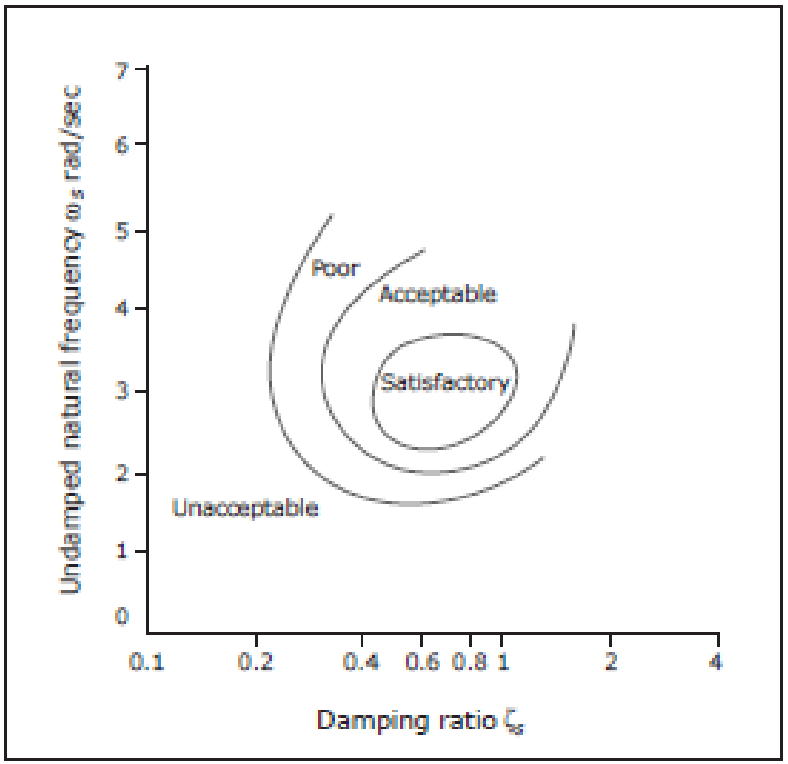
1. Flying qualities clearly adequate for the mission flight phase
2. Flying qualities adequate to accomplish the mission flight phase, with some increase in pilot workload or degradation of mission effectiveness
3. Flying qualities such that the aircraft can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate

9

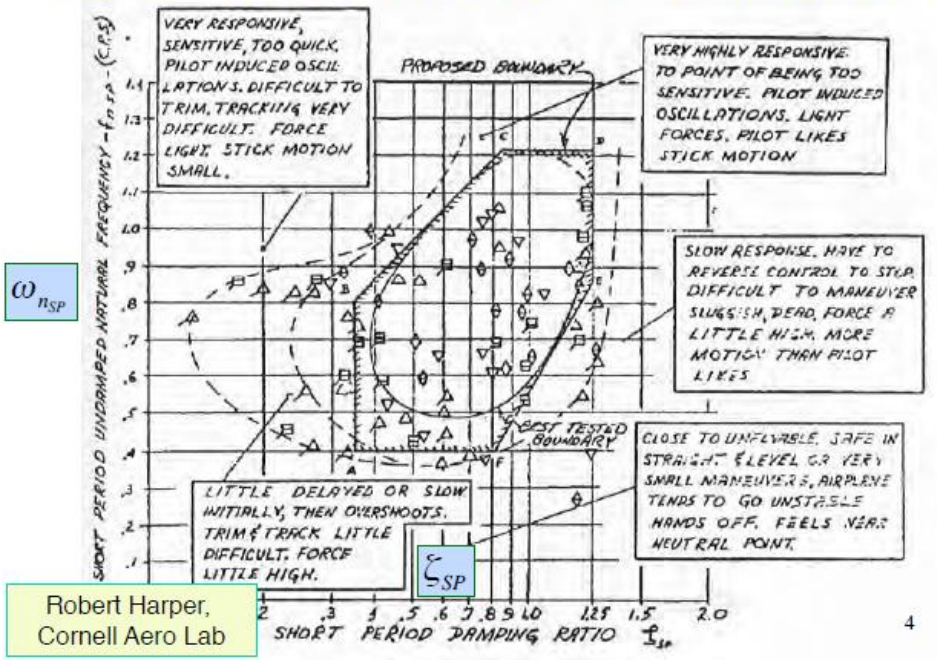
MIL-F-8785C Aircraft Types

I. Small, light airplanes, e.g., utility aircraft and primary trainers
II. Medium-weight, low-to-medium maneuverability airplanes, e.g., small transports or tactical bombers
III. Large, heavy, low-to-medium maneuverability airplanes, e.g., heavy transports, tankers, or bombers
IV. Highly maneuverable aircraft, e.g., fighter and attack airplanes

7



Short-Period "Bullseye" or "Thumbprint"



$$\frac{\Delta q(s)}{\Delta \delta E(s)} = \frac{k_q\left(s+\frac{1}{T_{\theta_2}}\right)}{s^2+2\zeta_{SP}\omega_{n_{SP}}s+\omega_{n_{SP}}^2} = \frac{k_q\left(s+\omega_{n_{SP}}/\zeta_{SP}\right)}{s^2+2\zeta_{SP}\omega_{n_{SP}}s+\omega_{n_{SP}}^2}$$

❑ Phugoid Mode

Long-Period Flying Qualities Criteria
(MIL-F-8785C)

Flight Phase	Level of Performance
A. Non-terminal flight requiring rapid maneuvering	1. Clearly adequate for the mission
B. Non-terminal flight requiring gradual maneuvering	2. Adequate to accomplish the mission, with some increase in workload
C. Terminal flight	3. Aircraft can be controlled safely, but workload is excessive

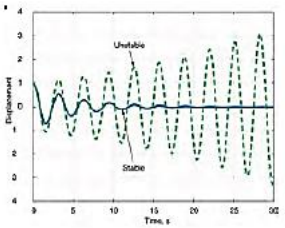
- Static speed stability
  - No tendency for aperiodic divergence
    - Phugoid oscillation -> 2 real roots, 1 that is unstable
  - Stable control stick position and force gradients
    - e.g., Increasing "pull" position and force with decreasing speed

Long-Period Flying Qualities Criteria
(MIL-F-8785C)

- Phugoid stability
  1. Damping ratio ≥ 0.04
  2. Damping ratio ≥ 0
  3. "Time to double", $T_2 \geq 55$ sec

Time to Double

$$T_{2_{Ph}} = -0.693/\zeta_{Ph}\omega_{n_{Ph}}$$



❑ Lateral – Directional Modes

Criteria for Lateral-Directional Modes (MIL-F-8785C)

Maximum Roll-Mode Time Constant

TABLE VII. Maximum roll-mode time constant, seconds.

