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Triple-step Nonlinear Control Design: Methodology and Automotive Applications

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Outline

※ **Motivation**

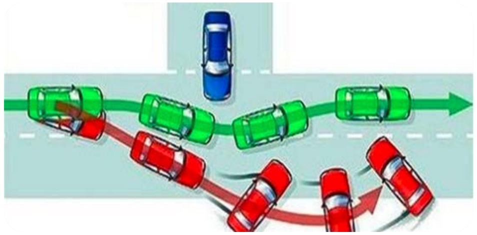
※ **Triple-Step Design Technique**

※ **Automotive Applications: Case Study**

※ **Conclusions**

Motivation

Case 1: Vehicle stability control



Control Requirements

◆ Make the vehicle response according to the action of the driver

◆ Guarantee the vehicle dynamics stability

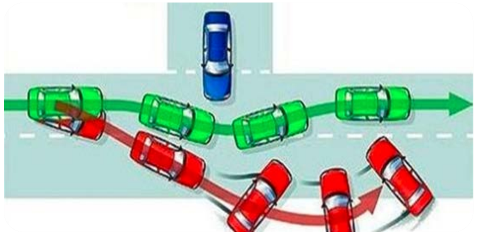
Control Problem Description

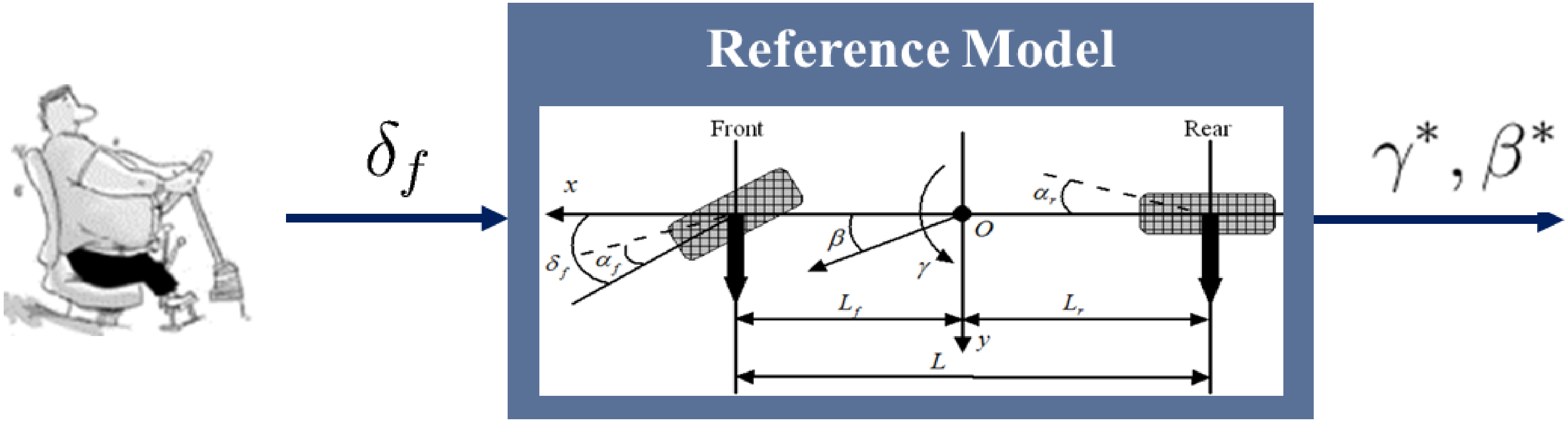
$$\beta \rightarrow \beta^* = 0, \gamma \rightarrow \gamma^*$$

□ Make sideslip angle β and yaw rate γ track the desired references

Motivation

Case 1: Vehicle stability control



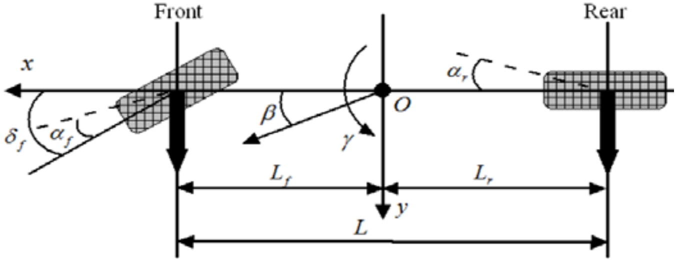


- Make sideslip angle β and yaw rate γ track the desired values

Control Output

Motivation

Modeling



- Newton's second law $m \cdot a = \sum F$
- The principle of moments $J \cdot \dot{\omega} = \sum M$
- Tire dynamics: magic formula, UniTire model, lookup tables

◆ Control-oriented model

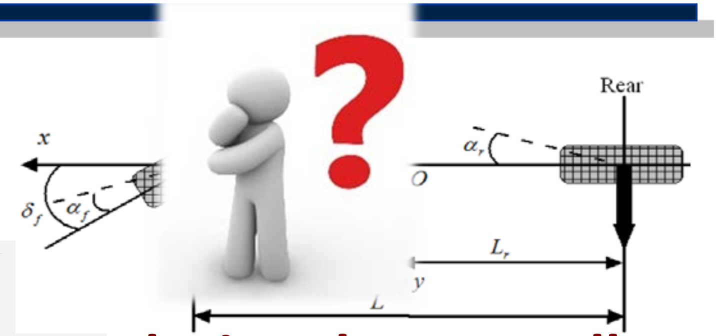
$$\dot{\beta} = \frac{F_{yf}(\beta, \gamma, \delta_f) + F_{yr}(\beta, \gamma)}{mV} - \gamma,$$

$$\dot{\gamma} = \frac{L_f F_{yf}(\beta, \gamma, \delta_f) - L_r F_{yr}(\beta, \gamma) + M_z}{I_z}$$

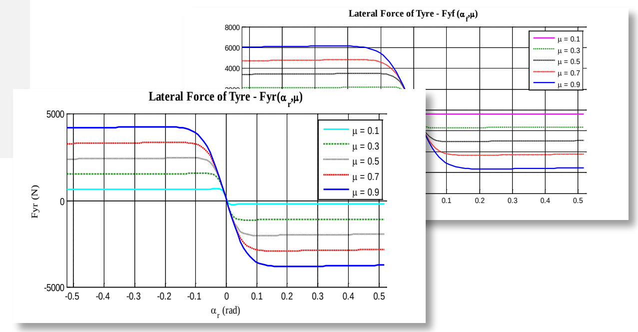
Motivation

Modeling

- With time varying parameters
- Lookup tables in the right side
- Non-affine in control input



How to design the controller



- Control outputs： $y = [\beta, \gamma]^T$
- Control inputs：$u = [\delta_f, M_z]^T$
- Time varying parameters：$p = [V, \mu]^T$

$$\dot{y}_1 = f_1(y, p, u)$$

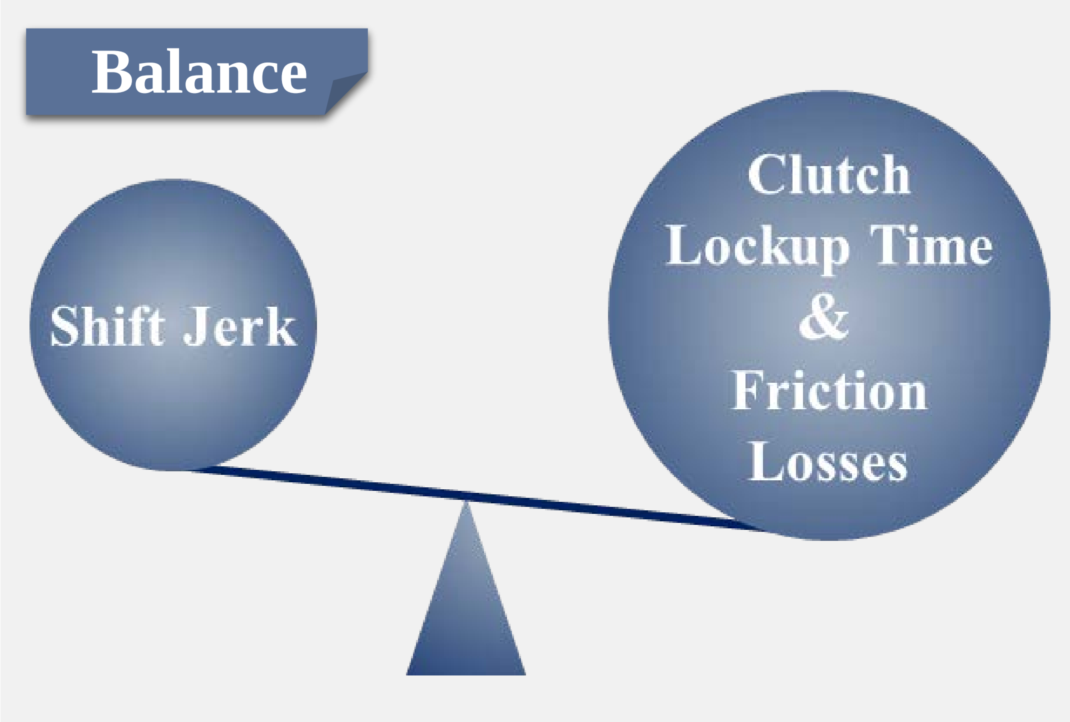
$$\dot{y}_2 = f_2(y, p, u)$$

Motivation

Case 2：Shift control of automated transmissions

Control Requirements

◆Improve smoothness of shift process

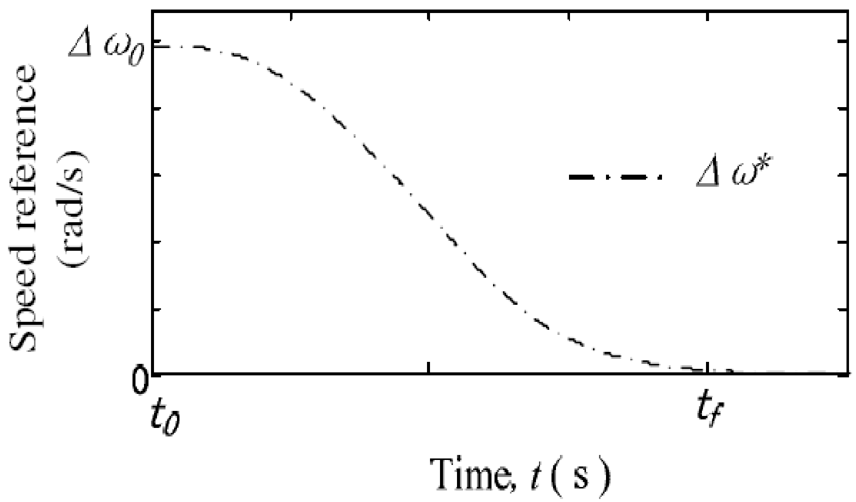


Motivation

Case 2：Shift control of automated transmissions

Control Requirements

- ◆Improve smoothness of shift process
- ◆Make the speed difference of clutch track a reference trajectory



