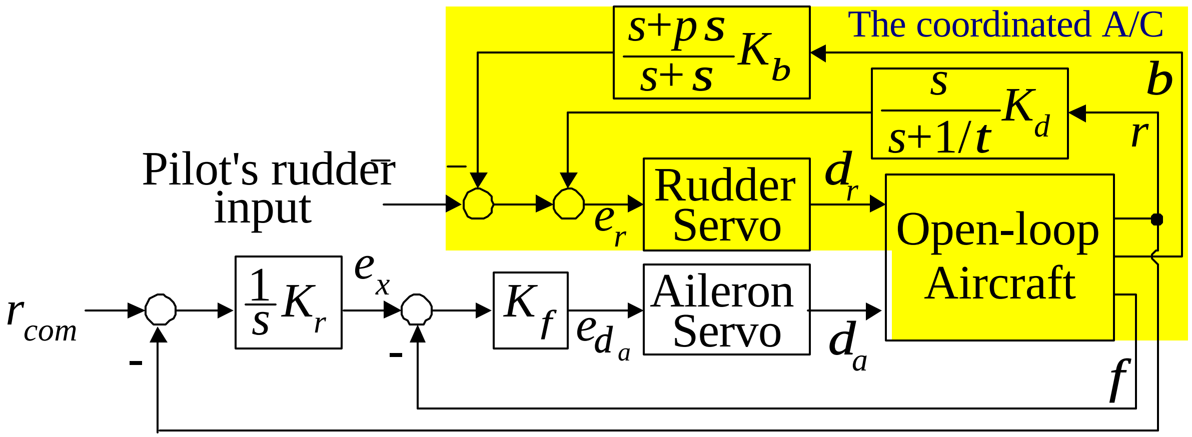
《Intermediate Lateral Autopilots (I) – Yaw orientation control》

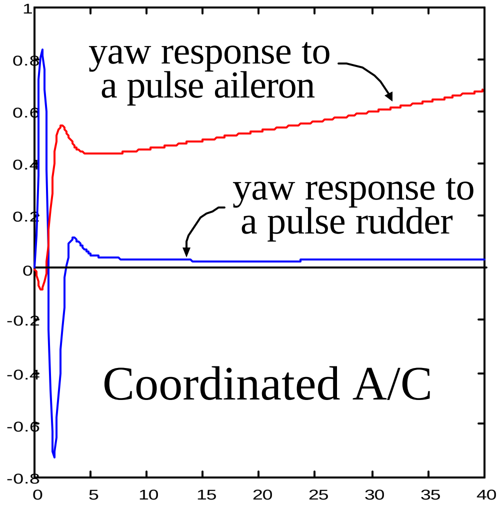
◎Yaw orientation autopilot – Lateral autopilot for yaw maneuver◎

○Designed to have the aircraft follow the pilot's yaw rate command or hold the aircraft with a reference yaw rate signal. ==> The autopilot will work on the ***coordinated aircraft***

--- A ***coordinated A/C*** will mean A/C with the Dutch roll damper and the coordination controller.

○Typical block diagram:

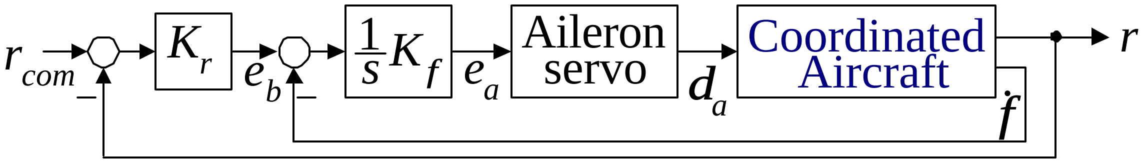




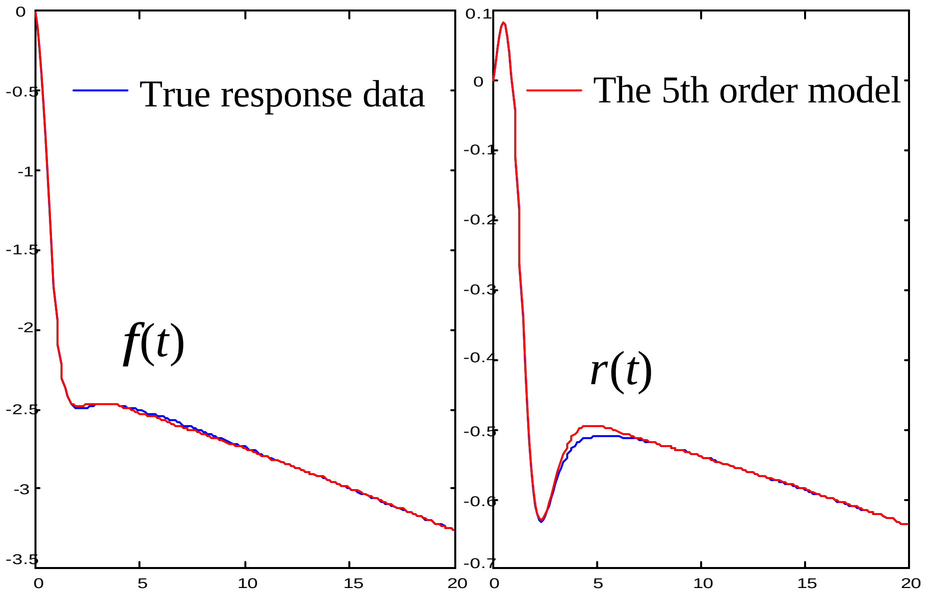
○Important features of the design:

- ○ The controlling input turns to the aileron, instead of the rudder.
  --- From the response plot shown in the right figure above, we can see that, ***in a coordinated A/C, the aileron becomes a more effective input for yaw motion***. (Appendix B)
- ○ An integrator feedback is included to remove the steady state error between $r(t)$ and r_{com}
  --- The coordinated A/C is normally with an unstable spiral mode, and the integrator feedback will further destabilize the system
- ○ An additional f feedback inner-loop is therefore included to stabilize the lateral motion.
  --- A roll angle feedback is most effective for stabilizing the spiral mode.

- ○Working block diagram
  - **○ *The block diagram shows what is implemented.***



  - ○ The roll angle feedback is replaced with a roll rate feedback.
    --- Roll rate signal is much easier to obtain than the roll angle signal.
    --- As the turn gets steady, $\dot{f} = 0$ and the roll rate feedback terminates (self-washout).
- ○A/C model for the design:
  - ○ Require d_a to f and d_a to r transfer functions of the coordinated A/C.
  - ○ Approximated model estimated from the response data (of the coordinated A/C) will be used.
    --- True model of the coordinated A/C is complicated to compute (see Appendix C).
  - ○ The following fifth order model was estimated for the coordinated A/C presented in p.84 of this note:

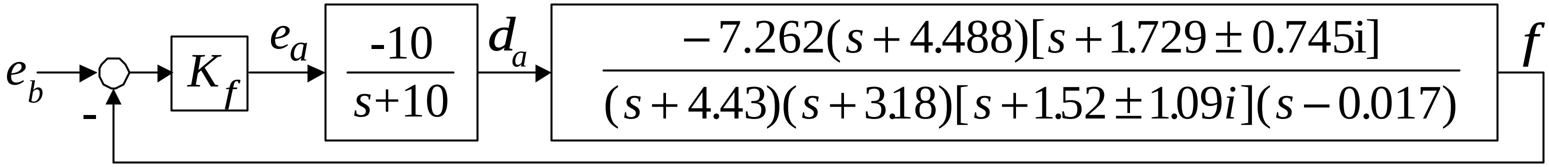


$$r(s) = \frac{1.76(s+8.406)(s+0.767)(s-1.967)}{(s+4.427)(s+3.179)[s+1.516\pm 1.086i](s-0.017)}d_a(s)$$

$$f(s) = \frac{-7.262(s+4.488)[s+1.729\pm 0.745\text{i}]}{(s+4.427)(s+3.179)[s+1.516\pm 1.086i](s-0.017)}d_a(s)$$

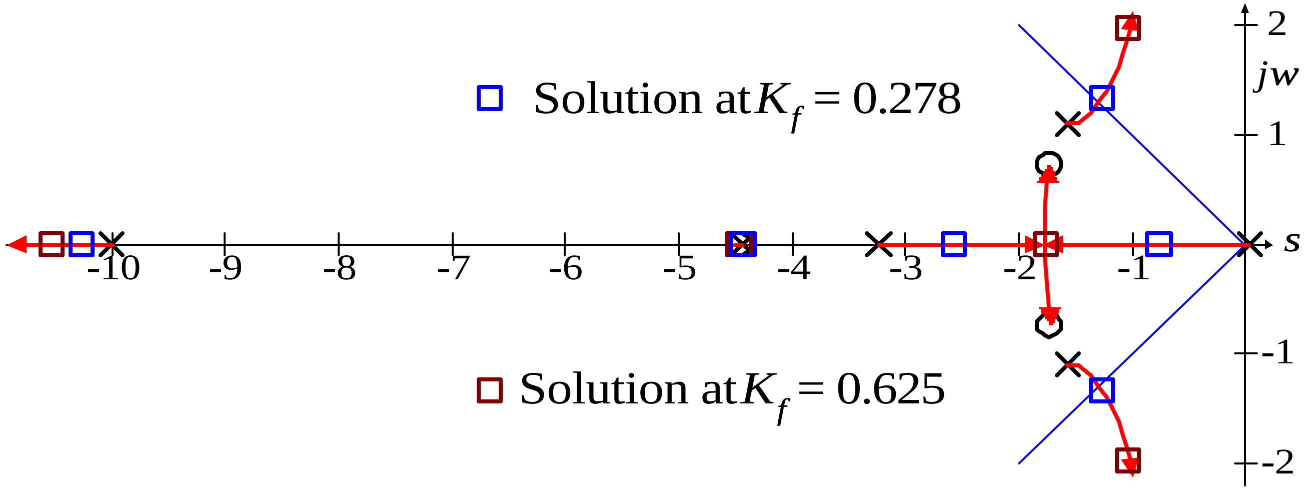
○Inner-loop analysis

- ○ Inner-loop block diagram:



--- We have retained the roll angle feedback format, to simplify the analysis.