Flight Phase Category	Class	Level 1	Level 2	Level 3
A	I, IV	1.0	1.4	
	II, III	1.4	3.0	
B	All	1.4	3.0	10
C	I, II-C, IV	1.0	1.4	
	II-L, III	1.4	3.0	

Minimum Spiral-Mode Time to Double

TABLE VIII. Spiral stability - minimum time to double amplitude.

Flight Phase Category	Level 1	Level 2	Level 3
A & C	12 sec	8 sec	4 sec
B	20 sec	8 sec	4 sec

Minimum Dutch Roll Natural Frequency and Damping (MIL-F-8785C)

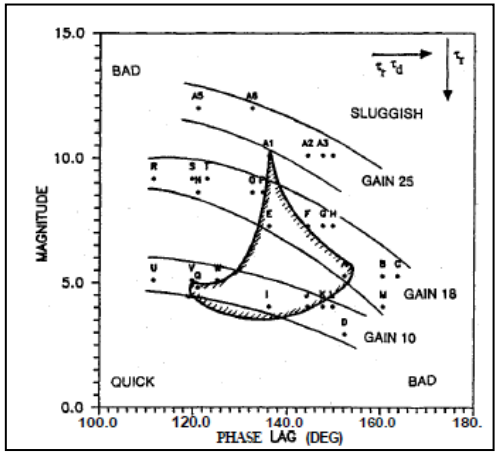
TABLE VI. Minimum Dutch roll frequency and damping.

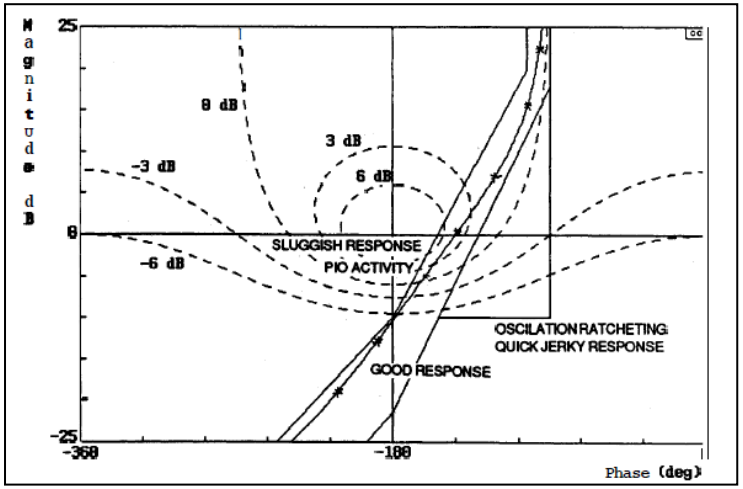
Flight Phase Level	Flight Phase Category	Class	Min ζ_d*	Min $\zeta_{d}\omega_{n_d}$* rad/sec.	Min ω_{n_d} rad/sec.
1	A (CO and GA)	IV	0.4	-	1.0
	A	I, IV	0.19	0.35	1.0
		II, III	0.19	0.35	0.4**
	B	All	0.08	0.15	0.4**
	C	I, II-C, IV	0.08	0.15	1.0
		II-L, III	0.08	0.10	0.4**
2	All	All	0.02	0.05	0.4**
3	All	All	0	-	0.4**

* The governing damping requirement is that yielding the larger value of ζ_d, except that a ζ_d of 0.7 is the maximum required for Class III.

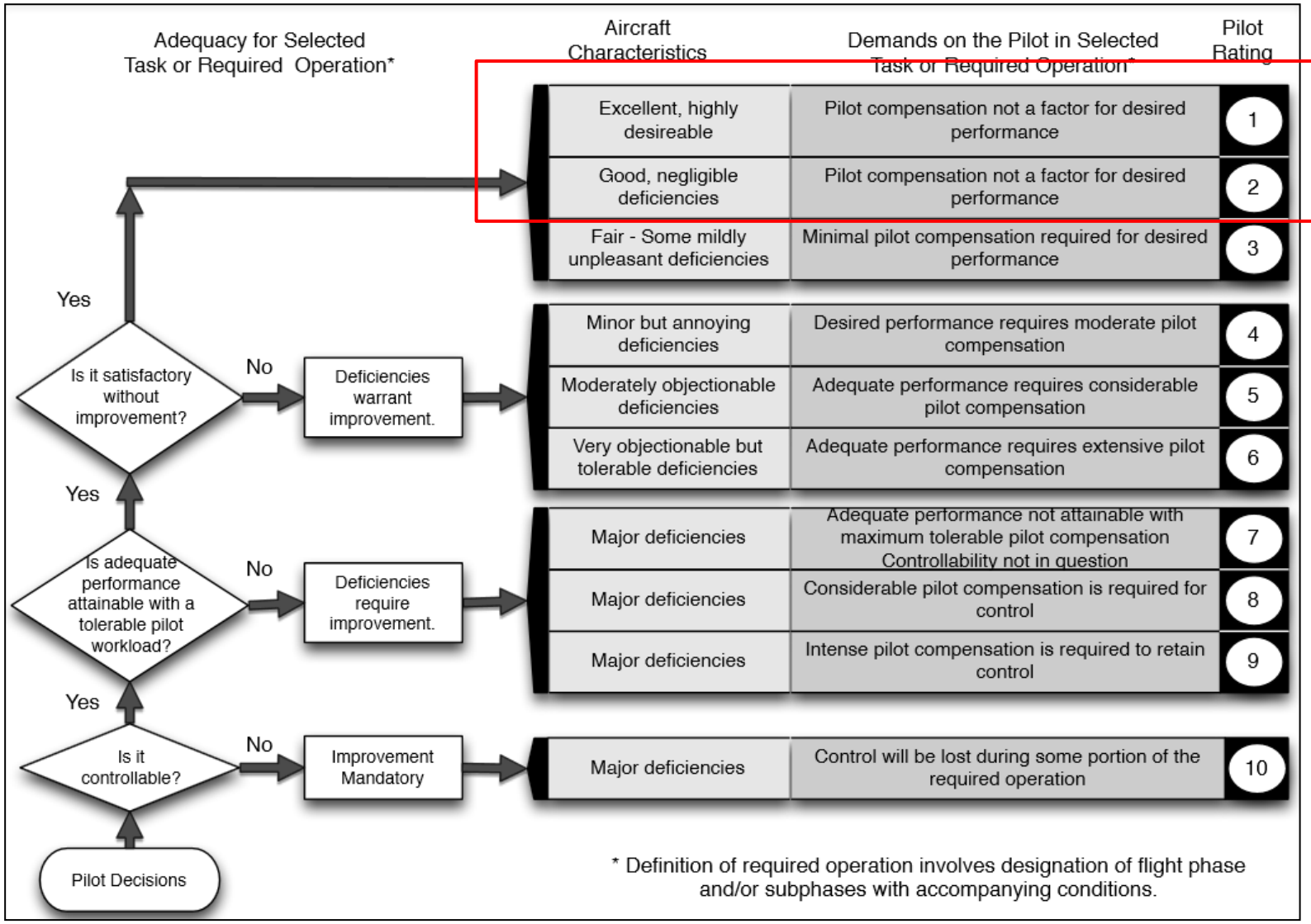
** Class III airplanes may be excepted from the minimum ω_{n_d} requirement, subject to approval by the procuring activity, if the requirements of 3.3.2 through 3.3.2.4.1, 3.3.5 and 3.3.9.4 are met.

