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$$U(s) = \frac{\tau s + 1}{K(\tau_c s + 1 - e^{-\tau_D s})} E(s)$$

$$U(s) = \underbrace{C(s)}_{a(s)} E(s)$$

$$U(s) K(\tau_c s + 1 - e^{-\tau_D s}) = (\tau s + 1) E(s)$$

$$\frac{K \tau_c s}{\tau s + 1} U(s) = E(s) - \frac{K}{\tau s + 1} U(s) + \frac{K e^{-\tau_D s}}{\tau s + 1} U(s)$$

$$\frac{K \tau_c s}{\tau s + 1} U(s) = E(s) - (G_M^* - G_M) U(s),$$

where  $G_M^*$  is the model of the process without the delay term

$$U(s) = \frac{\tau s + 1}{K \tau_c s} (E(s) - (G_M^* - G_M) U(s))$$

- $\frac{\tau s + 1}{K \tau_c s}$  represents a PI controller of the form  $\frac{\tau}{K \tau_c} \left( 1 + \frac{1}{\tau s} \right)$   
 where the gain of the controller is  $\frac{\tau}{K \tau_c}$  and the integral constant is  $\tau$
- The error term  $E(s)$  is corrected as  $(E(s) - (G_M^* - G_M) U(s))$  using the model information



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$$U(s) = \underbrace{C(s)}_{\substack{\text{PI} \\ a(t)}} E(s) \quad \substack{\uparrow \\ \text{act}}$$

$$\frac{K \tau_c s}{\tau s + 1} U(s) + \frac{K}{\tau s + 1} U(s) - \frac{K e^{-\tau_D s}}{\tau s + 1} U(s)$$

$$U(s) = \boxed{PI} E(s)$$

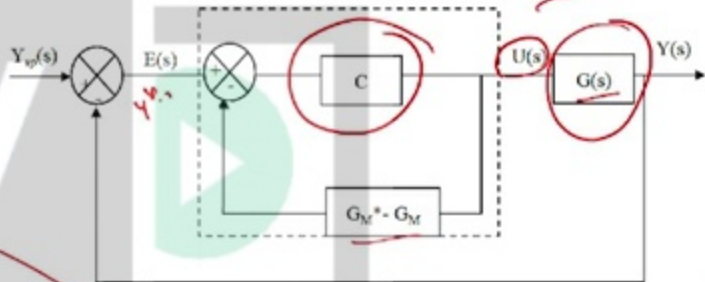


# Controller design for time delay systems – analysis of model information

Model information is used in the controller calculations

$$Y^{des} = \frac{e^{-\tau_D s}}{\tau_c s + 1}$$

$$U(s) = \frac{\tau s + 1}{K \tau_c s} (E(s) - (G_M^* - G_M)U(s))$$



If the model is perfect, then  $G(s) = G_M(s)$  and  $Y(s) = G(s)U(s) = G_M(s)U(s)$ .

$$\begin{aligned} U(s) &= \frac{\tau s + 1}{K \tau_c s} (Y_{sp}(s) - Y(s) - (G_M^* - G_M)U(s)) \\ &= \frac{\tau s + 1}{K \tau_c s} (Y_{sp}(s) - \cancel{G_M(s)}U(s) - (G_M^* - \cancel{G_M})U(s)) \\ &= \frac{\tau s + 1}{K \tau_c s} (Y_{sp}(s) - G_M^*(s)U(s)) \end{aligned}$$

$$U(s) = \frac{\tau s + 1}{K \tau_c s} (Y^{sp} - \underbrace{Y(s)}_{G_M(s)U(s)} - (G_M^* - G_M)U(s))$$

$$\begin{aligned} Y(s) &= G(s)U(s) \\ &= G_M(s)U(s) \end{aligned}$$

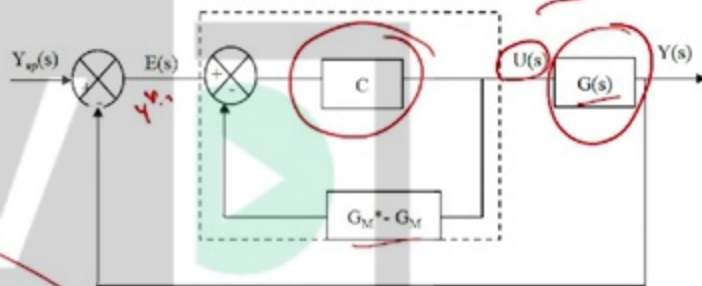


# Controller design for time delay systems – analysis of model information

Model information is used in the controller calculations

$$Y^{des} = \frac{e^{-\tau D^s}}{\tau_c s + 1}$$

$$U(s) = \frac{\tau s + 1}{K \tau_c s} (E(s) - (G_M^* - G_M)U(s))$$



If the model is perfect, then  $G(s) = G_M(s)$  and  $Y(s) = G(s)U(s) = G_M(s)U(s)$ .

$$\begin{aligned} U(s) &= \frac{\tau s + 1}{K \tau_c s} (Y_{sp}(s) - Y(s) - (G_M^* - G_M)U(s)) \\ &= \frac{\tau s + 1}{K \tau_c s} (Y_{sp}(s) - \cancel{G_M(s)U(s)} - (G_M^* - \cancel{G_M})U(s)) \\ &= \frac{\tau s + 1}{K \tau_c s} (Y_{sp}(s) - G_M^*(s)U(s)) \end{aligned}$$

$$U(s) = \frac{\tau s + 1}{K \tau_c s} (Y^{sp} - Y(s) - (G_M^* - G_M)U(s))$$

$$\begin{aligned} Y(s) &= G(s)U(s) \\ &= G_M(s)U(s) \end{aligned}$$



Consider controller TF between the input and the error

$$U(s) = \frac{\tau s + 1}{K(\tau_c s + 1) - e^{-\tau_D s}} E(s)$$

$$\frac{K(\tau_c s + 1)}{\tau s + 1} U(s) = E(s) + \frac{K e^{-\tau_D s}}{\tau s + 1} U(s)$$

$$U(s) = \frac{\tau s + 1}{K(\tau_c s + 1)} E(s) + \frac{e^{-\tau_D s}}{(\tau_c s + 1)} U(s)$$

Let  $e^{-\tau_D s}$  be denoted as  $U^d(s)$

$$U(s) = \frac{\tau s + 1}{K(\tau_c s + 1)} E(s) + \frac{1}{(\tau_c s + 1)} U^d(s)$$

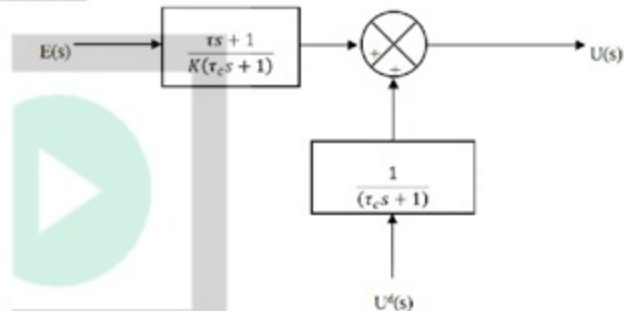


Fig: Inverting TF with time delay without approximation

$$e^{-\tau_D s} U(s) = \frac{U(s)}{u(t - \tau_D)}$$





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