- ➢ $t_f - t_0$ does not exceed the required shift time
- ➢ the change rate at t_f is zero
- ➢ the change rate at t_0 should be small

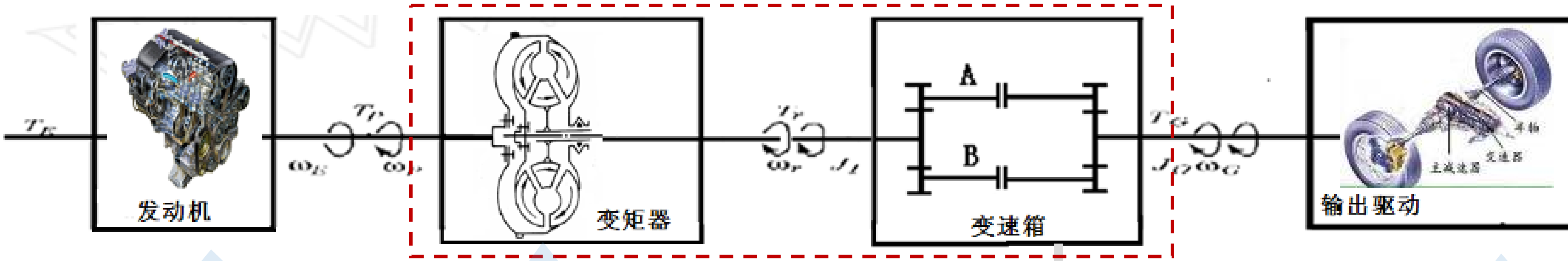
- ➢ **Speed difference of clutch**

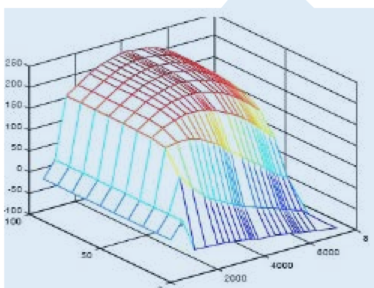
$$y = \Delta\omega$$

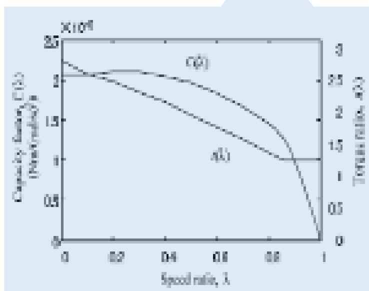
Control Output

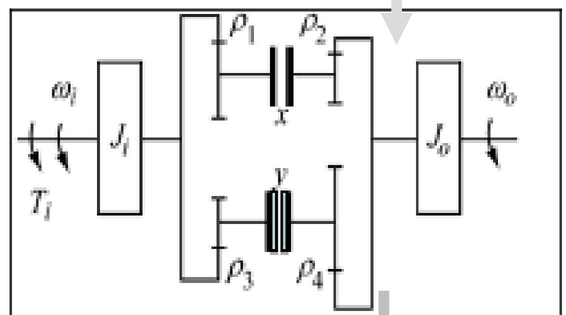
Motivation

Case2：Shift control of transmissions









$$F_x = F_{x\max}\tanh\left(\frac{2S_x}{dS_z}\right)$$

$$S_x = \frac{R_w\omega_w - V}{V}$$

$$F_G = mg\sin\theta_g$$

$$F_A = \frac{1}{2}\rho C_D A_A V^2$$

Modeling

Inertia Phase

- **The principle of moments**
- **Valve pressure dynamics**

$$\Delta\dot{\omega} = (C_{13} - C_{23})\mu(\Delta\omega)\,RNA\,p_{cb} + f_2(\omega_e, \omega_t, \Delta\omega$$

$$\dot{p}_{cb} = -\frac{1}{\tau_{cv}}p_{cb} + \frac{K_{cv}}{\tau_{cv}}u$$

Motivation

Model Concept

$$\ddot{y} = A_0(y, p) + A_1(y, p)\dot{y} + B(y, p)u$$

Control output :

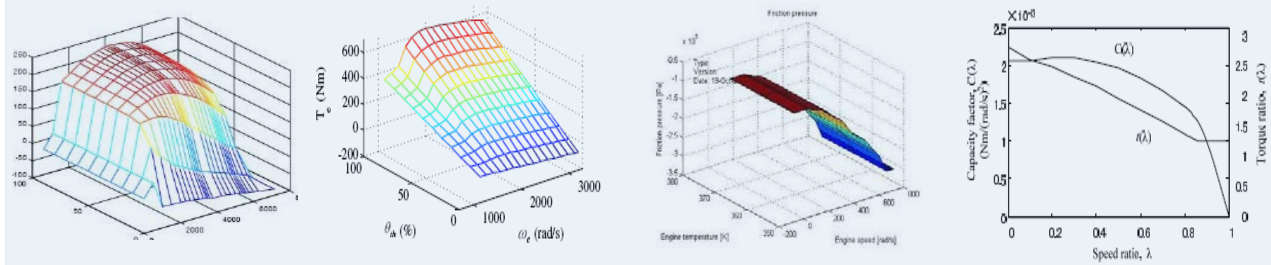
$$y = \Delta\omega$$

Control input :

$$u = i$$

Time varying parameter :

$$p = [\omega_e, \omega_t, p_{\mathrm{cb}}]$$



DCT/AT Engine Torque Map   Engine Friction Properties Map   Torque Converter

Data-physics-mixed model

Model Features

- is nonlinear and in the form of DE
- contains lookup tables
- with time varying parameters
- may be non-affine as in the case of vehicle stability control

How to design the controller

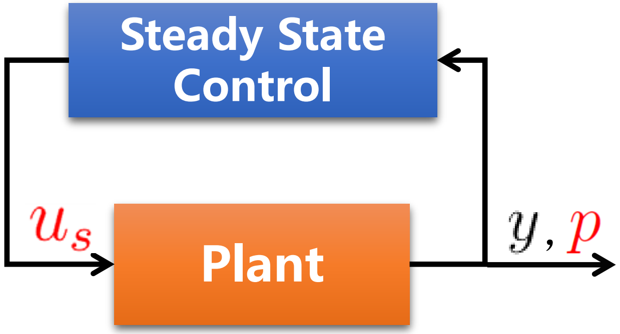
Triple Step Design Technique

for affine systems

Take 2nd order systems as example

$$\ddot{y} = A_0(y, p) + A_1(y, p)\dot{y} + B(y, p)u$$

First Step: Steady State Control



Let $\ddot{y} = 0$ and $\dot{y} = 0$

$$u_s(y, p) = -\frac{A_0(y, p)}{B(y, p)} \quad \text{with} \quad (B(y, p) \neq 0)$$

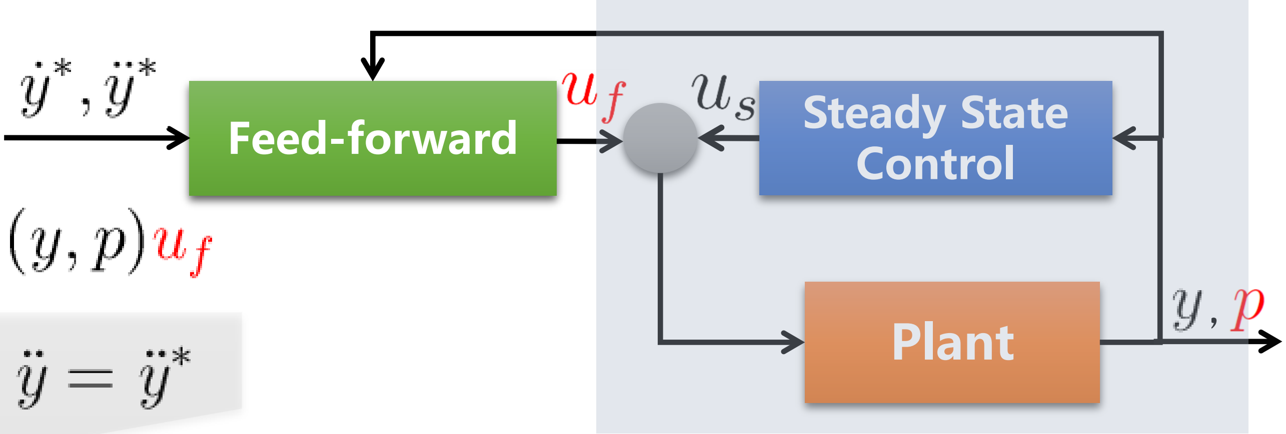
Triple Step Design Technique

for affine systems

Second Step: Reference Variation Based Feed-forward Control

$$\ddot{y} = A_0(y,p) + A_1(y,p)\dot{y} + B(y,p)u$$

$$u = u_s + u_f$$



$$\ddot{y} = A_1(y,p)\dot{y} + B(y,p)u_f$$

Let $\dot{y} = \dot{y}^*$ **and** $\ddot{y} = \ddot{y}^*$

$$u_f = \frac{1}{B(y,p)}\ddot{y}^* - \frac{A_1(y,p)}{B(y,p)}\dot{y}^* =: u_f(y,p,\dot{y}^*,\ddot{y}^*)$$

Introduce reference variation in feed-forward → Improve the transient of tracking

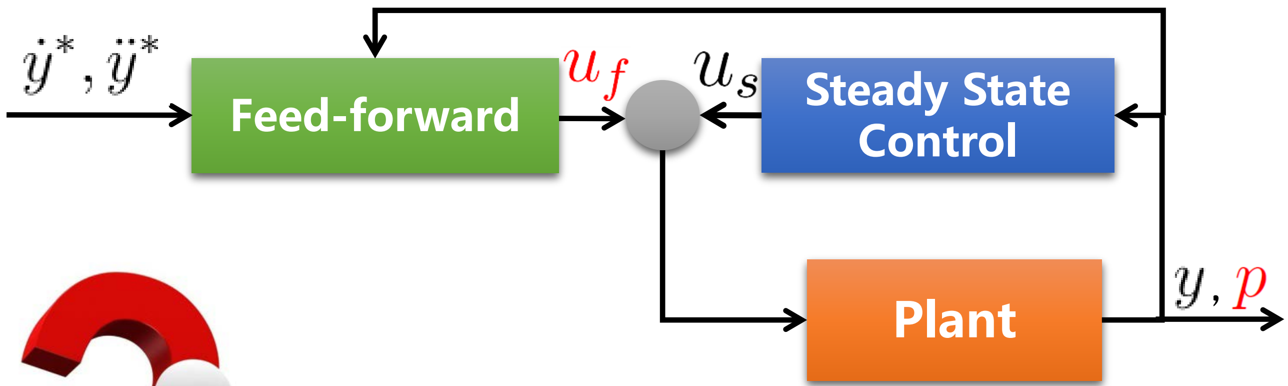
Gains depend on the system states and varying parameters y, p