- Current Roll Metrics for Landing, Boeing Co, Military Aircraft Division, St. Louis, MO, USA



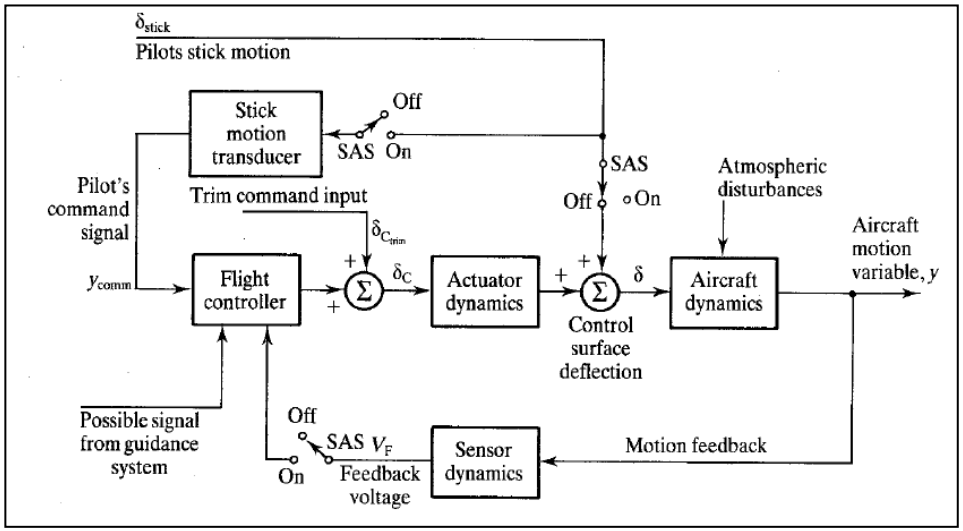


❑ Cooper – Harper Rating Scale



Aircraft Control

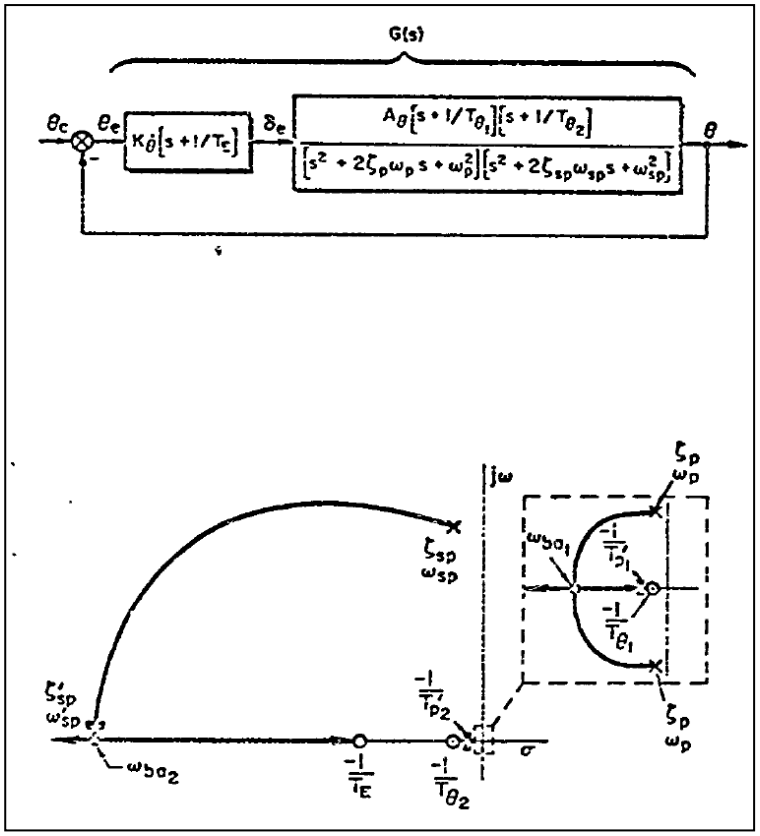
- Classical, historical Improvement of transient properties of natural modes is achieved with direct feedback of appropriate measured state variables, and frequency response methods, using approximate modes transfer functions.



- **Longitudinal Feedbacks**
  - Pitch Angle and Pitch Rate to Elevator (PH, SP)
  - Angle of Attack to Elevator (SP)
  - Normal Acceleration to Elevator (SP, Turn)
  - Altitude to Elevator (Altitude Hold), Engine Compensation
  - Forward Speed to Elevator (Mach Hold), Engine Compensation

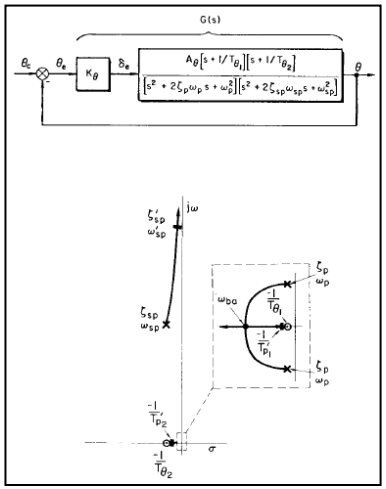
- **Lateral - Directional Feedbacks**
  - Bank Angle and Roll Rate to Ailerons (Spiral, Roll Modes)
  - Heading Angle to Rudder (Turn)
  - Yaw Rate to Rudder (DR)
  - Sideslip to Rudder (Coord.)
  - Lateral Acceleration to Rudder (Coord.)