--- A negative gain aileron servo is used, because that $f(s)/d_a(s)$ has a negative gain.



--- The spiral mode will be stabilized, but the Dutch roll mode will suffer, by the inner-loop feedback. However, the later will regain its nice damping with the outer-loop feedback.

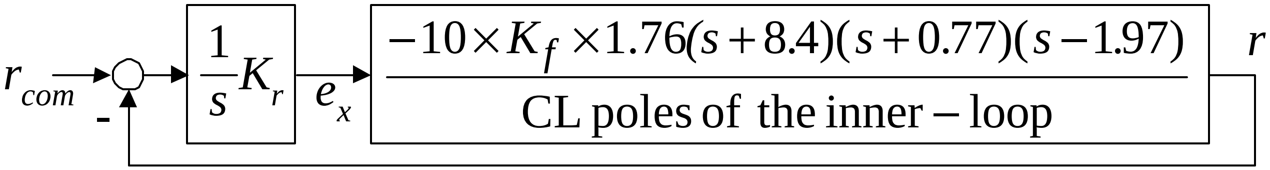
--- $K_f = 0.625$ corresponds to the highest stability for the spiral mode.

--- However, a zero at $s = -0.767$ will appear in the outer-loop locus. If not removed, this zero will stop the outer-loop integrator pole from going left.

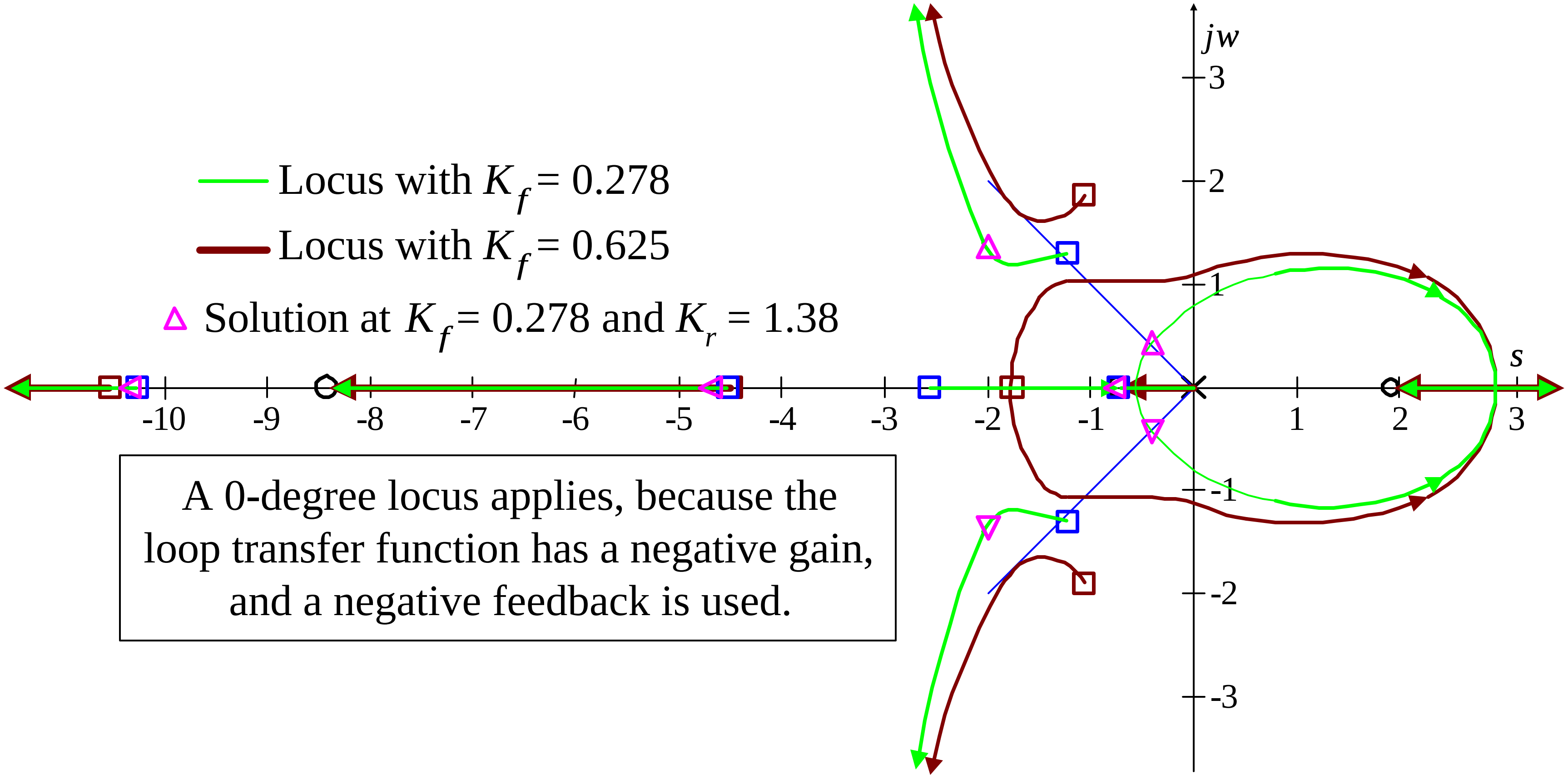
--- $K_f = 0.278$ will produce a inner-loop CL pole to cancel the outer-loop zero at $s = -0.767$

○Outer-loop analysis:

- ○ The numerator of the loop transfer function has been changed from the numerator of $f(s)/d_a(s)$ to the numerator of $r(s)/d_a(s)$.