Triple Step Design Technique

for affine systems

$$\ddot{y} = A_0(y, p) + A_1(y, p)\dot{y} + B(y, p)u$$

- **1. Step: Steady State Control**
- **2. Step: Reference Variation Based Feed-forward Control**



$$y \rightarrow y^*$$

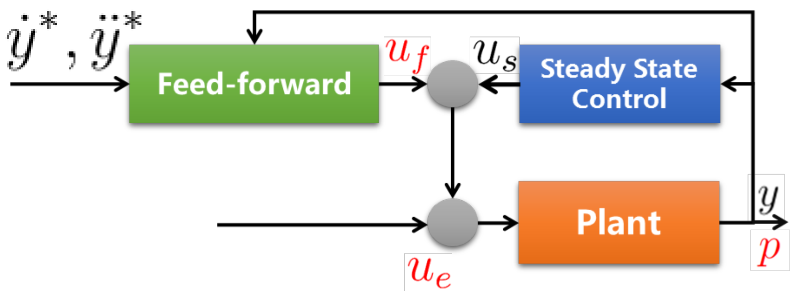
Triple Step Design Technique

for affine systems

Third Step: Error Feedback Control

$$\ddot{y} = A_0(y, p) + A_1(y, p)\dot{y} + B(y, p)u$$

$$u = u_s + u_f + u_e$$



$$\ddot{y} = \ddot{y}^* - A_1(y, p) \cdot (\dot{y}^* - \dot{y}) + B(y, p)u_e$$

Error dynamics $(e = y^* - y)$

$$\ddot{e} = A_1(y, p)\dot{e} - B(y, p)u_e$$

Define Lyapunov function $V : D \rightarrow R$

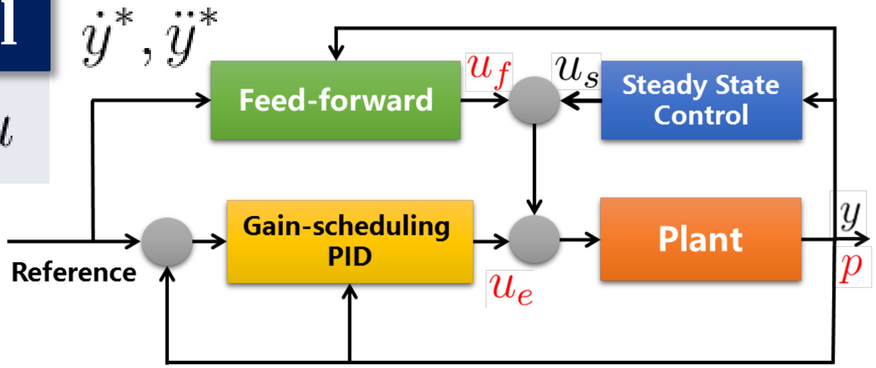
$$V = \frac{1}{2}e^2 + \frac{1}{2}\left(\int e\,dt\right)^2 + \frac{1}{2}\dot{e}^2$$

Triple Step Design Technique

for affine systems

Third Step: Error Feedback Control

$$\ddot{y} = A_0(y,p) + A_1(y,p)\dot{y} + B(y,p)u$$



Gain-scheduling PID

$$u_e = \underbrace{\frac{k_0}{B(y,p)}}_{f_P(y,p)} e + \underbrace{\frac{k_1}{B(y,p)}}_{f_I(y,p)} \int e dt + \underbrace{\frac{k_2 + A_1(y,p)}{B(y,p)}}_{f_D(y,p)} \dot{e}$$

Closed-loop error dynamics

$$\ddot{e} = -k_0 e - k_1 \int e\, dt - k_2 \dot{e}$$

$$\dot{V} \leq 0 \;\; (\dot{V} < 0 \text{ in } D - \{0\})$$

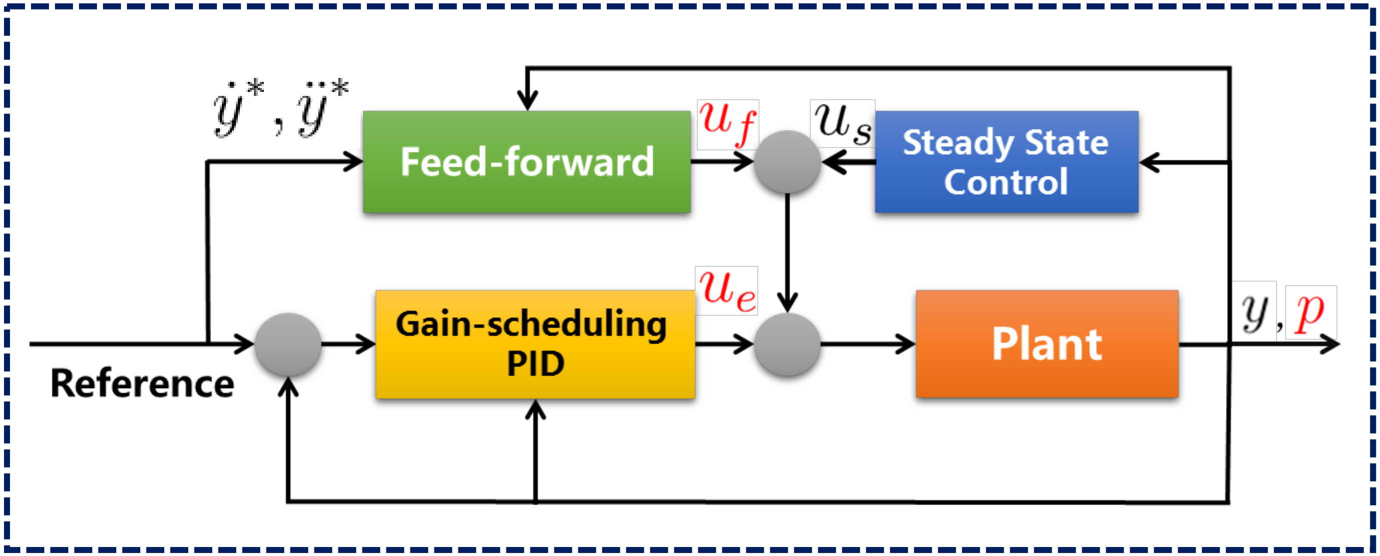
LaSalle's invariance principle

Triple Step Design Technique

for affine systems

Final Control Law (Second order)

$$u = -\frac{A_0(y,p)}{B(y,p)} + \frac{1}{B(y,p)}\ddot{y}^* - \frac{A_1(y,p)}{B(y,p)}\dot{y}^* + \frac{k_0}{B(y,p)}e + \frac{k_1}{B(y,p)}\int e dt + \frac{k_2 + A_1(y,p)}{B(y,p)}\dot{e}$$



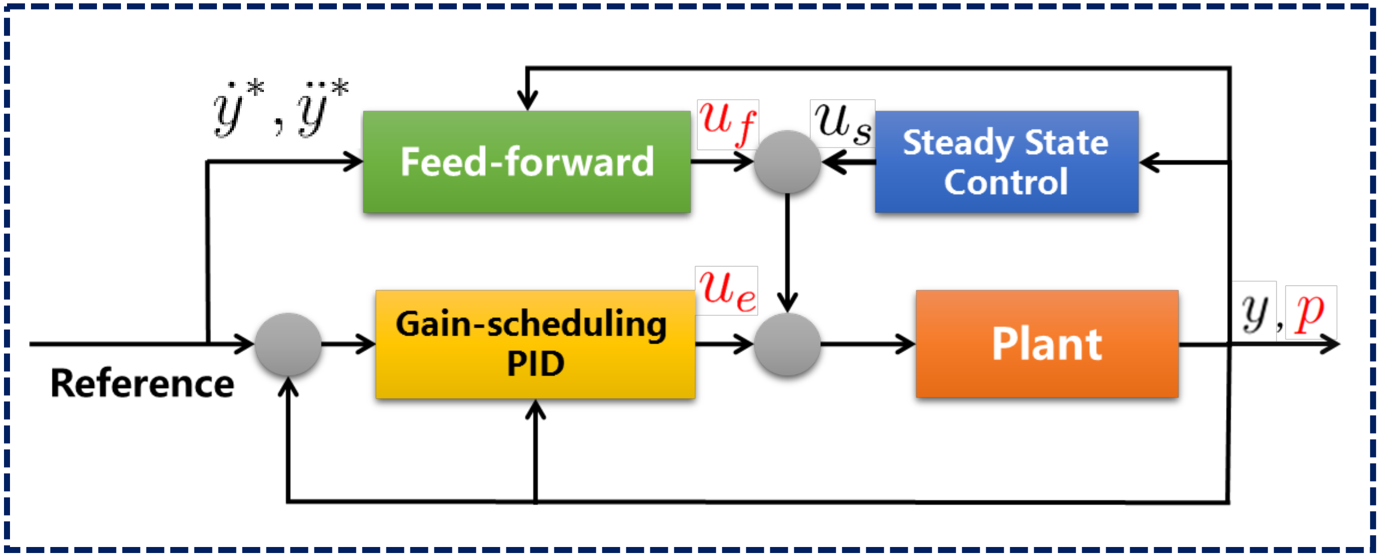
Triple Step Design Technique

for affine systems

Final Control Law (Second order)

$$u = -\frac{A_0(y, p)}{B(y, p)}$$

- **If** $e = 0$
- **If** $y^* = \text{const}$



Triple Step Design Technique

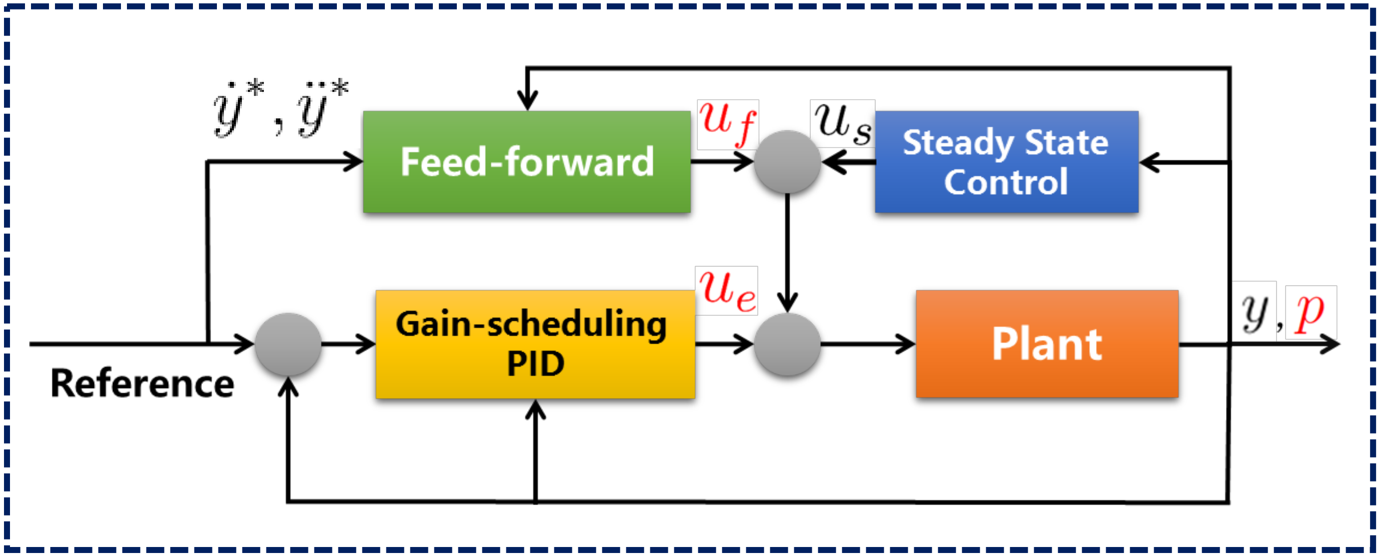
for affine systems

Final Control Law (Second order)

$$u = -\frac{A_0(y,p)}{B(y,p)} + \frac{1}{B(y,p)}\ddot{y}^* - \frac{A_1(y,p)}{B(y,p)}\dot{y}^*$$