Feedback of Pitch Angle and Pitch Rate to Elevator



$$\frac{\theta(s)}{\delta_e(s)} = \frac{k_{\theta\delta}(T_{\theta 1}s+1)(T_{\theta 2}s+1)}{\left(\frac{s^2}{\omega_{nsp}^2}+\frac{2\zeta_{sp}}{\omega_{nsp}}s+1\right)\left(\frac{s^2}{\omega_{np}^2}+\frac{2\zeta_p}{\omega_{np}}s+1\right)}$$

- The figure illustrates the combined effect of pitch rate and pitch angle feedback for a high speed, high altitude case.
- Now, at only moderately high controller gains, the phugoid is heavily damped and suppressed for attitude commands and the short-period motion is also heavily damped.
- This technique is so effective that it has become nearly universal, and most modern autopilots feedback pitch angle and pitch rate signals to the elevator.
- The technique is applicable not only to aircraft with typical dynamics, such as the ones which have been illustrated, but also in cases where the longitudinal motions of the vehicle alone (open-loop) are unstable.



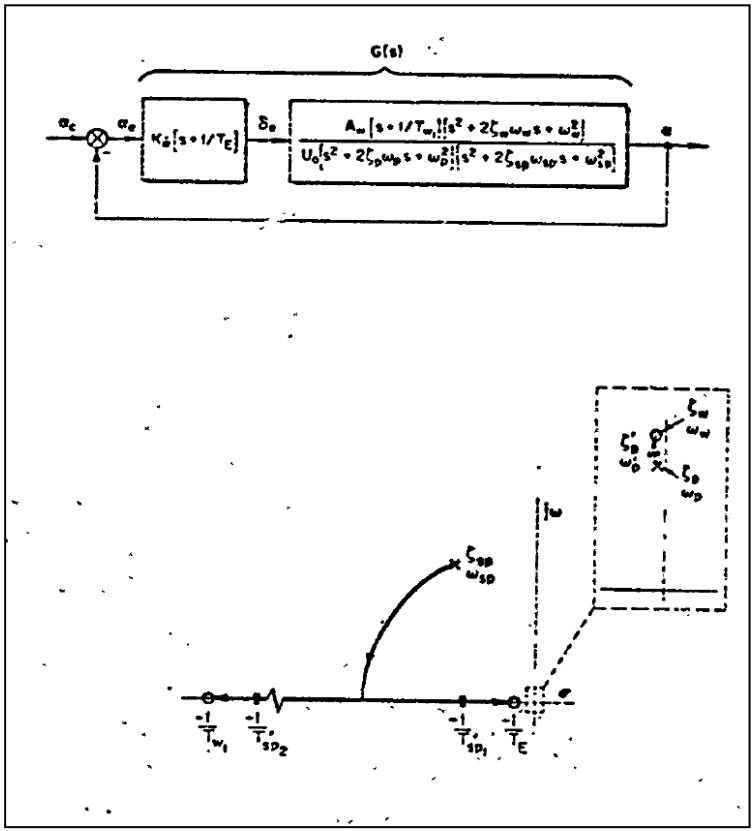
- Note the difference on natural modes damping by feeding back **pitch angle only** !

Aircraft Control

❑ Feedback of Angle of Attack to Elevator

$$2(\zeta\omega)_{sp} = -\left(Z_w + M_q + M_{\dot{\alpha}_{augmented}}\right)$$

$$\omega^2_{sp} = Z_w M_q - M_{\alpha_{augmented}}$$



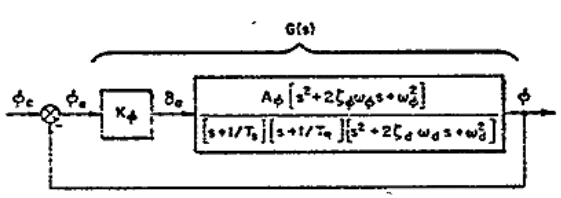
- Angle of attack and its derivative are, in principle, very desirable feedbacks to the elevator. Considered as stability derivative augmentation, increase the magnitude of $M\alpha dot$ and $M\alpha$ directly, which will increase the damping ratio and undamped natural frequency, respectively. These features are indicated by the short-period approximate factors on the left.
- The close proximity of the complex zeros to the phugoid poles implies very little angle of attack change in the phugoid mode. This, of course, is an inference already well established. Under the condition of closed-loop operation, the angle of attack motion in the phugoid mode will be suppressed to an even greater extent than, in the open-loop case, but otherwise this feedback does not appreciably alter the phugoid characteristics.
- The short period roots, on the other hand, are greatly affected by the feedback. To improve the short period damping, in practice, lead equalization is added, with the result shown in the figure on the left. Here again the effect of the, lead at moderate gains is just as would be predicted by the approximated factors.
- The angle of attack system, when tightly closed, is similar to the pitch attitude plus rate. Both systems stabilize attitude and damp the short period mode.
- However, the reference for orientation stabilization is quite different, being the g vector (or horizon) for pitch attitude and the relative wind for angle of attack. Consequently, a substantial difference occurs, when vertical gust disturbances are encountered.
- The angle of attack system rotates the aircraft into the new relative wind direction, thereby tending to keep angle of attack and load factor constant.
- In these same circumstances, pitch attitude control will resist any tendencies to rotate the craft relative to inertial space. Also, the pitch attitude system has a beneficial effect on phugoid s, whereas the angle of attack system, as noted above, has essentially none.