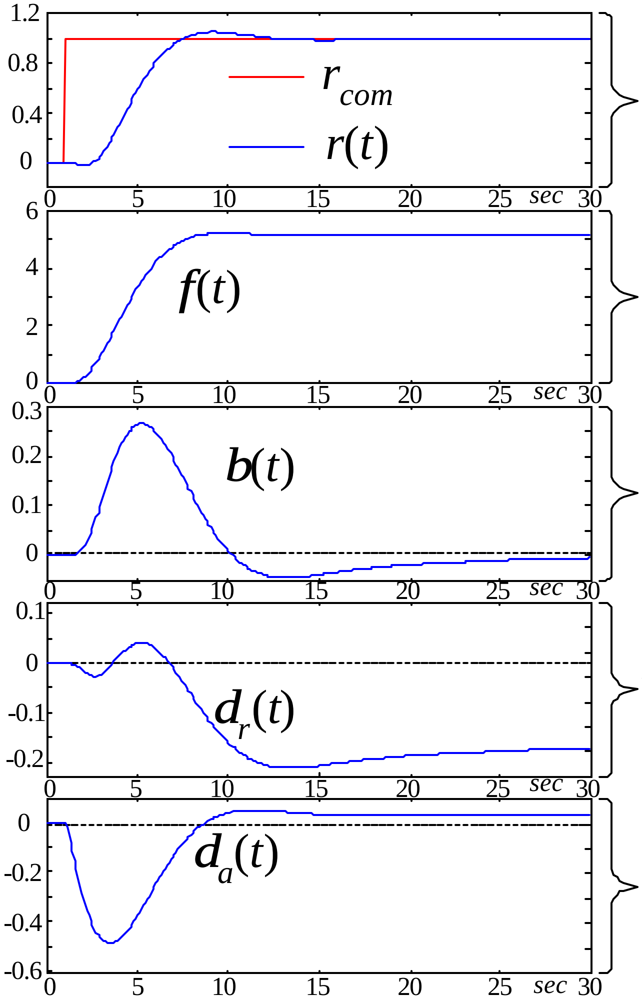
--- Because that the two feedback loops are for the same controlling input, change in feedback signal is equivalent to change in the numerator of the corresponding model.



A 0-degree locus applies, because the loop transfer function has a negative gain, and a negative feedback is used.

○Closed-loop simulation of the yaw orientation autopilot:

- ○ The simulated design was with $K_f = 0.278$ and $K_r = 1.38$.
  - --- For the coordinated A/C, we have used the example presented on p.84 of this note.



$r(t)$ does follow r_{com}, though with certain time delay, a result of the high relative order of the system

A steady state $f(t)$ is also established, creating a steady turn.

A coordinated turn is established, the steady state sideslip is nearly nulled..

A steady state $d_r(t)$ results to hold the sustaned yaw.rate

The steady state $d_a(t)$ is to compensate the unbalanced relative wind on two sides of the wing due to yaw

--- Basically, all lateral controllers discussed thus far perform as they are designed to.

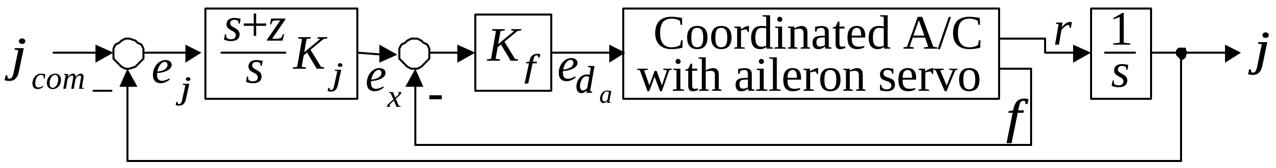
《Intermediate Lateral Autopilots (II) – Heading Autopilot pilot》

◎Heading autopilot: A displacement autopilot for yaw◎

〇Preliminaries about the autopilot:

- Design goal: To have the aircraft follow a reference heading signal Ψ_{com}
  - --- In general, Ψ is the heading of the A/C in the horizontal plane.
  - --- For small bank angle, $f \ll 1$, we will have $r = \dot{\Psi}\cos f \approx \dot{\Psi}$; hence, $\Psi \approx r/s = j$
  - --- As a result, we can treat Ψ_{com} as a yaw angle command j_{com}.
  - --- j_{com} (Ψ_{com}) signal may be generated through integrating r_{com} in a pilot operated maneuver or be sensed by a directional gyro in an automatic flight control loop.
- Again, this autopilot will work on the coordinated aircraft