- **If** $e = 0$
- **If** $y^* = \text{const}$

$y^* \neq \text{const}$



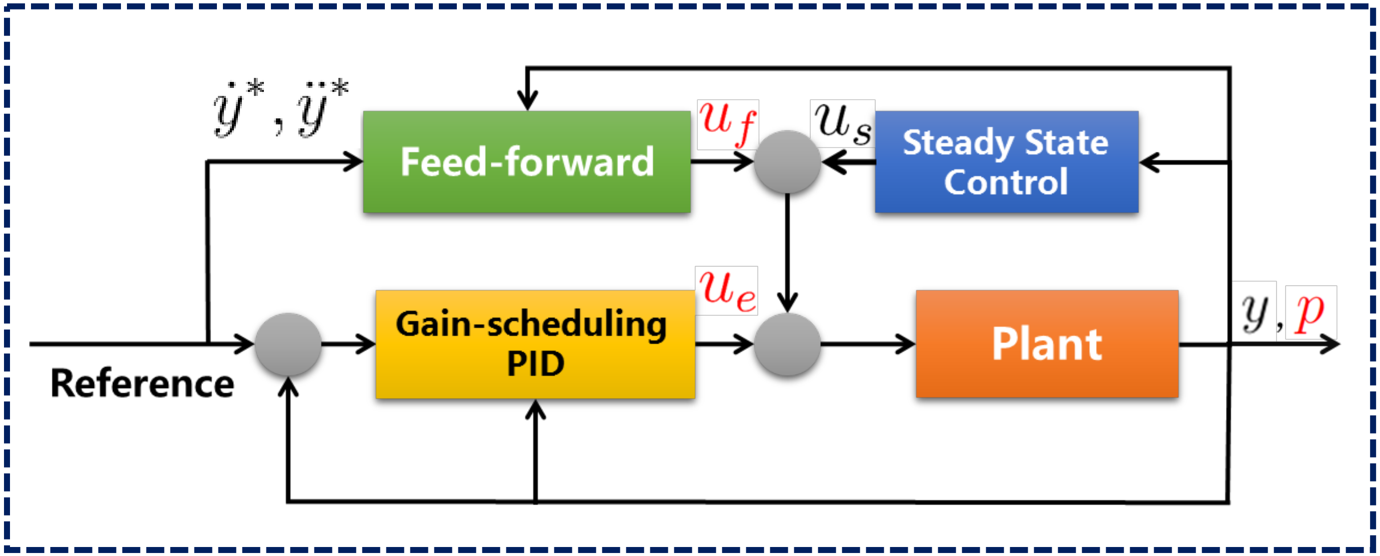
Triple Step Design Technique

for affine systems

Final Control Law (Second order)

$$u = -\frac{A_0(y,p)}{B(y,p)} + \frac{1}{B(y,p)}\ddot{y}^* - \frac{A_1(y,p)}{B(y,p)}\dot{y}^* + \frac{k_0}{B(y,p)}e + \frac{k_1}{B(y,p)}\int e\,dt + \frac{k_2 + A_1(y,p)}{B(y,p)}\dot{e}$$

- **If** $e \neq 0$
- **If** $y^* \neq \text{const}$



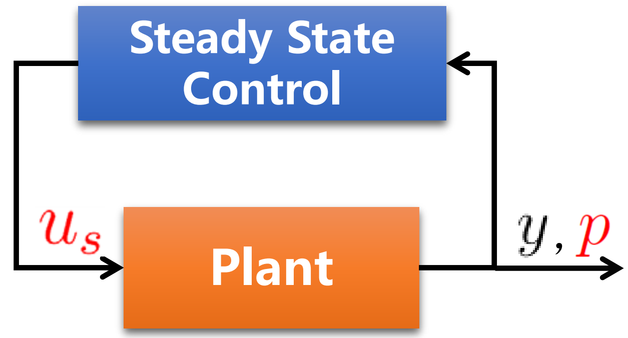
Triple Step Design Technique

for non-affine systems

Take SISO as example

$$\dot{y} = f(y, p, u)$$

First Step: Steady State Control



Let $\dot{y} = 0$ ➡ $0 = f(y, p, u_s)$

- **Analytical solution can be obtained** $u_s = f^{-1}(y, p)$
- **Solved numerically and presented in look-up tables**

$$u_s = f_{map}^{-1}(y, p)$$

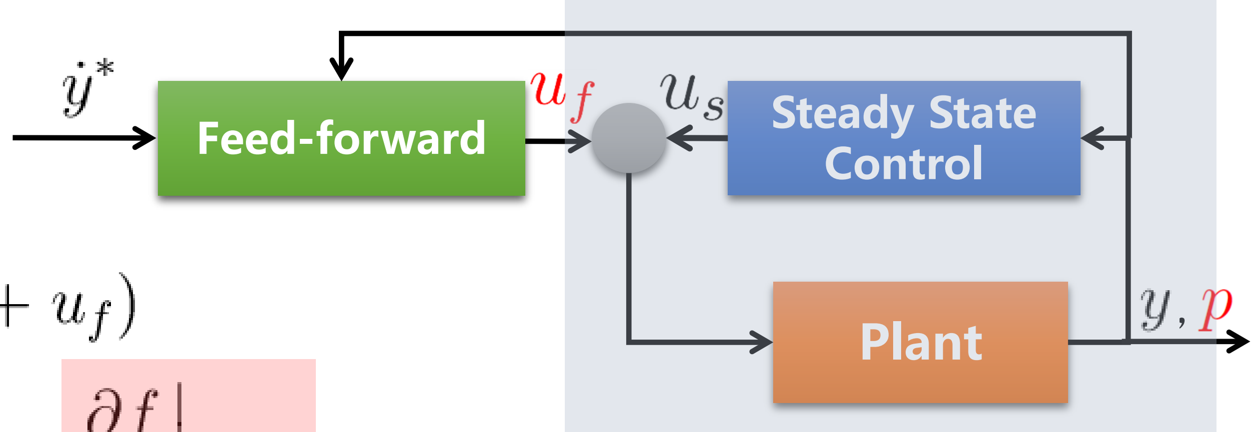
Triple Step Design Technique

for non-affine systems

Second Step: Reference Variation Based Feed-forward Control

$$\dot{y} = f(y, p, u)$$

Let $u = u_s + u_f$



$$\dot{y} = f(y, p, u_s + u_f)$$

$$= \underbrace{f(y, p, u_s)}_{0} + \left.\frac{\partial f}{\partial u}\right|_{u_s} u_f + \mathcal{O}$$

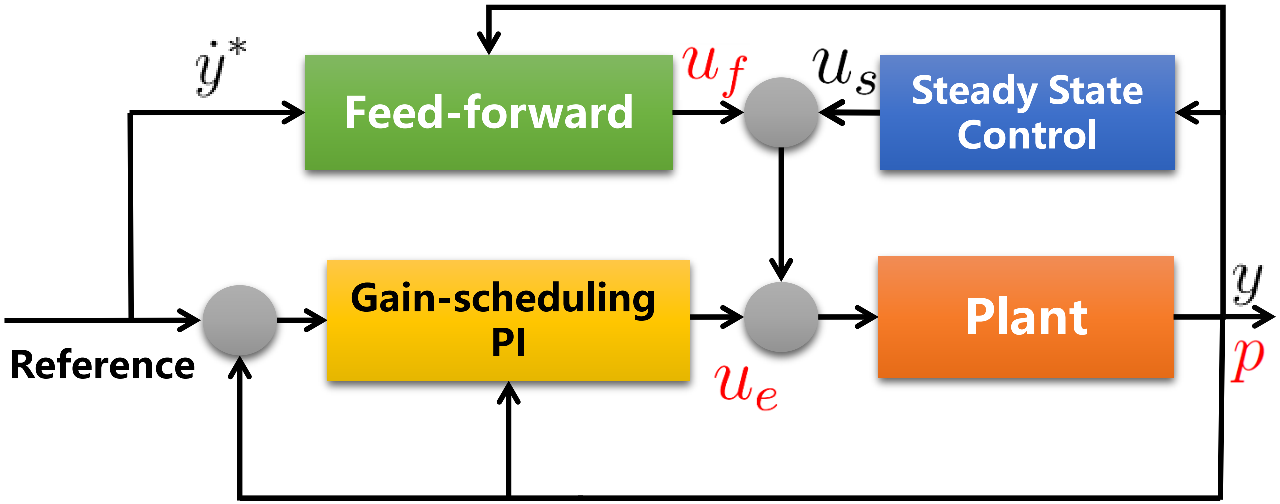
Let $\left.\frac{\partial f}{\partial u}\right|_{u_s} u_f = \dot{y}^*$ ➡ $u_f = \left.\frac{\partial f}{\partial u}\right|_{u_s}^{-1} \dot{y}^*$ **with** $\left(\left.\frac{\partial f}{\partial u}\right|_{u_s} \neq 0\right)$

Triple Step Design Technique

for non-affine systems

Third Step: Error Feedback Control

$$\dot{y} = f(y, p, u)$$



Let $u = u_s + u_f + u_e$

$$\dot{y} = f(y, p, u_s + u_f + u_e) = \underbrace{f(y, p, u_s)}_{0} + \overbrace{\left.\frac{\partial f}{\partial u}\right|_{u_s} u_f}^{\dot{y}^*} + \left.\frac{\partial f}{\partial u}\right|_{u_s} u_e + \mathcal{O}$$

Triple Step Design Technique

for non-affine systems

$$\dot{y} = \dot{y}^* + \left.\frac{\partial f}{\partial u}\right|_{u_s} u_e + \mathcal{O}$$

Define $e = y^* - y$ →

$$\dot{e} = -\left.\frac{\partial f}{\partial u}\right|_{u_s} u_e - \mathcal{O}$$

Design

affine in u_e

$$u_e = \left.\frac{\partial f}{\partial u}\right|_{u_s}^{-1} \cdot \left(k_0 \cdot e + k_1 \cdot \int e\, dt\right)$$