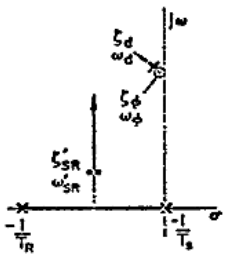
- **Primary Feedback to the Ailerons: Feedback of Bank angle and Roll Rate**

  - The first successful aircraft automatic pilots employed the same vertical gyroscope, which sensed the rolling motions to detect departures from a wings-level attitude and to cause the ailerons to move so as to oppose the bank angle. This action can be thought of as negative feedback of the bank angle motion variable to the aileron actuating quantity.

$$\frac{\varphi(s)}{\delta_a(s)} = \frac{N^{\varphi}_{\delta_a}}{\Delta_{lat}} = \frac{A_\varphi\left[s^2 + 2\zeta_\varphi\omega_\varphi s + \omega_\varphi^2\right]}{\left(s + \frac{1}{T_S}\right)\left(s + \frac{1}{T_R}\right)\left[s^2 + 2\zeta_d\omega_d s + \omega_d^2\right]}$$

  - Typically, in cruising flight the spiral mode constant is very large and the mode itself can be either neutrally stable, or a slow convergence, or a slight divergence. Both the neutral and the unstable conditions are undesirable for unattended operation, and the low convergence is little better. Consequently, one purpose of an automatic pilot is to impose a higher degree of spiral stability. With roll attitude control this is achieved by the creation of static stability in roll.

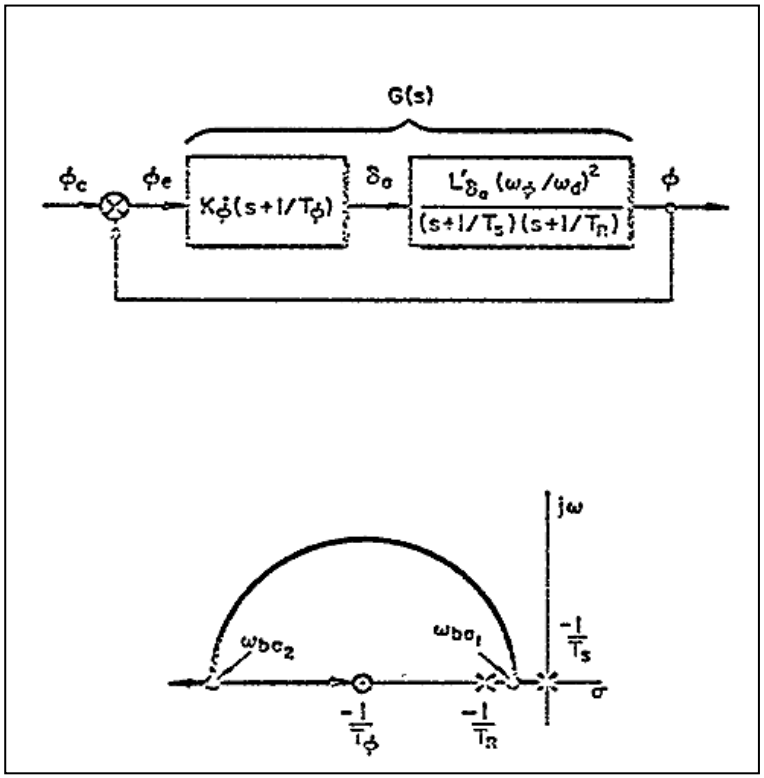


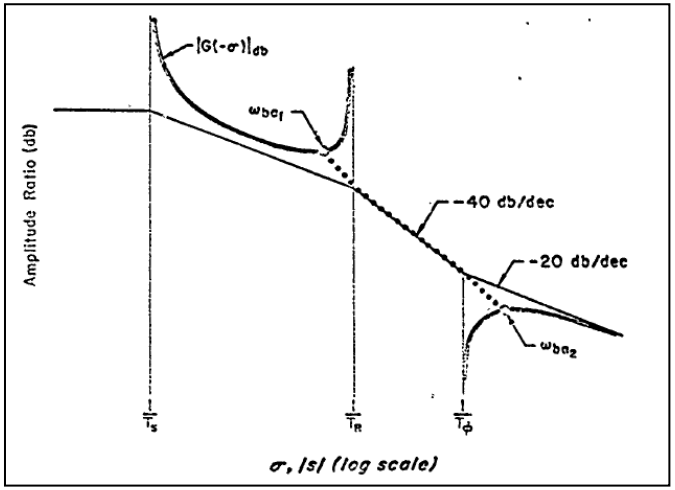


  - While the dutch roll mode in this airplane is weakly damped, the close proximity of the numerator zeros to the dutch roll poles implies that there will be very little excitation of this mode in response to aileron inputs.

Aircraft Control

- In many practical situations a roll control system based on only roll angle feedback is inadequate from the standpoint of tightness of control in response to disturbances and commands. This deficiency can be traced back, fundamentally, to the fact that with pure roll attitude feedback the open-loop and closed-loop total effective dampings are the same.
- To improve this situation the order of the open-loop transfer function numerator must be made no less than one below that of the denominator. To accomplish this increase in relative numerator/denominator order, the controller transfer function is changed by adding a lead term.
- Another possibility is a direct feedback of roll rate to the ailerons.





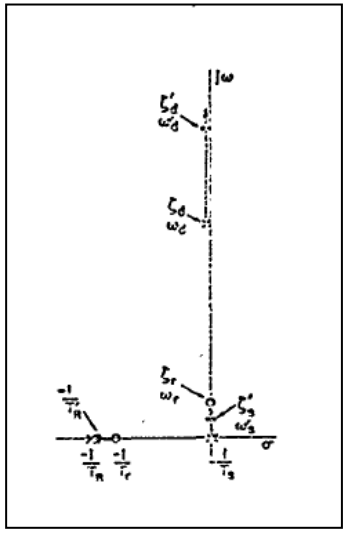
❑ Primary Feedbacks to the Rudder

▪ Feedback of Heading to the Rudder

- The earliest autopilots employed a feedback of heading angle to the rudder as a means of steering the airplane. For small perturbations about straight, level, and horizontal flight the appropriate transfer function is:

$$\frac{\psi(s)}{\delta_r(s)} = \frac{N^r_{\delta_r}}{s\Delta_{lat}} = \frac{A_r\left(s + \frac{1}{T_r}\right)\left[s^2 + 2\zeta_r\omega_r s + \omega_r^2\right]}{s\left(s + \frac{1}{T_s}\right)\left(s + \frac{1}{T_R}\right)\left[s^2 + 2\zeta_d\omega_d s + \omega_d^2\right]}$$

- The feedback of heading to rudder stabilizes the divergent spiral motion by forcing it to combine with the pole at the origin. At a comparatively high value of the feedback gain the resulting low frequency oscillation is made stable, while at the same time the damping of the dutch roll node is only slightly altered. Consequently, this type of system can be a very satisfactory for aircraft with heavy dutch roll damping.