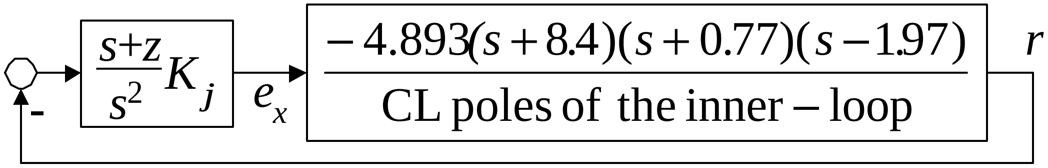
〇Typical block diagram:



- A roll angle feedback inner-loop is kept here for stabilization.
- An integrator is also adopted to ensure steady state command following.
- A zero at $s = -z, z > 0$ is included to attract the locus to enter the LHP.
  - --- The j -feedback introduces a pole at $s = 0$ to the system. With an integrator control, the outer-loop locus from the double integrator will not enter the LHP without a zero nearby.
- The inner-loop portion of this design is the same as that of the yaw orientation autopilot.
- We will go right with the outer-loop locus analysis. We will also set $K_f = 0.278$.

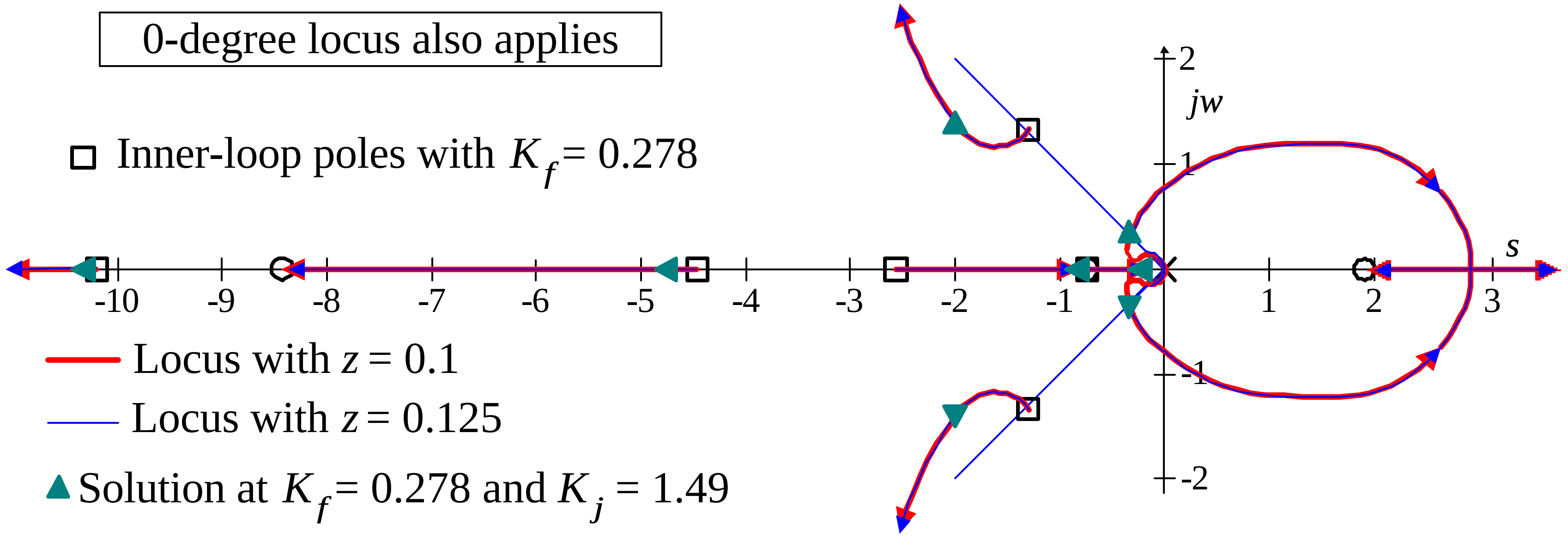
○Outer-loop root locus:

- ○ Please refer this block diagram to that of the yaw orientation autopilot design.
- ○ ***Note that this block diagram is for root locus analysis only.*** For the real system, its output is the yaw angle j .