Closed-loop error dynamics

$$\dot{e} = -k_0 \cdot e - k_1 \cdot \int e\, dt - \mathcal{O}$$

→ ISS

Final Control Law

$$u = f^{-1}(y, p) + \left.\frac{\partial f}{\partial u}\right|_{u_s}^{-1} \dot{y}^* + \left.\frac{\partial f}{\partial u}\right|_{u_s}^{-1} \cdot \left(k_0 \cdot e + k_1 \cdot \int e\, dt\right)$$

Triple Step Design Technique

Merits

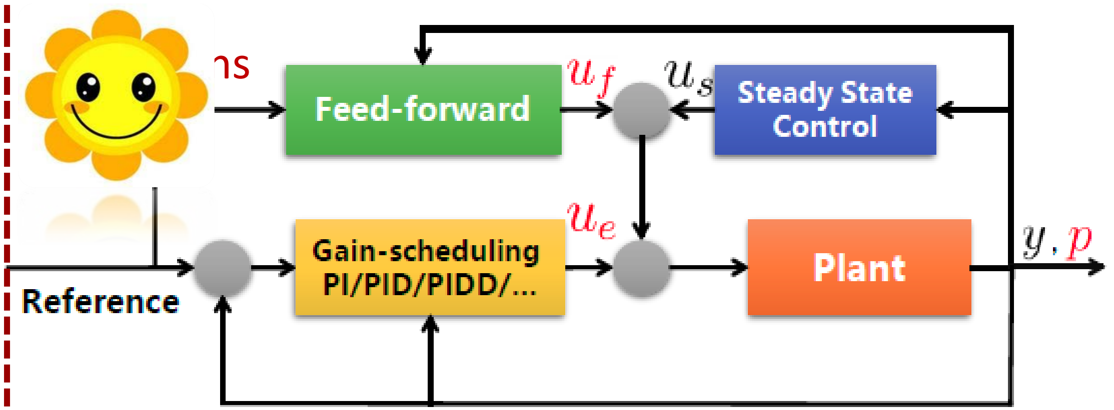
- Engineering-oriented model-based controller design
- All the procedure is algebraic operation
- 3 parts: steady state part, reference variation feedforward, error feedback
- The gains of all parts depend on system states and varying parameters
- Introduce the reference variation in the feed-forward

Nonlinear systems with

※ look-up tables

※ time-varying parameters

※ non-affine



Triple Step Design Technique

Merits

※ Closed loop stability in sense of ISS

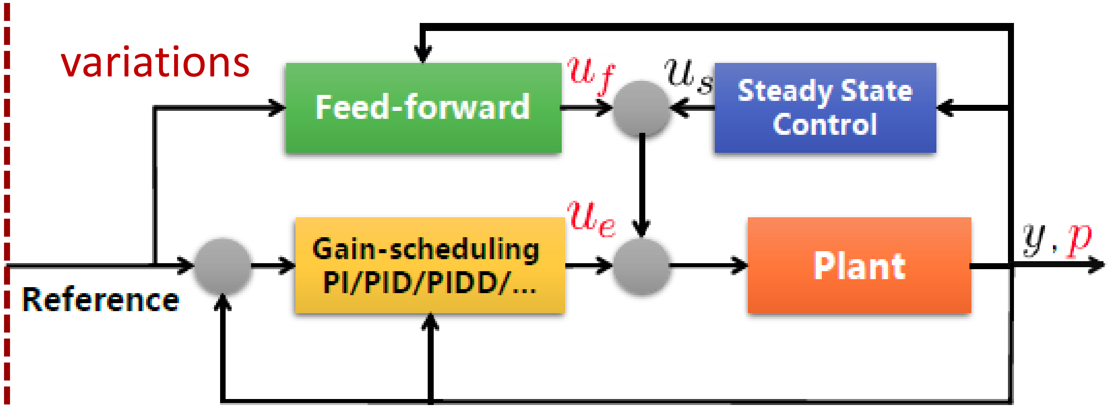
- Tracking error is asymptotically stable if no disturbances
- Bounded tracking error for bounded disturbance/uncertainty

Nonlinear systems with

※ look-up tables

※ time-varying parameters

※ non-affine



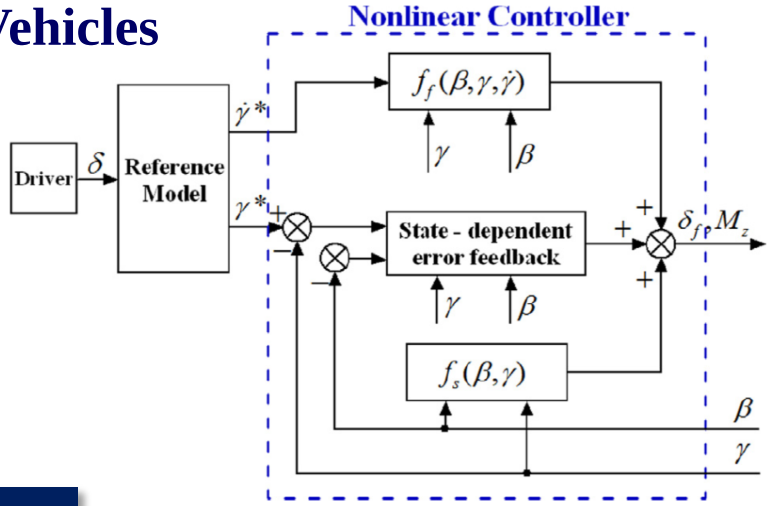
Case study I : Vehicle Dynamics Control in EV

J FRANKLIN I (2014)

Stability Control of In-wheel Motor Electric Vehicles

$$\dot{\beta} = \frac{F_{yf}(\beta,\gamma,\delta_f) + F_{yr}(\beta,\gamma)}{mV} - \gamma$$

$$\dot{\gamma} = \frac{L_f F_{yf}(\beta,\gamma,\delta_f) - L_r F_{yr}(\beta,\gamma) + M_z}{I_z}$$



2-Input-2-Output, 2nd Order, Non-affine

First step: steady state control

$$\frac{F_{yf}(u_{1s},\beta,\gamma) + F_{yr}(\beta,\gamma)}{mV} - \gamma = 0$$

$$\frac{L_f F_{yf}(u_{1s},\beta,\gamma) - L_r F_{yr}(\beta,\gamma) + u_{2s}}{I_z} = 0$$

$$u_{1s} = F^{-1}_{yf\,\mathrm{map}}(mV\gamma - F_{yr}(\beta,\gamma))$$

$$u_{2s} = -L_f F_{yf}(u_{1s},\beta,\gamma) + L_r F_{yr}(\beta,\gamma)$$

- **Implemented by look-up tables**

Case study Ⅰ: Vehicle Dynamics Control in EV

Second Step: reference variaiton feedforward

Reference:

$$\dot{\gamma}^* = -\frac{1}{\tau}\cdot\gamma^* + \frac{k}{\tau}\cdot\delta,$$

$$\beta^* = 0.$$

$$\dot{\beta} = \frac{1}{mV}\cdot\frac{\partial F_{yf}}{\partial u_1}\bigg|_{u_{1s}}\cdot u_{1f},$$

$$\dot{\gamma} = \frac{L_f\cdot\frac{\partial F_{yf}}{\partial u_1}\Big|_{u_{1s}}\cdot u_{1f} + u_{2f}}{I_z}.$$

$$u_{1f} = 0,$$

$$u_{2f} = \dot{\gamma}^*\cdot I_z.$$

Third Step: tracking error feedback

(**Define:** $e_\beta = \beta^* - \beta, \quad e_\gamma = \gamma^* - \gamma,$)

$$\dot{e}_\beta = -\frac{1}{mV}\cdot\frac{\partial F_{yf}}{\partial u_1}\bigg|_{u_{1s}}\cdot u_{1e},$$

$$\dot{e}_\gamma = -\frac{L_f\cdot\frac{\partial F_{yf}}{\partial u_1}\Big|_{u_{1s}}\cdot u_{1e} + u_{2e}}{I_z}.$$

$$u_{1e} = \frac{k_1 mV}{\frac{\partial F_{yf}}{\partial u_1}\Big|_{u_{1s}}}\cdot e_\beta$$

$$u_{2e} = k_2 I_z e_\gamma - k_1 L_f mV e_\beta$$

Case study Ⅰ: Vehicle Dynamics Control in EV

$$u = f_s(\beta,\gamma) + f_f(\beta,\gamma,\dot{\gamma}^*) + f_e(e_\beta, e_\gamma)$$

$$f_s(\beta,\gamma) = \begin{bmatrix} F_{yf\mathrm{map}}^{-1}(mV\gamma - F_{yr}(\beta,\gamma)) \\ -L_f F_{yf}(\beta,\gamma,u_{1s}) + L_r F_{yr}(\beta,\gamma) \end{bmatrix}$$

$$f_f(\beta,\gamma,\dot{\gamma}^*) = \begin{bmatrix} 0 \\ \dot{\gamma}^* \cdot I_z \end{bmatrix}$$

$$f_e(e_\beta,e_\gamma) = \begin{bmatrix} \frac{k_1 mV}{\frac{\partial F_{yf}}{\partial u_1}\big|_{u_{1s}}} \cdot e_\beta \\ I_z k_2 e_\gamma - L_f mV k_1 e_\beta \end{bmatrix}$$

- **Coupled Non-affine System:**
- **De-coupled Closed-loop Error Dynamics**

$$\dot{\beta} = \frac{F_{\mathrm{yf}}(\beta,\gamma,\delta_f) + F_{\mathrm{yr}}(\beta,\gamma)}{mV} - \gamma$$

$$\dot{\gamma} = \frac{L_f F_{\mathrm{yf}}(\beta,\gamma,\delta_f) - L_r F_{\mathrm{yr}}(\beta,\gamma) + M_z}{I_z}$$

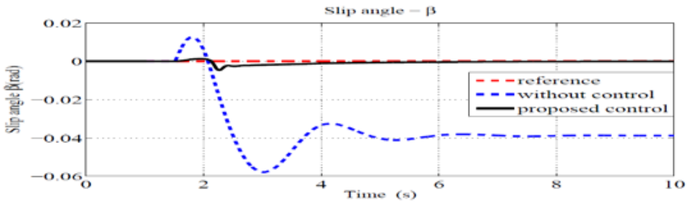
Decoupling →

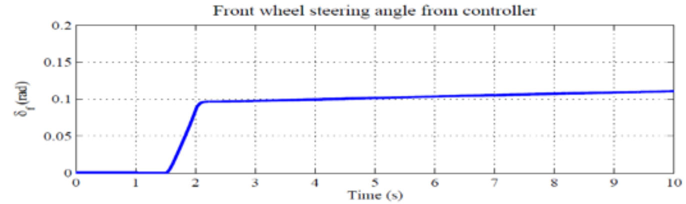
$$\dot{e}_\beta = -k_1 e_\beta \quad (k_1 > 0)$$