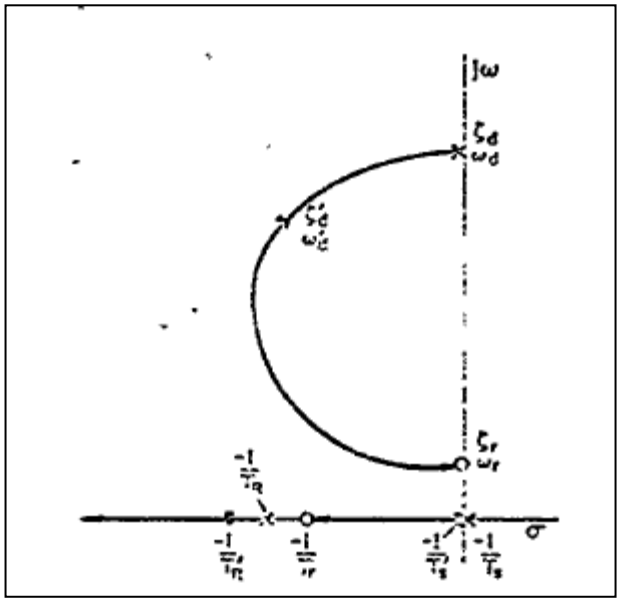


- **Feedback of Yaw Rate to the Rudder**

  - In a number of modern aircraft, the autopilot to the rudder is slaved to a rate gyro, which senses yawing velocity. This is particularly valuable in those aircraft which need dutch roll damping augmentation. Assuming that the yawing velocity sensor's input axis coincides approximately with the aircraft's stability axes, the appropriate transfer function is given by:

$$\frac{r(s)}{\delta_r(s)} = \frac{N^r_{\delta_r}}{\Delta_{lat}} = \frac{A_r\left(s + \frac{1}{T_r}\right)\left[s^2 + 2\zeta_1\omega_r s + \omega_r^2\right]}{\left(s + \frac{1}{T_s}\right)\left(s + \frac{1}{T_R}\right)\left[s^2 + 2\zeta_d\omega_d s + \omega_d^2\right]}$$

- The dynamics of this airplane and flight condition illustrate the powerful effect of yaw rate feedback on the lateral motions of the airplane.
- At a very low value of the feedback gain the spiral divergence is made stable, and at higher gains the very weakly damped dutch roll motion is made heavily damped.
- The presence of a wash out circuit (see later) may be necessary in order to provide steady turn properties.



- **Feedback of Sideslip Angle (and Rate) to the Rudder**

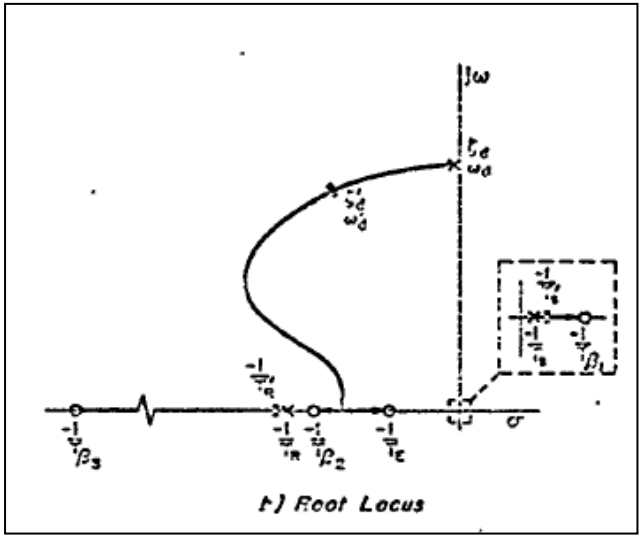
  - The feedback of sideslip angle β to the rudder has the function of increasing directional stability (N_β) and it is very useful in order to minimize sideslip and uncoordinated turns.

$$\frac{\beta(s)}{\delta_r(s)} = \frac{N^v_{\delta_r}}{U_o \Delta_{lat}} = \frac{A_\beta \left(s + \frac{1}{T_{\beta_1}}\right)\left(s + \frac{1}{T_{\beta_2}}\right)\left(s + \frac{1}{T_{\beta_3}}\right)}{\left(s + \frac{1}{T_S}\right)\left(s + \frac{1}{T_R}\right)\left[s^2 + 2\zeta_d \omega_d s + \omega_d^2\right]}$$

  - In many cases, sideslip rate effects are achieved by introducing a lead compensator, so that dutch roll damping is increased as well

$$\delta_R = -(K_\beta \beta + K_{\dot\beta}\dot\beta) = -K_{\dot\beta}(s + \frac{1}{T_E})\beta$$

  - This feedback has excellent characteristics as a as a single loop control for improvement of dutch roll damping and minimization of sideslip.
  - The system is also a good inner loop controller for roll attitude. One deficiency is the difficulty in measuring sideslip, which can be compensated by using lateral acceleration as feedback.



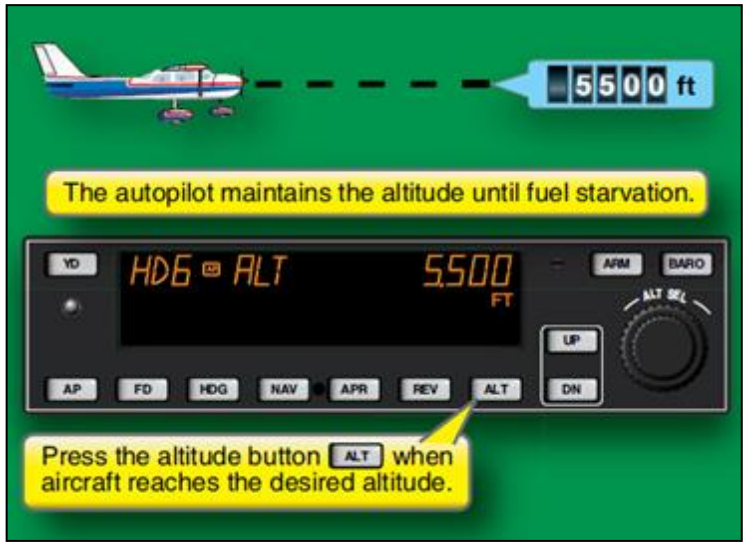
f) Root Locus

Aircraft Control

- **Autopilots:** Allow automatic control over some state variable and/or over a desired path. They are a basic component of a generic guidance system. Their primary function is pilot relief of continuous control
  - Main requirements are accuracy (steady state response), and disturbance rejection at low frequency