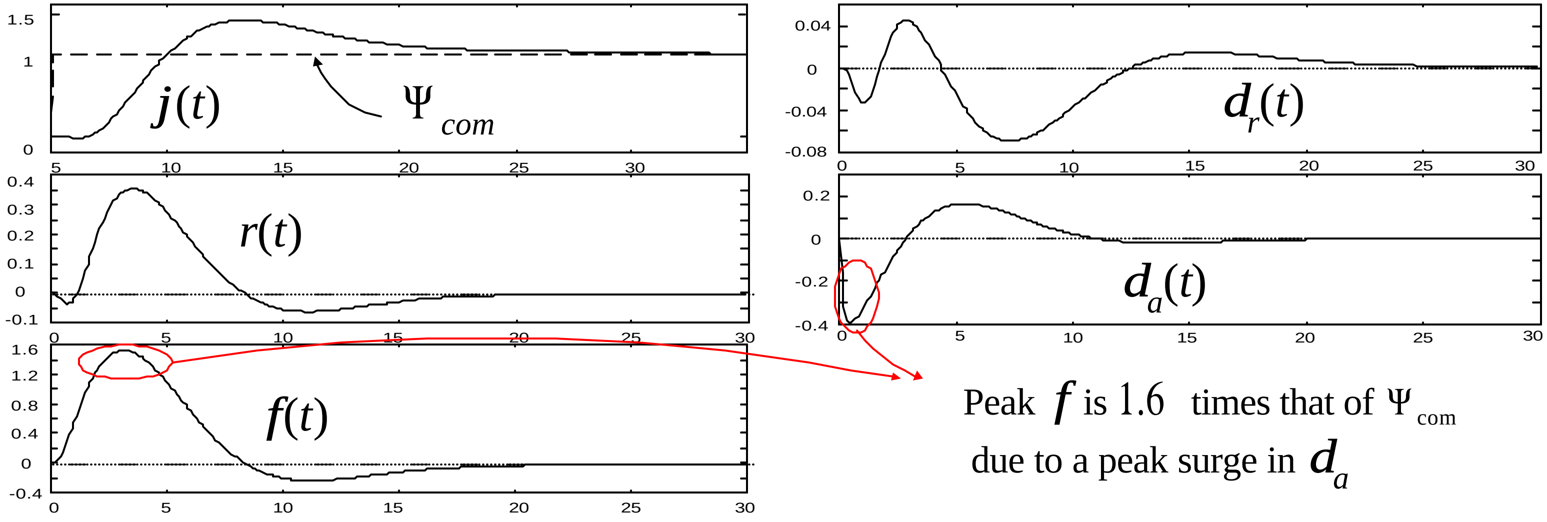
○The outer-loop locus

0-degree locus also applies



- ○ Two complex pole pairs result.
  - --- The Dutch roll pair will increase in stability, and is of no concern here.
  - --- The dominant pair will loose its obtainable damping ratio with increasing value of z .
  - --- If a damping ratio of 0.707 is a specification, then $z = 0.125$ is the upper bound for z .
- ○ The zero at $s = -z$ will also attracts a CL pole near by. Hence, a smaller z is not desirable,
  - --- A trade off design is necessary. Final choice may be determined from a CL simulation.

○Closed-loop system response:



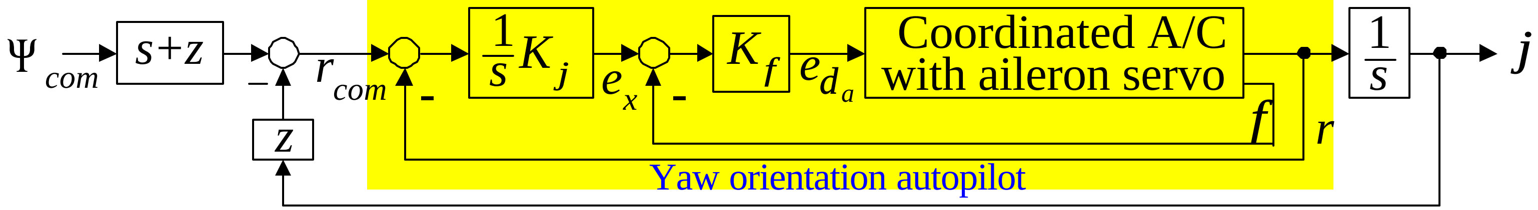
Peak f is 1.6 times that of Ψ_{com} due to a peak surge in d_a

- ○ This simulation is performed with $z = 0.1$ and $K_b = 1.49$, and on a coordinated A/C.
- ○ The heading error of the A/C is forced to zero at the steady state.
- ○ In addition, because that $\lim_{t \to 0} f(t) = 0$. the assumption, $j_{com} \approx \Psi_{com}$, or in a more general sense, $j \approx \Psi$ for any j, is valid.
  --- This result will allow us to control the A/C heading through control of the yaw angle j.
- ○ However, a large peak value of the bank angle occurred during the maneuver.
  --- With a peak f that equals $1.6\Psi_{com}$, a 30° turn maneuver would produce a peak f of 50°
  --- Normally, $30^\circ \approx 0.5\,rad$ will be the limit for f before the passengers begin to feel uncomfortable, or even panic, about the fight.
  --- The large peak value in f is a result of the large yaw rate that occurs during the maneuver.
  --- Some form of the improvement on the heading pilot design is necessary.