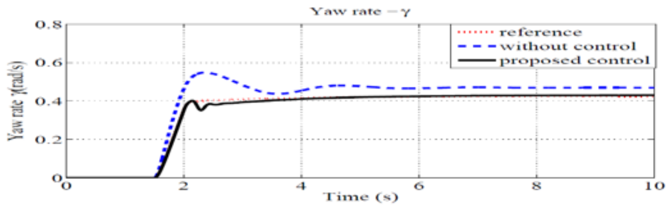
$$\dot{e}_\gamma = -k_2 e_\gamma \quad (k_2 > 0)$$

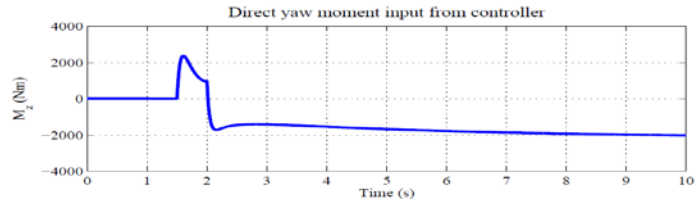
Case study Ⅰ: Vehicle Dynamics Control in EV

Cornering maneuver: (Initial velocity 60km/h)

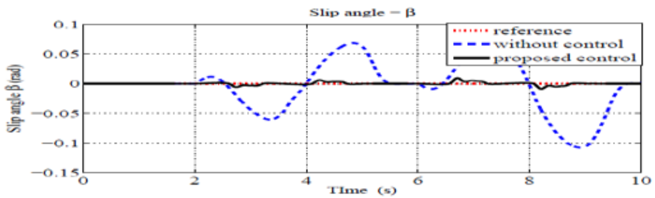


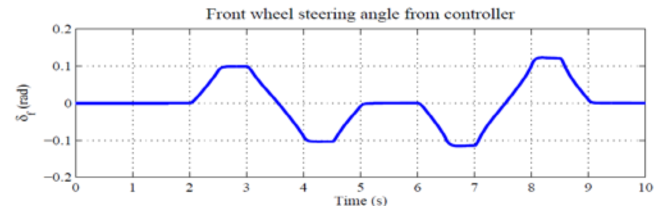


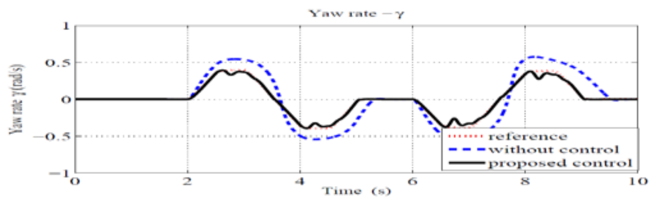


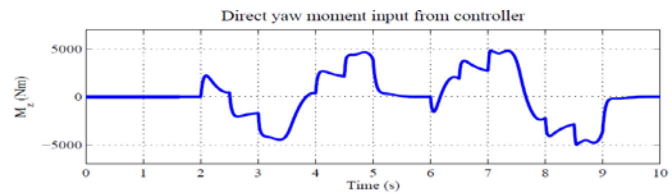


Double lane change:





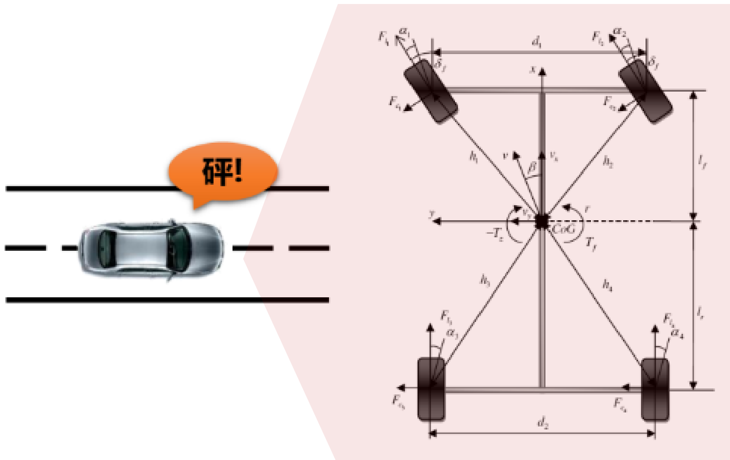




Case study II: Vehicle Control After a Tire Blowout

Vehicle Control After a Tire Blowout:

IEEE CST (2016)



Ensure driving safety:

- **Maintain vehicle directional stability** $y_1 = \psi$
- **Follow the center line of the road** $y_2 = Y$

$$\ddot{y}_1 = f_2(p, u_1) + \frac{1}{I_z} u_2 + w_1$$

$$\ddot{y}_2 = a_x \sin y_1 + f_1(p, u_1) \cdot \cos y_1 + w_2$$

Without control: go to the side of the failed tire

ψ → yaw angle Y → lateral displacement

2 Input 2 Output, 4th Order, Non-affine

$$u_1 = f_{u1s}(y_1, p) + f_{u1f}(y_1, \ddot{y}_2^*, p) + f_{u1e}(y_1, p, e_1, e_2, \dot{e}_2)$$

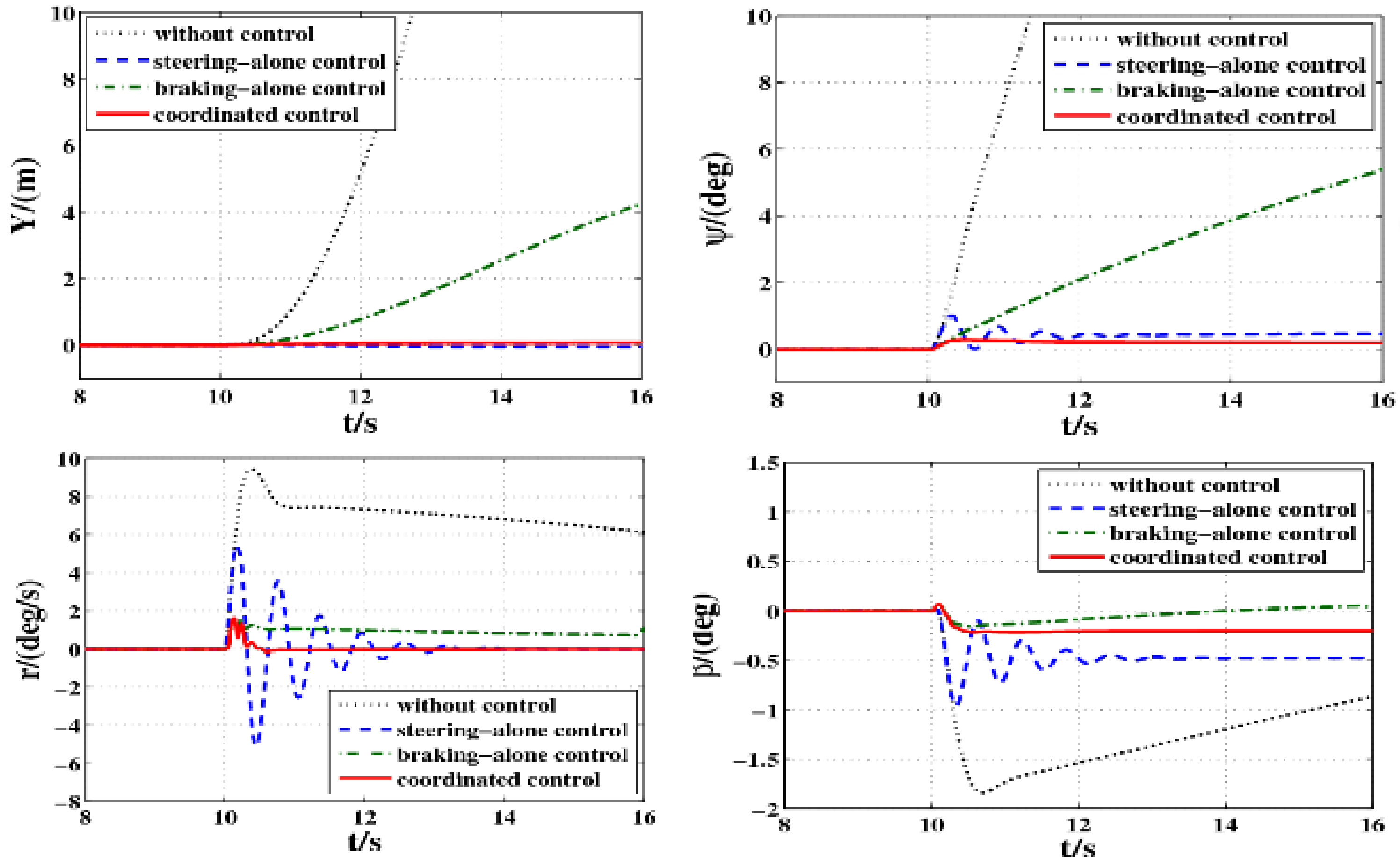
$$u_2 = f_{u2s}(y_1, p) + f_{u2f}(y_1, \ddot{y}_1^*, \ddot{y}_2^*, p) + f_{u2e}(y_1, p, e_1, e_2, \dot{e}_1, \dot{e}_2)$$

Steady State Control   Reference variation based FF   Gain-scheduling PID

Case study II: Vehicle Control After a Tire Blowout

Simulation Results

➢ **Test 1: Left front bursts: straight road**



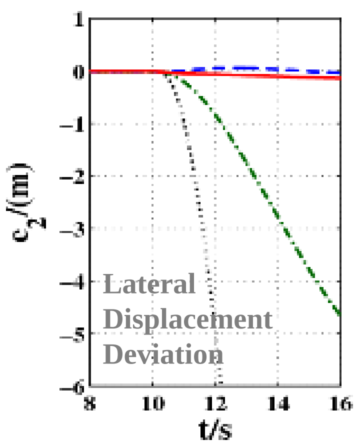
Path Following Performance

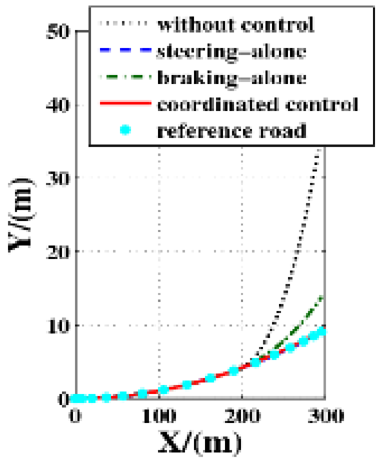
Improve Directional Stability

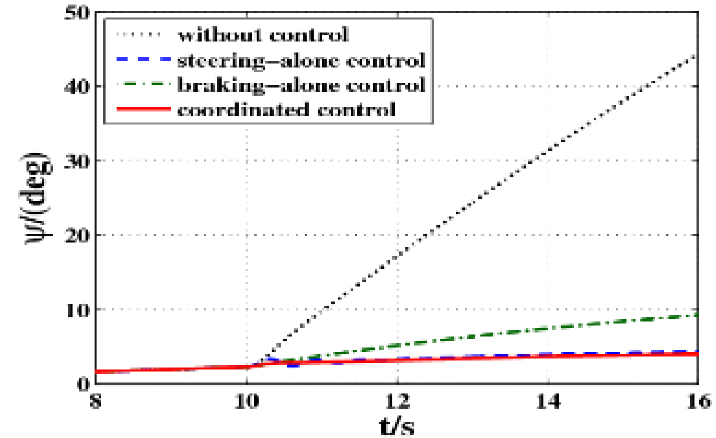
Case study II: Vehicle Control After a Tire Blowout

Simulation Results

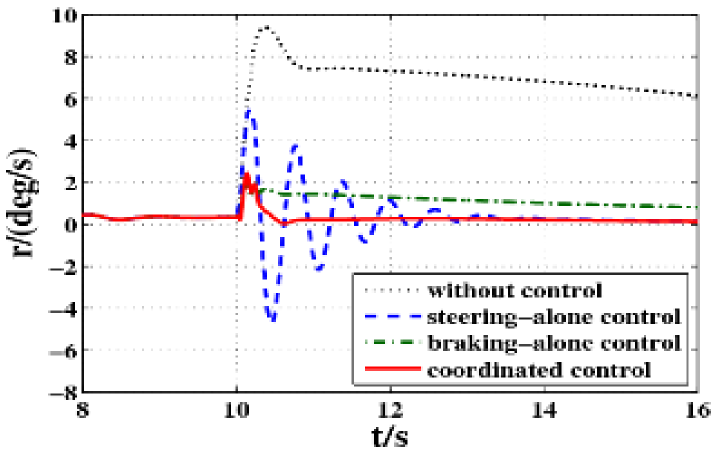
➢ **Test 2: Left front bursts: curved road**

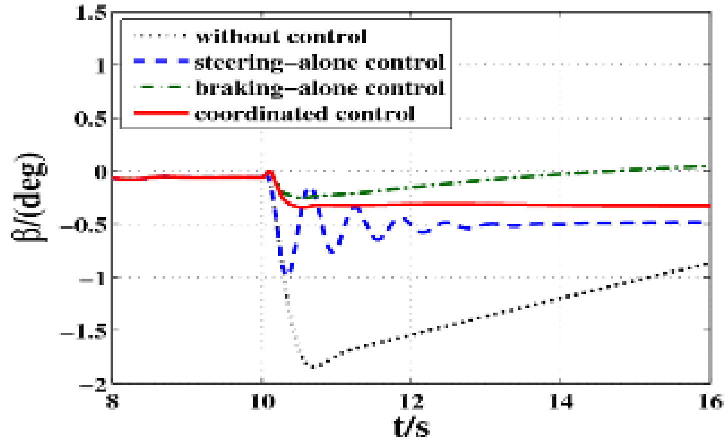






Path Following Performance

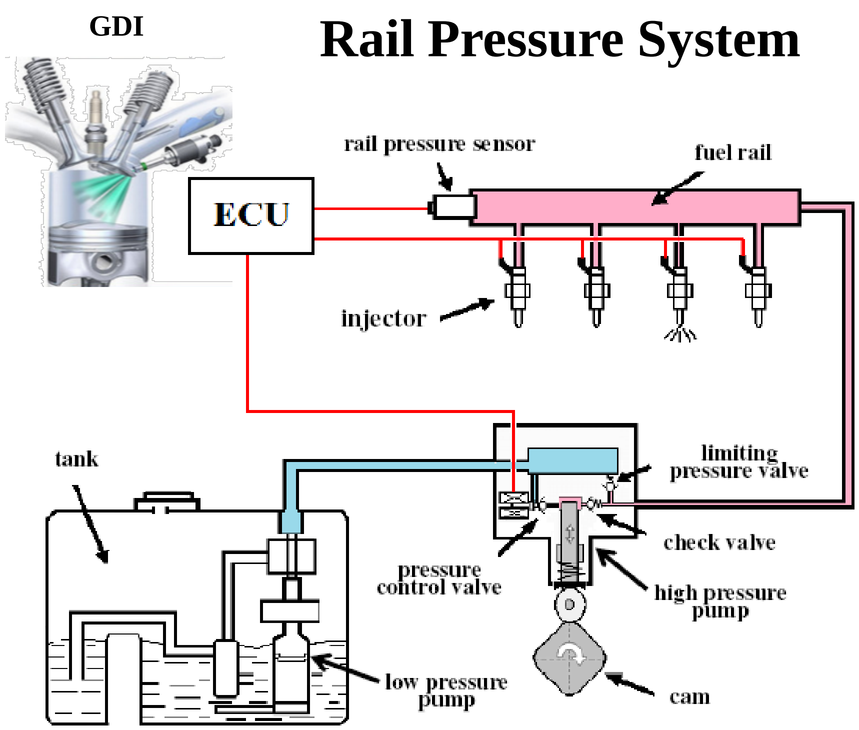




Improve Directional Stability

Case Study III : Rail Pressure Control in GDI Engines

IET CTA (2014)
ACC (2014)



➢ System description

- Control output: Rail Pressure $y = p_r$
- Control input: Inlet flow of the high pressure pump $u = q_u$

➢ Detailed control specifications

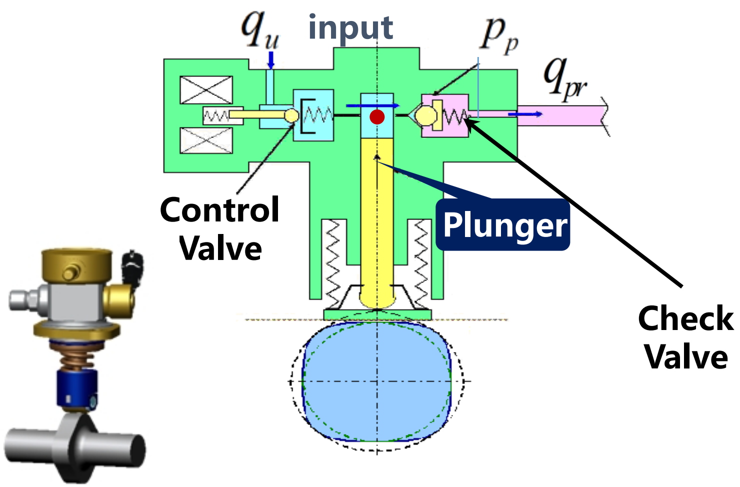
- Settling time: within 100ms
- Steady state error: <1 bar
- Maximum fluctuation: <5 bar

Objective: Inject precise and desired quantity of fuel into cylinder

Description: Rail pressure stable and track a given reference

Case Study III : Rail Pressure Control in GDI Engines

High Pressure Pump



Pressure Dynamics in HPP:

$$\dot{p}_p = -\frac{K_f(p_p)}{V_p(\theta)}\left(\frac{dV_p(\theta)}{dt} - q_u + q_{pr} + q_0\right)$$

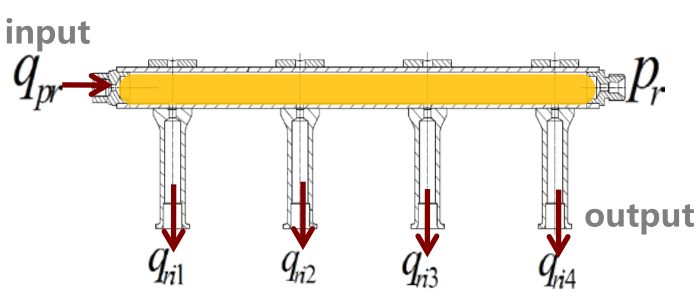
Motion Dynamics of Plunger:

$$\frac{dV_p(\theta)}{dt} = -A_p \omega_{\text{rpm}} \frac{dh_p}{d\theta}$$

Outflow:

$$q_{pr} = \begin{cases} 0\,, & \text{if } p_p \le p_r\,, \\ c_{pr} A_{pr} \sqrt{\frac{2(p_p - p_r)}{\rho}}\,, & \text{if } p_p > p_p\,. \end{cases}$$

Common Rail



Common Rail Pressure:

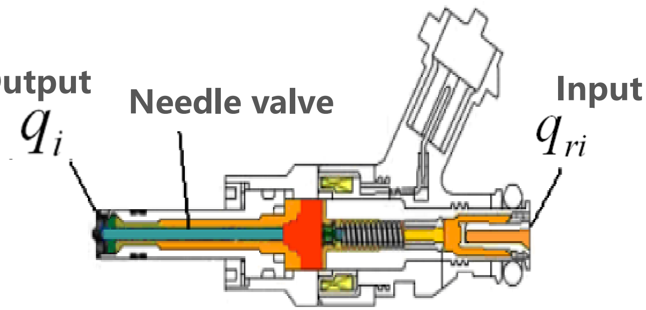
$$\dot{p}_r = \frac{K_f(p_r)}{V_r}(q_{pr} - q_{ri})$$

Outflow:

$$q_{ri} = \sum_{k=1}^{4} q_{ri,k}$$

Case Study III：Rail Pressure Control in GDI Engines

Injector



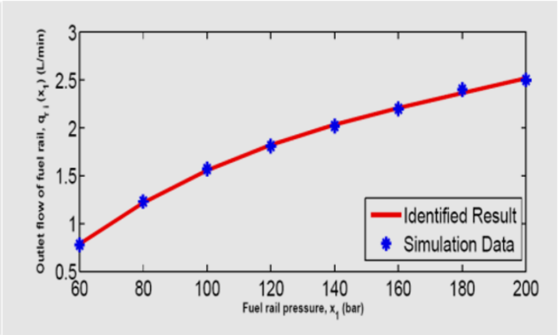
Neglecting the transient dynamics：

- Fast subsystem
- Reduced order system

Injecting Pressure

$$\dot{p}_{i,k} = \frac{K_f(p_{i,k})}{V_{i,k}}(q_{ri,k} - q_{i,k}),\ k = 1,2,3,4$$

$$q_{ri}(p_r)$$



$$\ddot{y} = A_0(y,p) + A_1(y,p)\dot{y} + B(y,p)u$$

- Control Output： $y = p_r$
- Control Input： $u = -q_u$
- Time-varying Parameter: $p = [\omega_{\mathrm{rpm}}, p_p, \theta]$