- Examples:
  - Attitude hold: to maintain constant Attitude angles (pitch, Roll, Yaw)
  - Auto Throttle: to maintain a specified IAS
  - Mach hold: to maintain constant speed
  - **Altitude hold: to maintain constant altitude**
  - **Glide Slope, GS: to maintain constant vertical speed in approach; part of the InstrumentLandingSystem (AutoLand)**
  - Localizer VOR, **V**eryhighfrequency**O**mnidirectional**R**adiorange: to acquire a radio frequency, also to maintain lateral trajectory aligned to the vertical plane; part of the **InstrumentLandingSystem (AutoLand)**
  - **Flare autopilot: to follow specified flare angle**
  - Heading hold: to keep constant heading
  - Coordinated turn: to reduce sideslip during turn at constant altitude (coupled LO+LAT)
  - TFTA autopilot: to follow a terrain at specified time varying altitude
  - ….

- **Altitude Hold Autopilot No. 1:** Altitude changes due to changes in speed (lift and drag) and changes in pitch.
  - **Variables of interest:** forward speed, vertical speed, pitch angle, **altitude**, flight path angle
  - **Control variables:** Elevator δ_E (Thrust δ_T)



$$\dot{u} = X_u u + X_w w + X_{\dot{w}} \dot{w} + X_q q - g\theta + \sum_i X_{\delta_i} \delta_i$$
$$\dot{w} - U_0 q = Z_u u + Z_w w + Z_{\dot{w}} \dot{w} + Z_q q + \sum_i Z_{\delta_i} \delta_i$$
$$\dot{q} = M_u u + M_w w + M_{\dot{w}} \dot{w} + M_q q + \sum_i M_{\delta_i} \delta_i$$
$$\dot{\theta} = q$$
$$\dot{h} = U_0 \theta - w$$

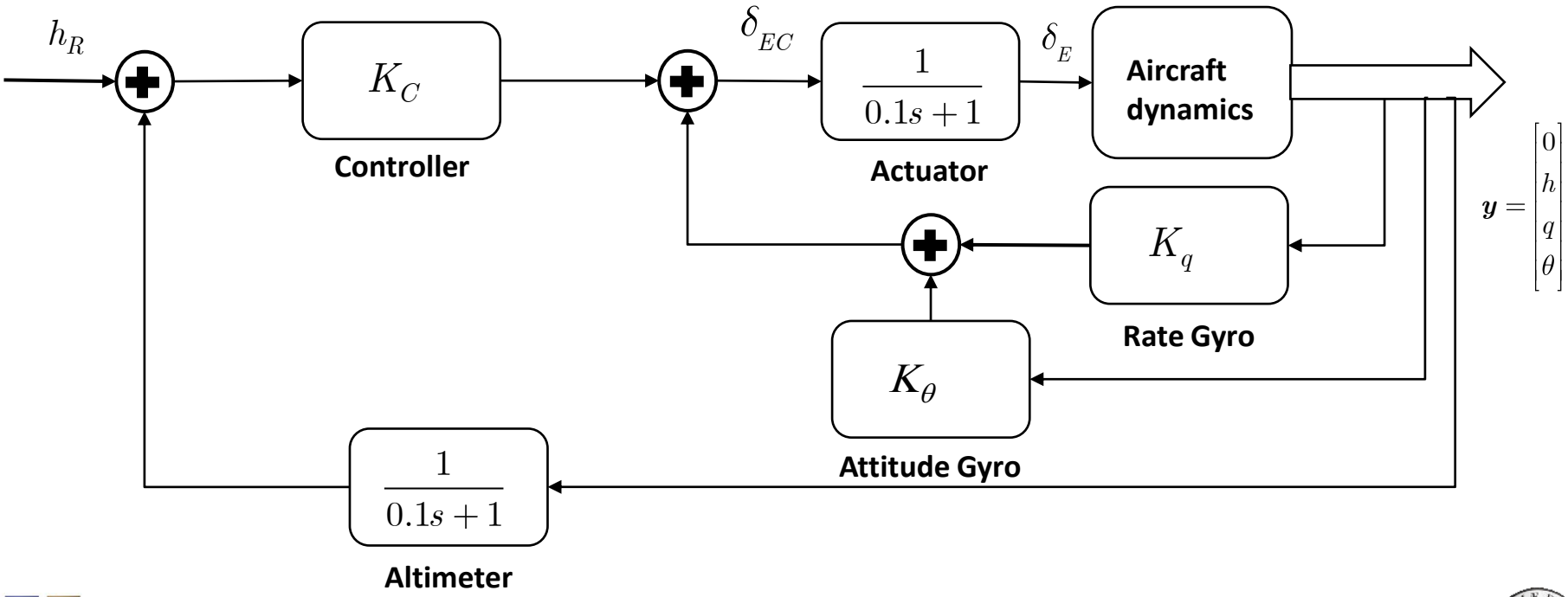
VARIABILI AGGIUNTIVE

$$\gamma = \theta - \alpha$$
$$\alpha = \frac{w}{U_0}$$
$$a_x = \dot{u}$$
$$a_z = \dot{w} - U_0 q = -\ddot{h}$$

- State vector used for autopilot design $x = \begin{bmatrix} u \\ \gamma \\ \theta \\ h \end{bmatrix}$

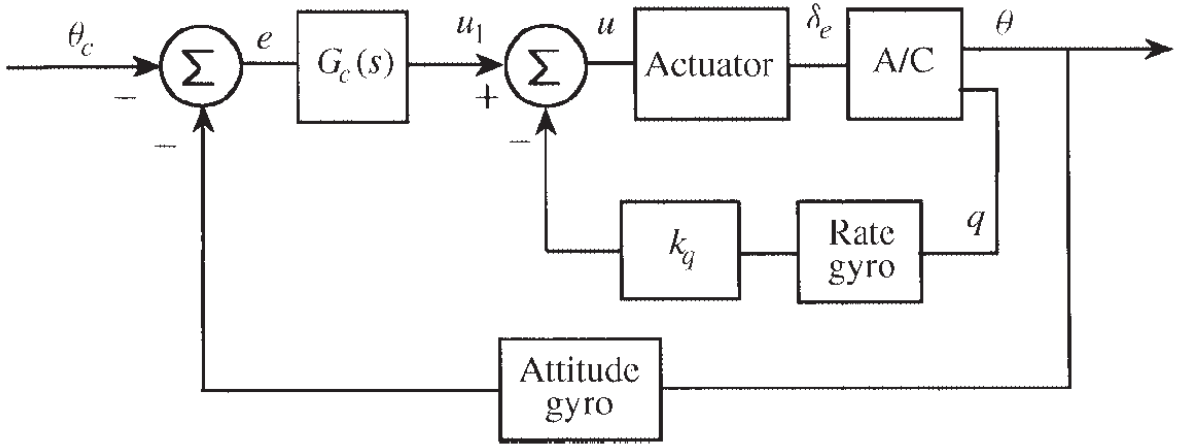
- **Altitude Hold No. 2:** Alternate solution with pitch rate feedback