◎Improved design: Heading autopilot with a yaw limiter◎

○Remedy to the peak surge in bank angle:

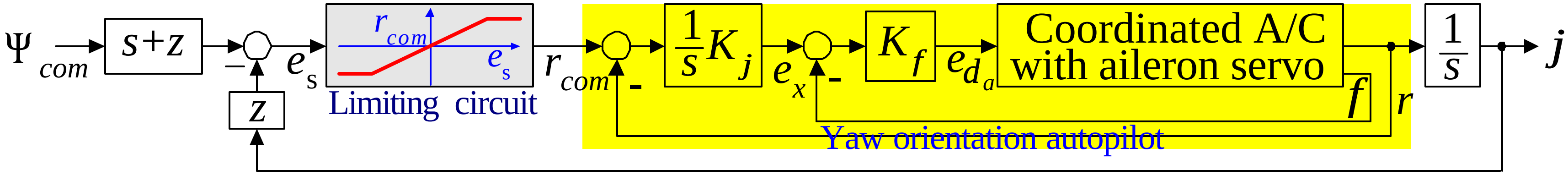
- ○ First of all, the following equivalent form of the heading autopilot can be drawn:



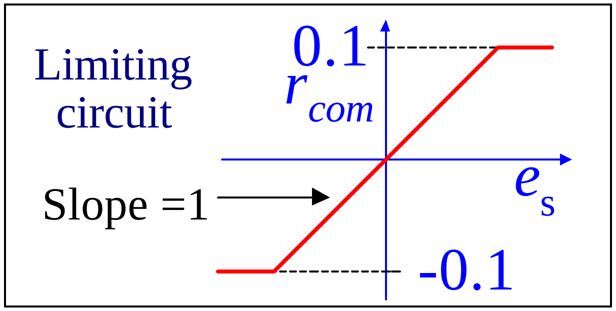
==> ***A heading autopilot is a heading feedback outer-loop to a yaw orientation autopilot.***

--- Implementing the heading autopilot in this form will require differentiation on the heading command Ψ_{com}. However, any noise amplification due to this differentiation will be restored by the integrator inside the second feedback loop.

- ○ Since we regard the large peak value in f is a result of the large yaw rate that occurs during the maneuver., we can improve this effect by limiting the yaw rate as follows:



--- A saturation limit on r_{com} is installed.



○Design of the yaw rate limiting circuit:

- ○ Assume that a $f \le 30^\circ \approx 0.5\, rad$ is sought.
- ○ CL simulation of the yaw orientation autopilot reveals that the ratio between f and r will be about $5:1$.
- ○ Then, a limit of r_{com} can be set at $r_{com} \le 0.1\, rad/\sec$.

《Intermediate Lateral Autopilots (III) – Roll orientation control》

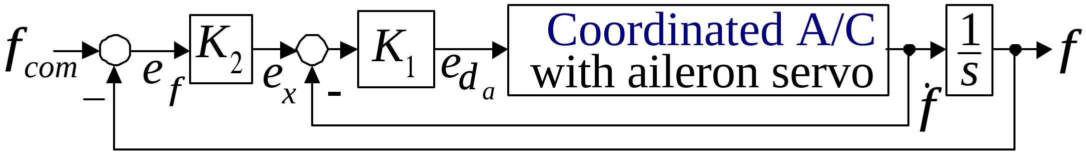
◎Roll orientation autopilot – A command following control for roll◎

○Definition of the problem:

- Design an autopilot to have the A/C follows the pilot's roll angle command or hold the aircraft with a reference roll angle.
- The autopilot will also work on the **coordinated aircraft**

○Typical block diagram

--- A roll rate feedback inner-loop is kept for stability improvement.

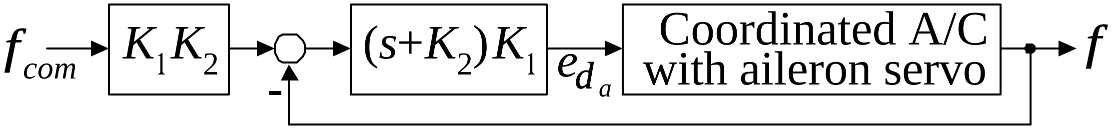


- The feedback structure is equivalent to a proportional plus differentiator (PD) control:

--- Mathematically, $e_{d_a}(s) = K_1[K_2(f_{com}(s) - f(s)) - \dot{f}(s)]$

$$= K_1K_2 f_{com}(s) - K_1(s+K_2)f(s)$$

--- Equivalent block diagram:



==> The PD control structure seems indicate that steady state output error may persist.