Case Study III : Rail Pressure Control in GDI Engines

Control law for rail pressure control:

$$u = u_s(y,p) + u_f(y,p,\dot{y}^*,\ddot{y}^*) + f_P(y,p)e + f_I(y,p)\int edt + f_D(y,p)\dot{e}$$

$$u_s(y,p) = A_p\omega_{rpm}\frac{dh_p}{d\theta} + \frac{V_p(\theta)}{V_r}q_{ri}(y) - q_0 - (\frac{V_p(\theta)}{V_r}+1)\eta_1\sqrt{p_p - y},$$

$$u_f(y,p,\dot{y}^*,\ddot{y}^*) = -2\sqrt{p_p - y}\frac{V_p(\theta)V_r}{K_f^2\eta_1}(\ddot{p}_r^* + \frac{K_f}{V_r}q_{ri}(y)\dot{p}_r^*),$$

$$f_P(y,p) = -2\sqrt{p_p - y}\frac{V_p(\theta)V_r}{K_f^2\eta_1}(1+k_1k_2),$$

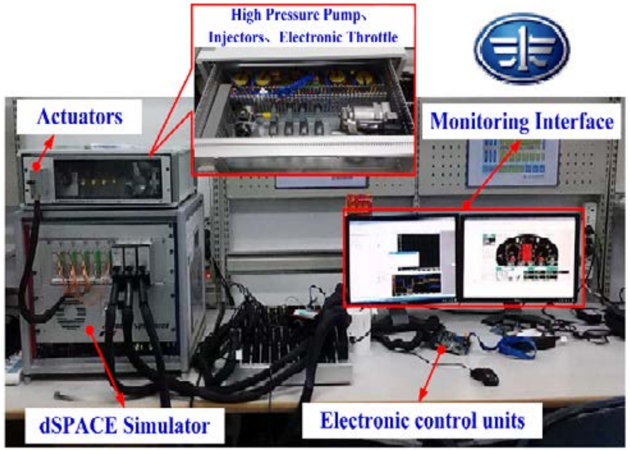
$$f_I(y,p) = -2\sqrt{p_p - y}\frac{V_p(\theta)V_r}{K_f^2\eta_1}k_0k_2,$$

$$f_D(x,p) = -2\sqrt{p_p - p_r}\frac{V_p(\theta)V_r}{K_f^2\eta_1}(k_1 + k_2 - \frac{K_f}{V_r}q_{ri}(p_r)),$$

Implement according to ECU computational resource

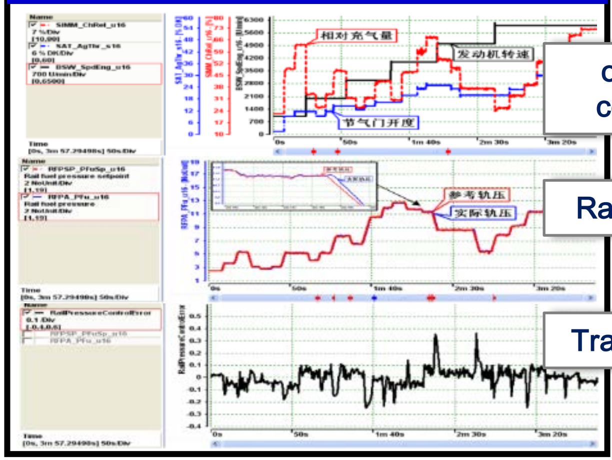
- ◆ **neglect less-dominant terms**
  e.g. 2. order derivative of reference
- ◆ **implement with lookup tables**

Case Study III：Rail Pressure Control in GDI Engines

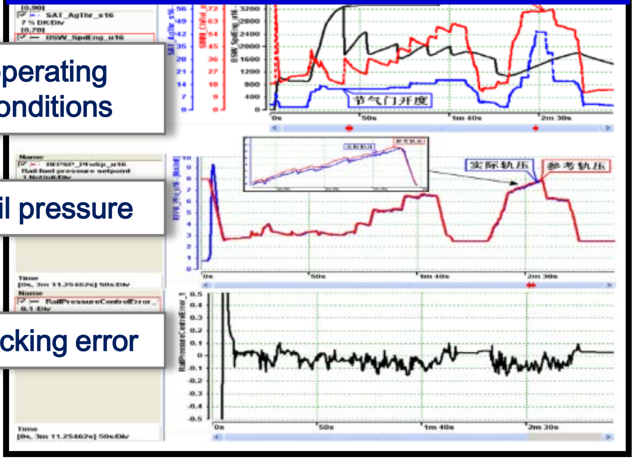


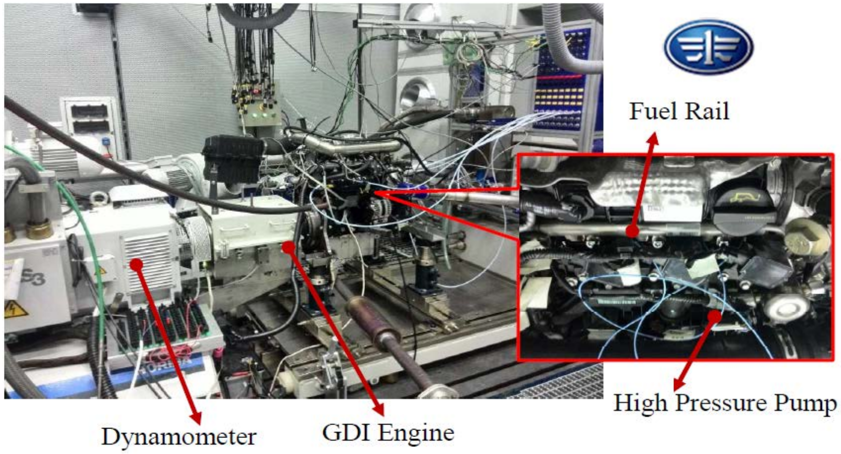
GDI HiL Platform

Engine speed：1000,2000,3000,4000, 5000 , 6000rpm；Load：20-75 (%) ,

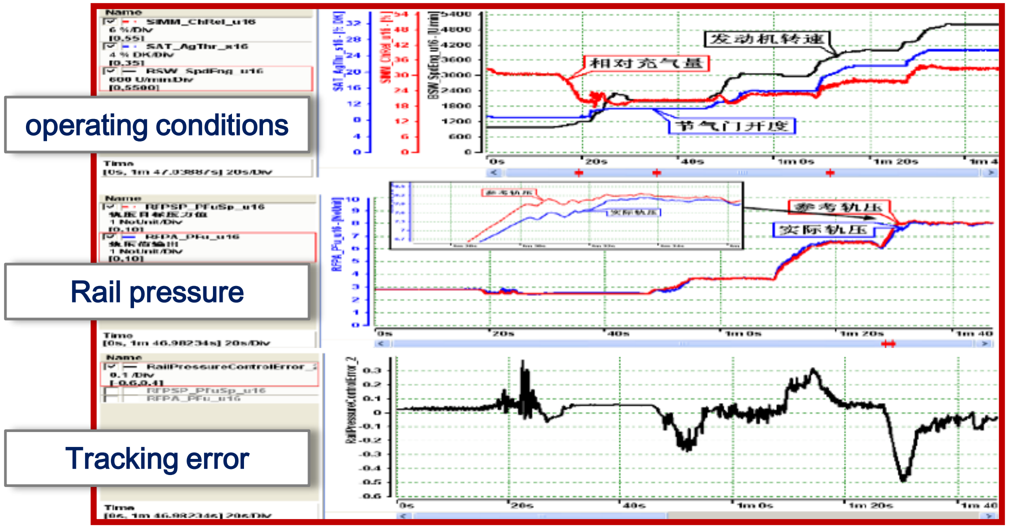


Engine speed：1000-3500 rpm
Load：15-75 (%)





GDI Testbench

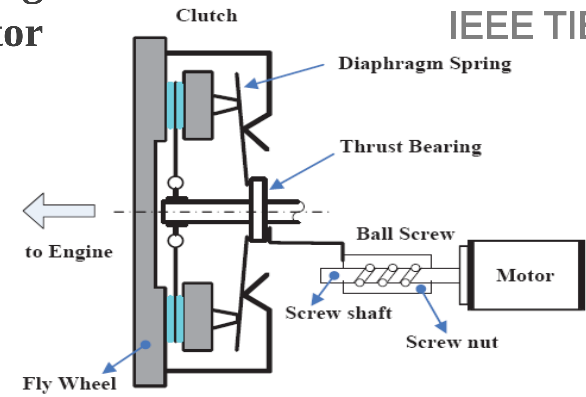


Extended Applications : Transmission Actuator Control and SCR Control

Transmission Actuator Control

- Improve the performance of the position tracking control for a novel electric clutch actuator

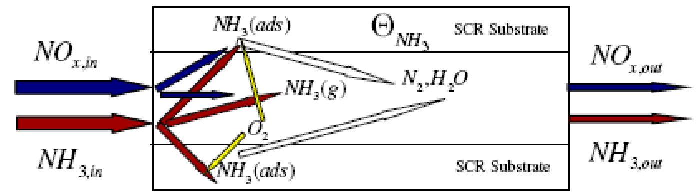
IEEE TIE (2014)



$u \rightarrow$ PWM duty rate $\quad y \rightarrow$ Displacement of Screw nut

urea-SCR Control

- For simultaneously achieving high NOx conversion efficiency and low ammonia slip



Mass flow of Ammonia $\quad u = n^{*}_{\mathrm{NH_3,in}}$

Ammonia coverage ratio $\quad y = \Theta_{\mathrm{NH_3,m}}$

$$p := [C_{\mathrm{NH_3,m}}\ C_{\mathrm{NH_3,s}}\ T_m\ T_s\ C_{\mathrm{NO_x}}\ m^{*}_{\mathrm{EG}}\ \Theta_{\mathrm{NH_3,s}}]^T$$

3rd Order System

$$\dddot{y} = A_0(y,p) + A_1(y,p)\dot{y} + A_2(y,p)\ddot{y} + B(y,p)u$$

Gain Scheduling

$$u = -\frac{A_0(y,p)}{B(y,p)} + \frac{1}{B(y,p)}\dddot{y}^{*} - \frac{A_2(y,p)}{B(y,p)}\ddot{y}^{*} - \frac{A_1(y,p)}{B(y,p)}\dot{y}^{*} + \frac{k_0}{B(y,p)}e + \frac{k_1}{B(y,p)}\int e\,dt + \frac{k_2 + A_1(y,p)}{B(y,p)}\dot{e} + \frac{k_3 + A_2(y,p)}{B(y,p)}\ddot{e}$$

Steady State Control — Reference variation based FF — Gain-scheduling PIDD

Conclusions

Nonlinear systems

- ✓ with lookup tables
- ✓ with time-varying parameters
- ✓ may be non-affine

Triple step design technique

- Engineering-oriented model-based controller design
- 3 parts: steady state, reference variation feedforward, error feedback
- The gains of all parts depend on system states and varying parameters
- Introduce the reference variation in the feed-forward
- Tracking error stability in the sense of ISS

Case study

- ✓ rail pressure control, shift control (2^{nd} order, affine)
- ✓ vehicle stability control (MIMO, non-affine)
- ✓ actuator control and SCR control (3^{rd} order, affine)

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10. …

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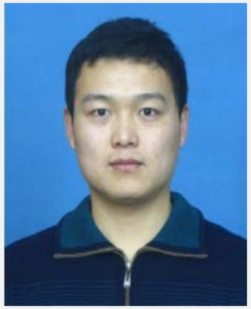
Hongqing Chu

Thank you!