$$\dot{\boldsymbol{x}} = A\begin{bmatrix}\gamma\\ h\\ q\\ \theta\end{bmatrix} + B\delta_E;\ \boldsymbol{y} = \begin{bmatrix}h\\ q\\ \theta\end{bmatrix} = C\boldsymbol{x} + D\delta_E$$



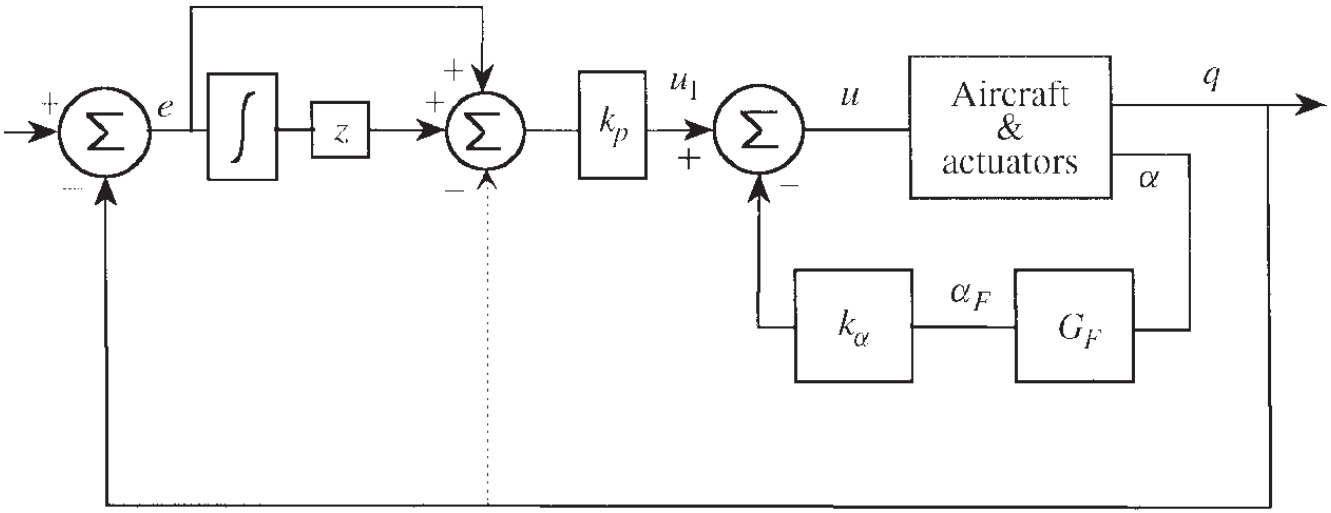
Pitch Angle Hold Autopilot

- Used to track a Pitch Angle reference θ_c
  - From outer loop control
    - Altitude Controller
    - Position Controller (e.g. for Helicopters)
  - From Pilot Command (in FBW system)



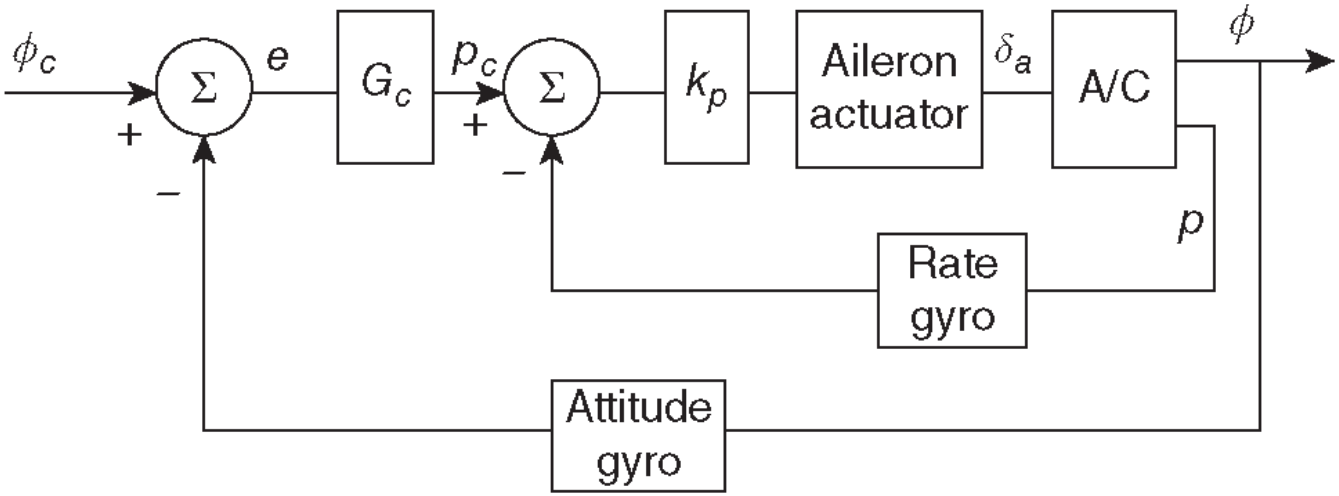
Pitch Rate Controller

- Used to track a Pitch Rate reference
  - For high performance maneuvers (under pilot control)
  - Precise pointing (under pilot control)
  - Approach Landing (under pilot control)



Roll Angle Hold Autopilot

- Used to track a Roll Angle reference ϕ_c
  - From outer loop control
    - Heading Controller
    - Position Controller (e.g. for Helicopters)
  - From Pilot Command (in FBW system)



Heading Angle Hold Autopilot

- Used to track a Heading Angle reference Ψ_c
  - From outer loop control
    - Waypoint Guidance
    - Instrumental Landing
    - VOR Localizer
  - From Pilot set-point
    - Desired route