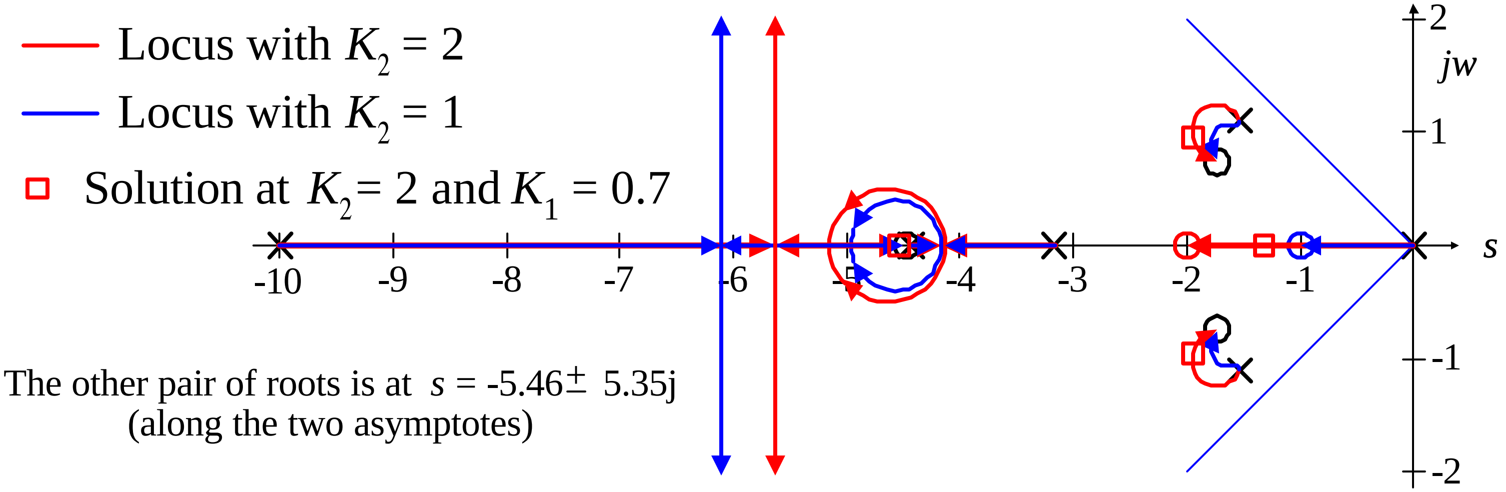
○Dynamic model of the coordinated A/C and of the aileron servo:

- For the same coordinated aircraft used in the yaw orientation autopilot design, we have:

$$\frac{f(s)}{d_a(s)} = \frac{-7.262(s+4.488)[s+1.729\pm0.745i]}{(s+4.427)(s+3.179)[s+1.516\pm1.086i](s-0.017)}, \quad \frac{d_a(s)}{e_{d_a}(s)} = \frac{-10}{s+10}$$

--- A positive gain will result for the overall system; hence, a 180-degree locus will apply.

○Closed-loop system of the design



The other pair of roots is at $s = -5.46 \pm 5.35j$
(along the two asymptotes)

- ○ The leftward moment of the spiral model will increase with larger value of K_2.
- ○ The following CL system is also obtained for the selected controller gains:

$$TF_{CL}(s) = \frac{f(s)}{f_{com}(s)} = \frac{50.8(s+2)(s+4.488)[s+1.729 \pm 0.745i]}{(s+1.307)(s+4.516)[s+1.936 \pm 0.958i][s+5.46 \pm 5.347i]}$$

$$= \frac{50.8s^4 + 505.5s^3 + 1776.6s^2 + 2745.9s + 1616.6}{s^6 + 20.6s^5 + 197.5s^4 + 978.2s^3 + 2508.5s^2 + 3222.6s + 1608.2}$$

--- A dominant CL pole at $s = -1.3$ results, indicating a fast CL response (in about 3 sec).

--- Also, with $TF_{CL}(s)\big|_{s=0} = 1.005$, a 0.5% steady state error also results for a step $f_{com}(s)$

--- For a PD feedback system, this near perfect output following is unusual.

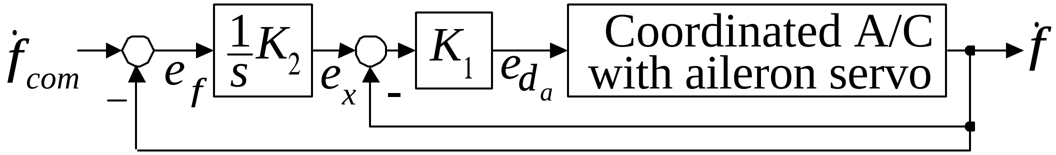
--- The fact is that the spiral mode of the open-loop model, being so close to the origin, acts like an integrator, thereby squeezing out the steady state output error.

◎Roll orientation autopilot – A rate command version◎

○Address the problem:

- ○ A roll angle command is used in the previous design.
- ○ In a manual maneuver, the pilot’s control stick input normally represents a roll rate command.
- ○ Need to provide the pilot with a capability to maneuver the A/C with a roll rate command.

○Block diagram of a roll orientation autopilot with a roll rate command:



--- A roll rate feedback inner-loop is still kept for stability improvement.

--- An integrator is also included to ensure the rate command following.

○ The CL system of this design is exactly the same as that of the previous design.

--- For the same A/C and the same controller gains, the CL system will remain as

$$\frac{\dot{f}(s)}{\dot{f}_{com}(s)} = \frac{50.8s^4 + 505.5s^3 + 1776.6s^2 + 2745.9s + 1616.6}{s^6 + 20.6s^5 + 197.5s^4 + 978.2s^3 + 2508.5s^2 + 3222.6s + 1608.2}$$

--- Again, a nice steady state command following will results for a step $\dot{f}_{com}(s)$

○Closed-loop system response to a pulse roll rate command: