

# 汽车传动系统控制



高炳钊

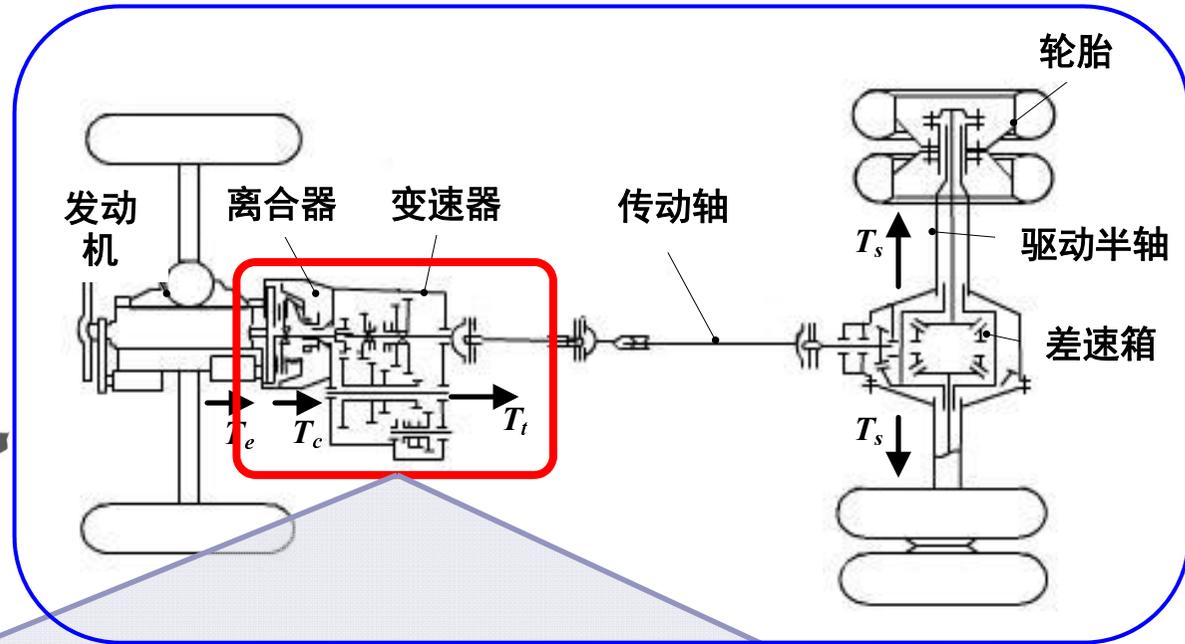
吉林大学汽车仿真与控制

国家重点实验室



- 一、研究背景
- 二、DCT换挡控制（控制需求、建模、控制方法）
- 三、AMT离合器执行机构控制
- 四、直喷发动机轨压控制
- 五、电动汽车稳定性控制

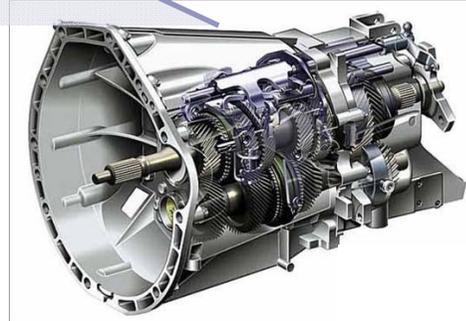
# 研究背景-传动系统基本组成



双离合 DCT  
(Dual Clutch Transmission)

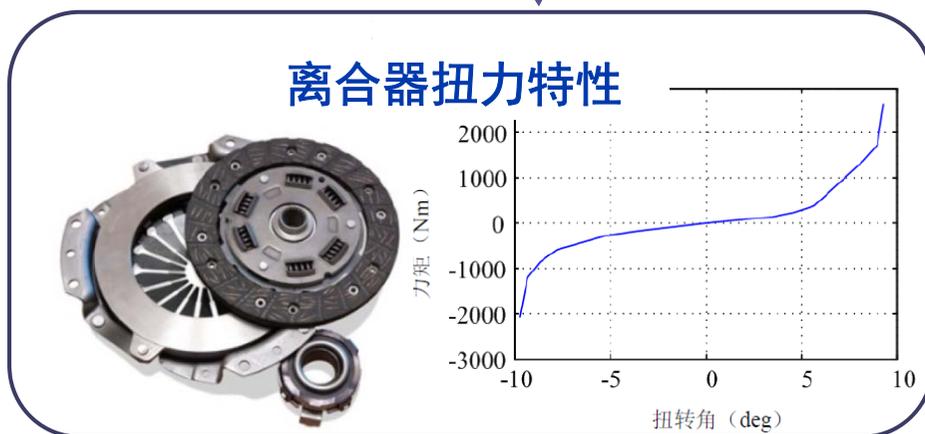
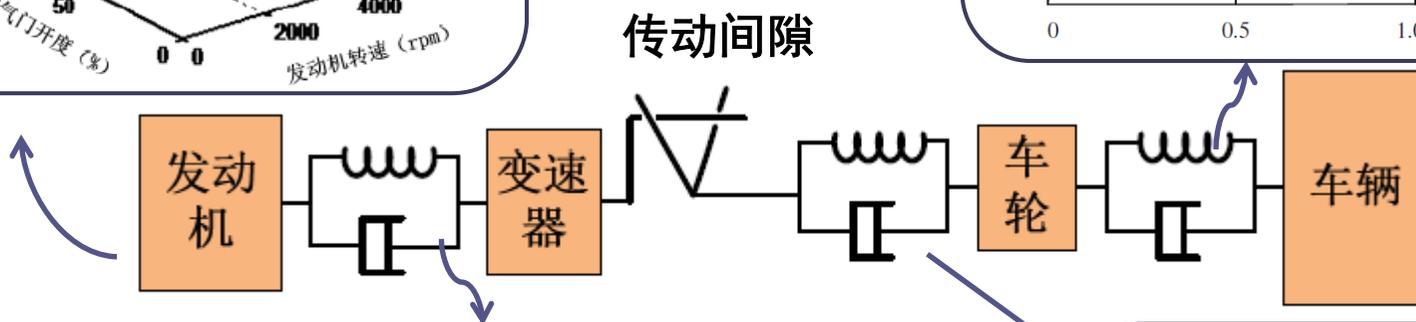
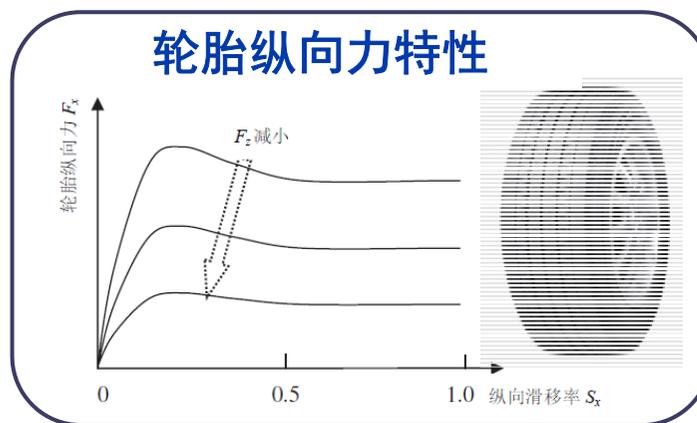
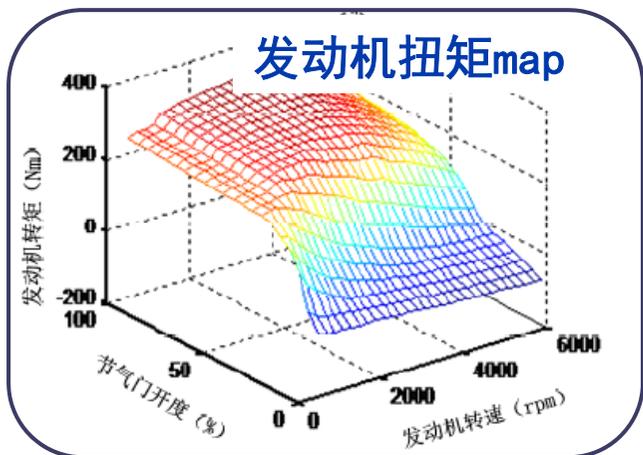


液力式 AT  
(Automatic Transmission)



电控机械 AMT  
(Automated Manual Transmission)

# 研究背景-传动系统动力学特征



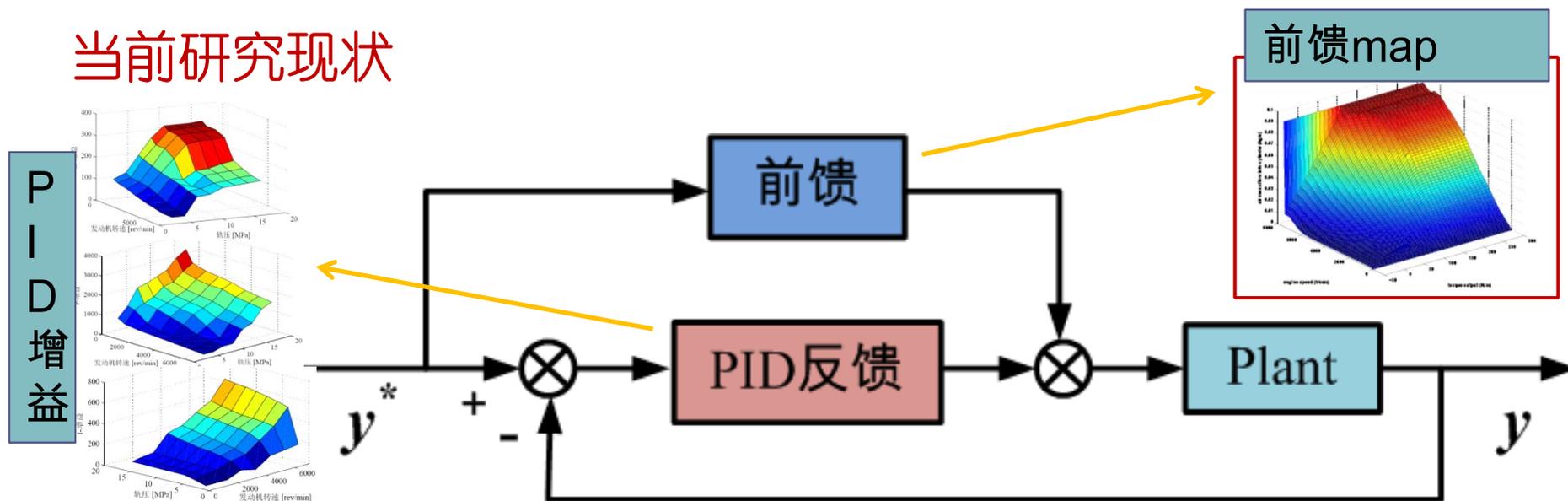
## 起步换挡等瞬态工况的平顺性控制问题 (Drivability control)

- 为了节能与动力性
  - 采用低摩擦元件、
  - 扭矩逐年增加、
  - 传动轴刚度逐渐降低



- 舒适性变差
  - 欠阻尼系统、
  - 易产生振动冲击、
  - 易产生齿隙撞击

### 当前研究现状



# DCT换挡控制

## ● 双离合式变速器DCT



- 燃油经济性
- 动力性
- 驾驶舒适性



IEEE/ASME T. Mechatronics 2011  
 Vehicle System Dynamics 2011, 2011  
 ASME J.DSMC 2012  
 Int. J. Vehicle Design 2011

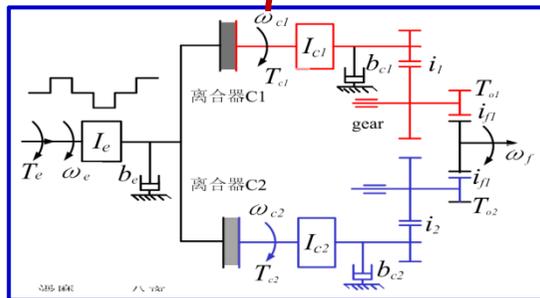
- 无动力中断
- 高换挡效率
- 结构紧凑

- 缺少液力变矩器
- 驾驶舒适性能的需求

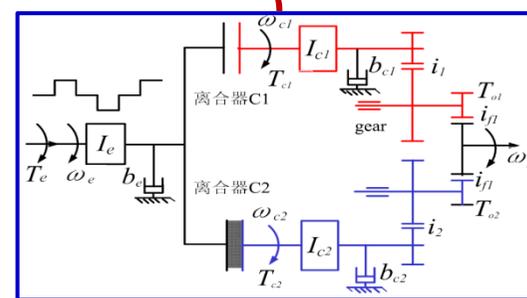


DCT换挡控制成为一个具有挑战的控制问题

力矩项



惯性项

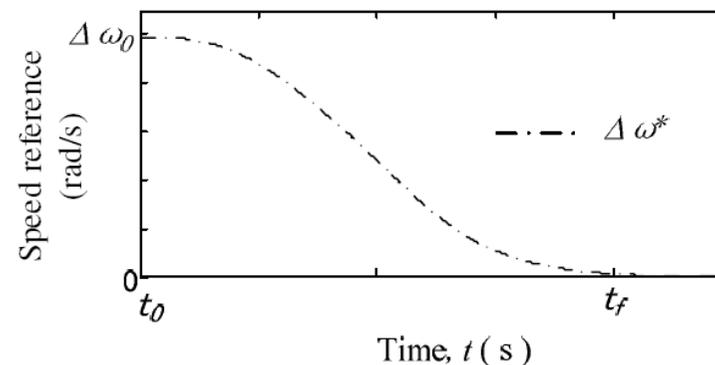


## ➤ 控制需求 离合器转速差跟踪期望值

$$y \rightarrow y^*$$



## 转速差跟踪控制方案

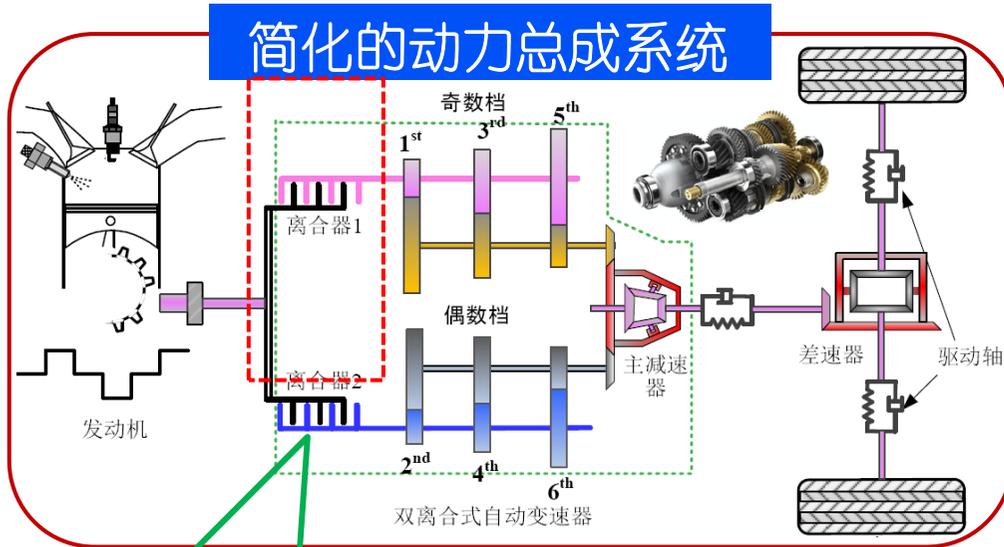


## ➤ 控制目标

- 转速跟踪误差  $e_{\Delta\omega} < 35\text{rpm}$ ;
- 结合时间  $t_f < 0.4\text{s}$ ;
- 换挡冲击度：低挡时  $J < 10\text{m/s}^2$ ，高挡时  $J < 5\text{m/s}^2$ ;
- 滑摩功：防止摩擦片表面温度过高， $W < 0.4\text{J/mm}^2$ 。

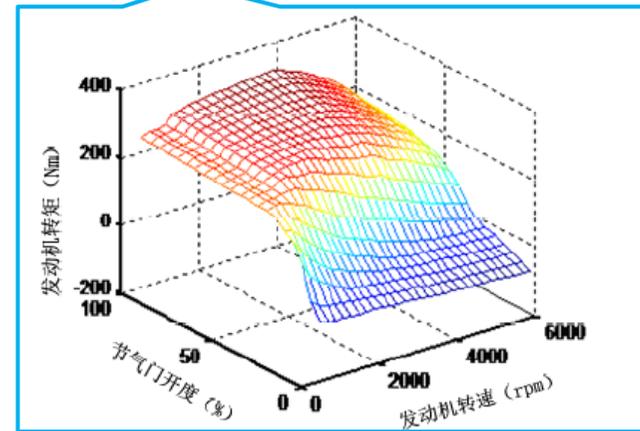
# DCT换挡控制-系统建模

## 简化的动力总成系统



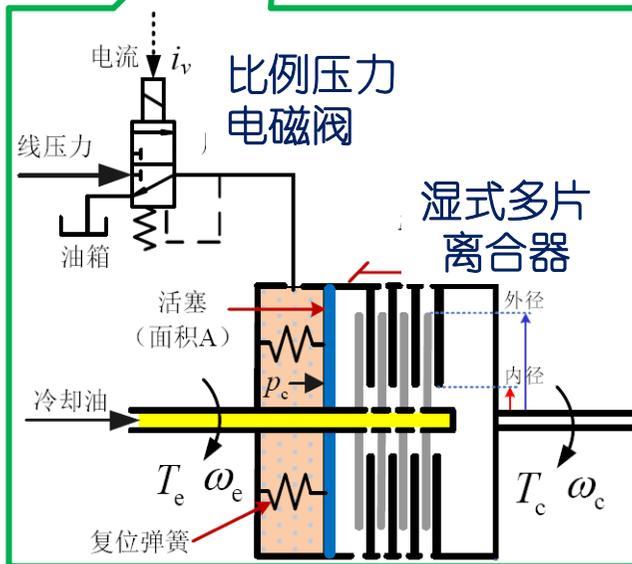
## 发动机模型

$$I_e \dot{\omega}_e = T_e(\omega_e, \theta_{th}) - b_e \omega_e - T_c$$



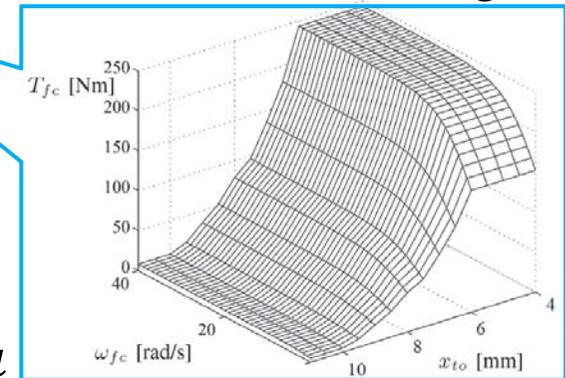
## 离合器模型

$$I_c \dot{\omega}_{c2} = \mu(\Delta\omega) R N A p_{c2} - b_c \omega_{c2} - T_l(\omega_{c2}, \theta_g)$$



## 电磁阀模型

$$\dot{p}_{c2} = -\frac{1}{\tau_v} p_{c2} + \frac{K_v(p_{c2})}{\tau_v} u$$



## 扭矩平衡方程

$$\Delta\dot{\omega} = \frac{1}{I_e} T_e(\omega_e, \theta_{th}) - \left(\frac{1}{I_e} + \frac{1}{I_c}\right) \mu(\Delta\omega) R N A p_{c2} + \frac{1}{I_c} T_l(\omega_{c2}, \theta_g) - \frac{1}{I_e} b_e \omega_e + \frac{1}{I_v} b_c \omega_{c2}$$

## 电磁阀动态特性

$$\dot{p}_{c2} = -\frac{1}{\tau_v} p_{c2} + \frac{K_v(p_{c2})}{\tau_v} u$$

数据map、机理方程  
混合建模方法

定义变量: 变量  $x = [\Delta\omega, p_{c2}]$  参变量  $p = [\omega_e]$

被控量  $y = \Delta\omega$  控制量  $u = i_v$

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

包含数据map表的二阶参变非线性系统

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

非线性三步设计方法

稳态控制

假设系统在稳态控制的作用下达到稳态  $\dot{y} = 0, \ddot{y} = 0$

$$u_s = -\frac{A_0(x, p)}{B(x, p)}$$

参考前馈

令系统  $\dot{y} = \dot{y}^*, \ddot{y} = \ddot{y}^*$ , 代入  $u = u_s + u_f$

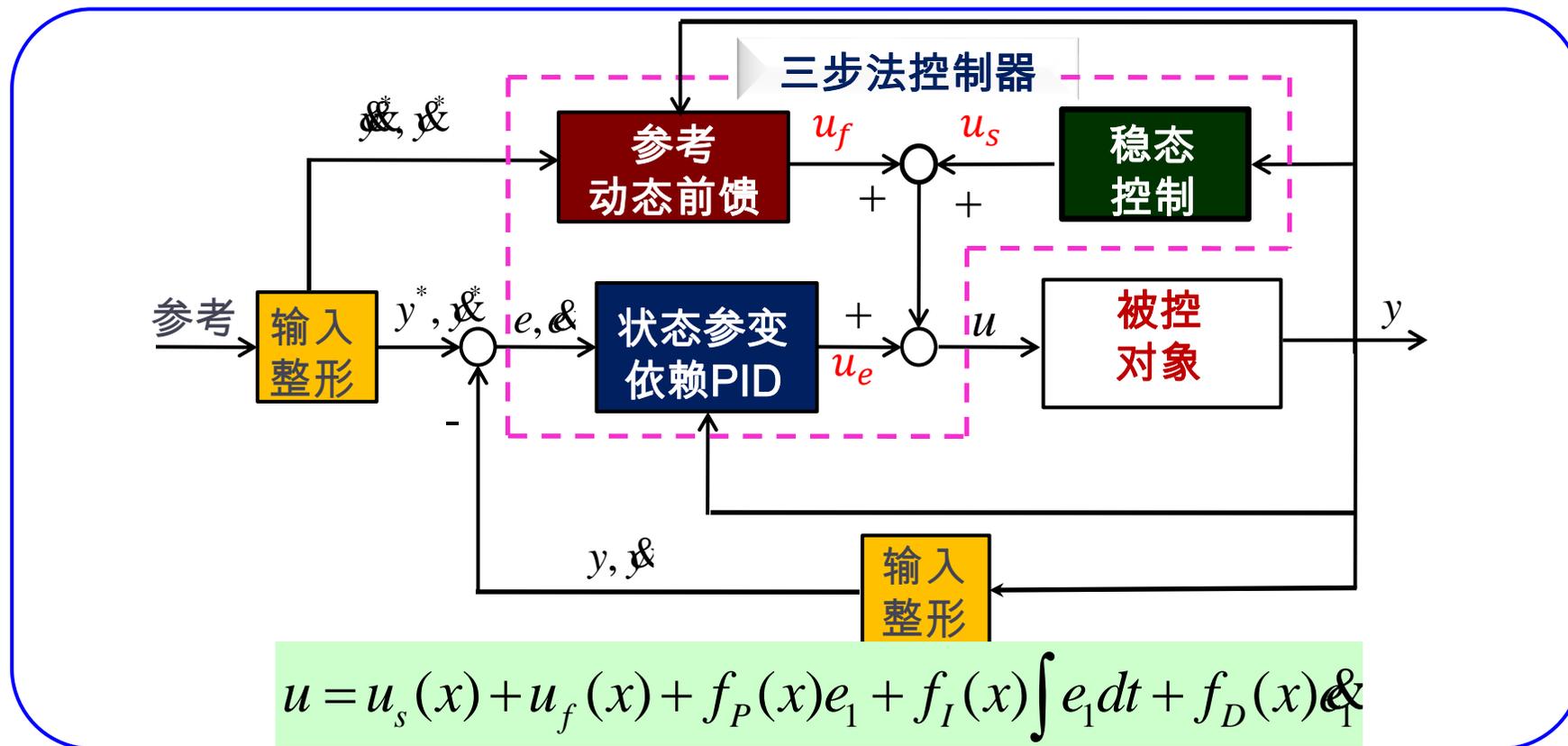
$$u_f = \frac{\ddot{y}^*}{B(x, p)} - \frac{A_1(x, p)\dot{y}^*}{B(x, p)} =: u_f(x, p, \dot{y}^*, \ddot{y}^*)$$

误差反馈

定义跟踪误差  $e = y^* - y$ , 代入  $u = u_s + u_f + u_e$

$$u_e = \frac{1 + k_0 + k_1 k_2}{B(x, p)} e + \frac{k_0 k_2}{B(x, p)} \int e dt + \frac{k_1 + k_2 + A_1(x, p)}{B(x, p)} \dot{e}$$

# DCT换挡控制-非线性三步设计方法



- 变增益PID，避免了盲目的控制参数标定过程；
- 考虑系统动态特性，保证了瞬态工况的平顺性能；
- 可以有效处理汽车传动系统中的数据map表。

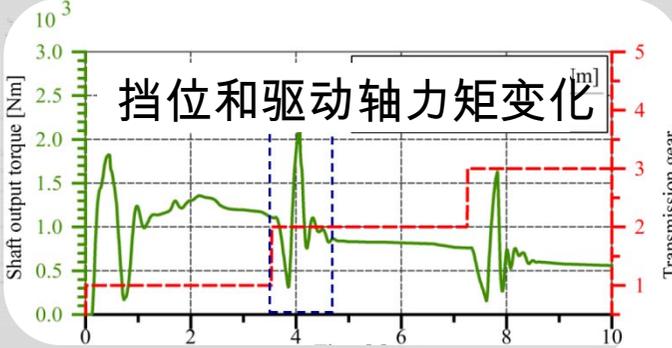
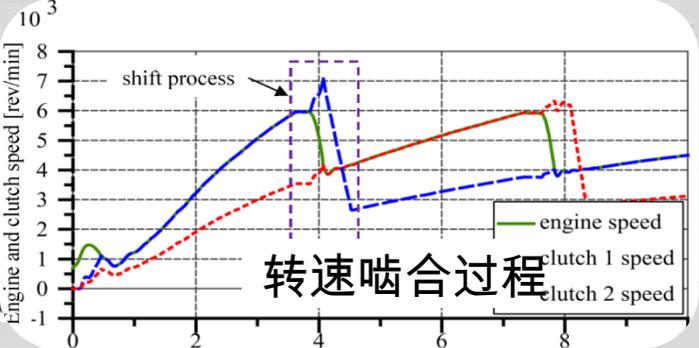
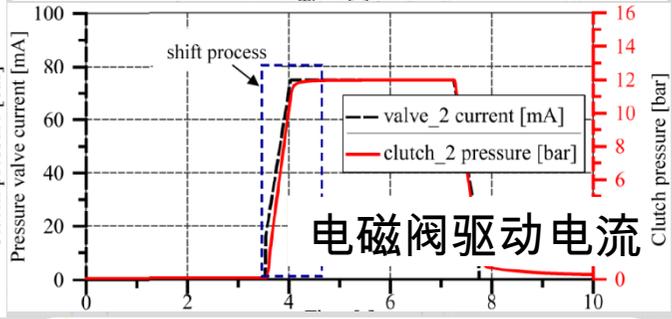
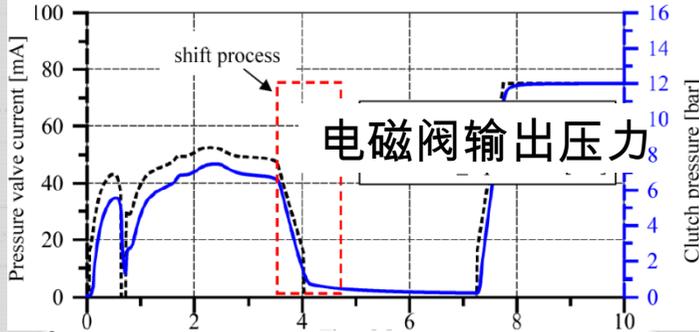
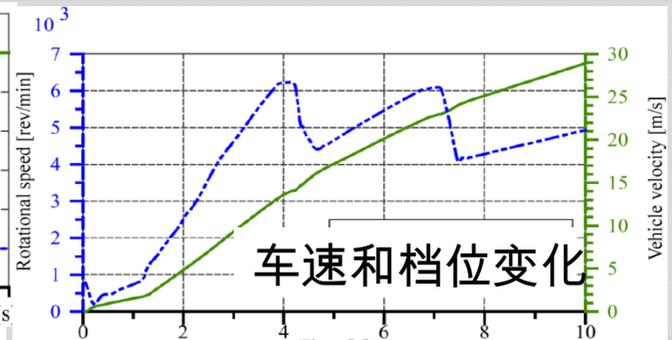
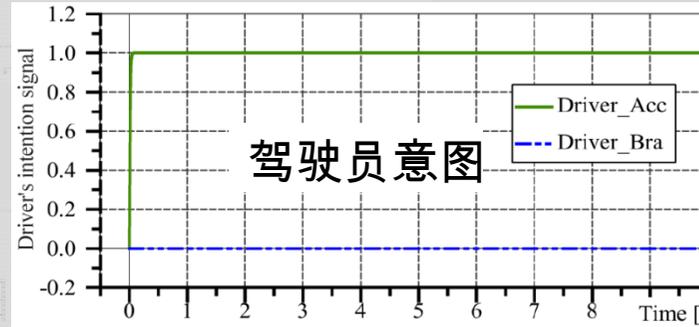
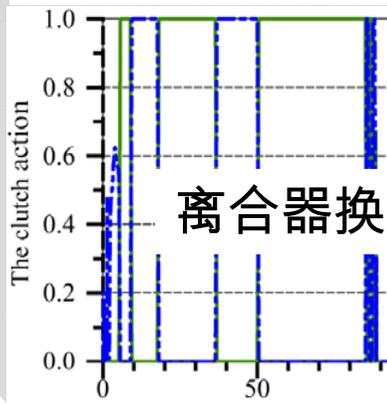
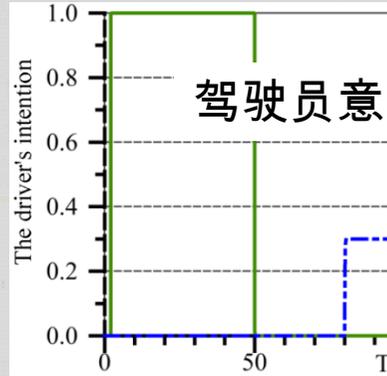
# DCT换挡控制-仿真结果

## ➤ 离线仿真

## 车辆百公里加速工况验证

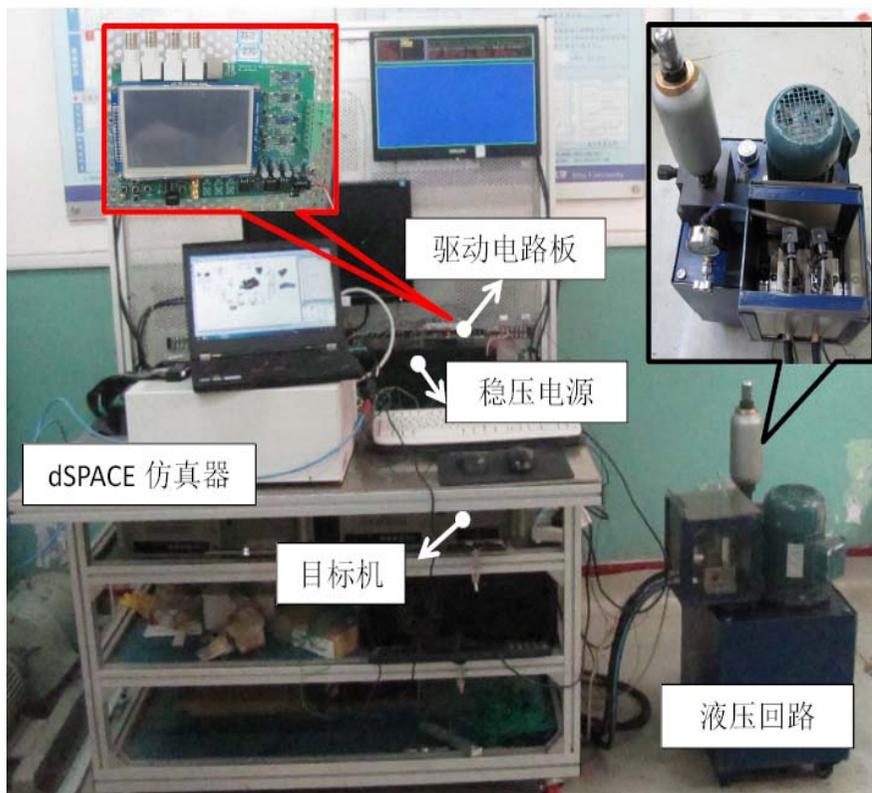
Powertrain model equipped with

车辆



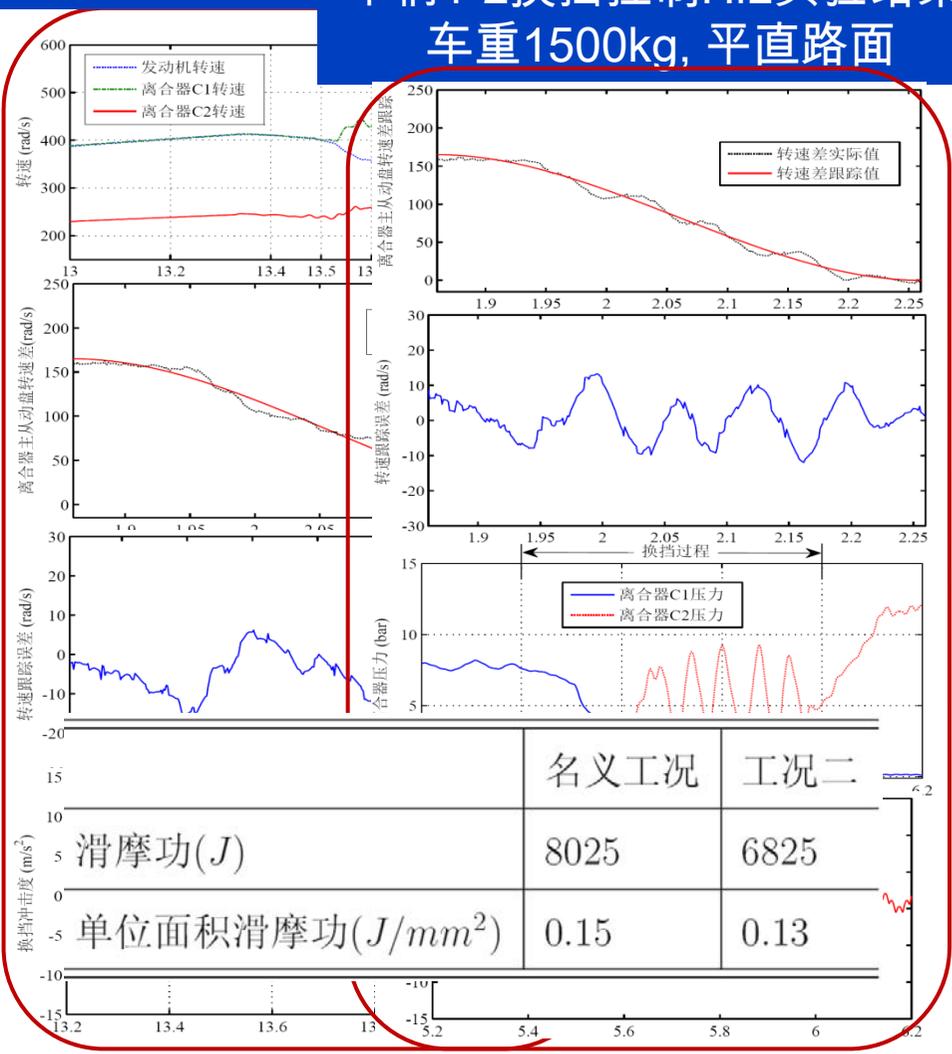
# DCT换挡控制-试验结果

## ➤ 硬件在环仿真

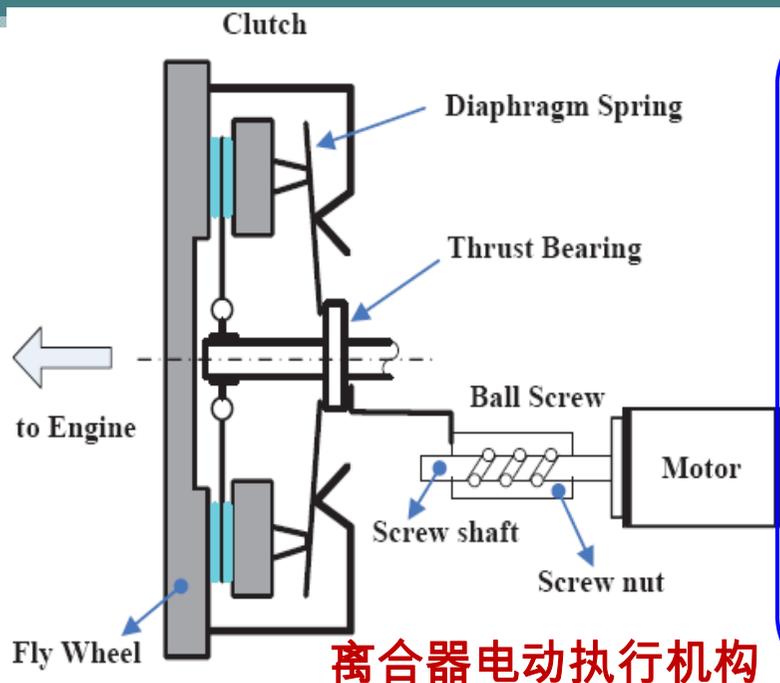


DCT控制系统HiL实验平台

## 车辆1-2换挡控制HiL实验结果 车重1200kg 车辆1-2换挡控制HiL实验结果 车重1500kg, 平直路面



# AMT离合器执行机构控制



## 模型建立

$$\ddot{x}_c = \frac{1}{\bar{m}} \frac{2\pi}{h} K_t i_a - \frac{1}{\bar{m}} F_s(x_c) - \frac{1}{\bar{m}} \bar{F}_f(x_c, \dot{x}_c)$$

$$\dot{i}_a = -\frac{1}{L_a} \frac{2\pi}{h} K_v \dot{x}_c - \frac{1}{L_a} v_a(i_a) + \frac{1}{L_a} v_{bat} u$$

三阶SISO非线性系统

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

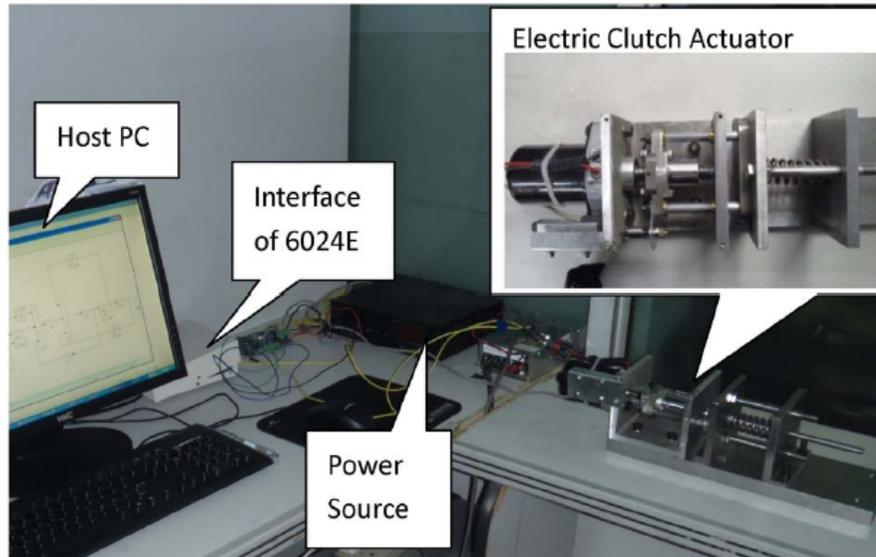
## 控制律

## 三步法

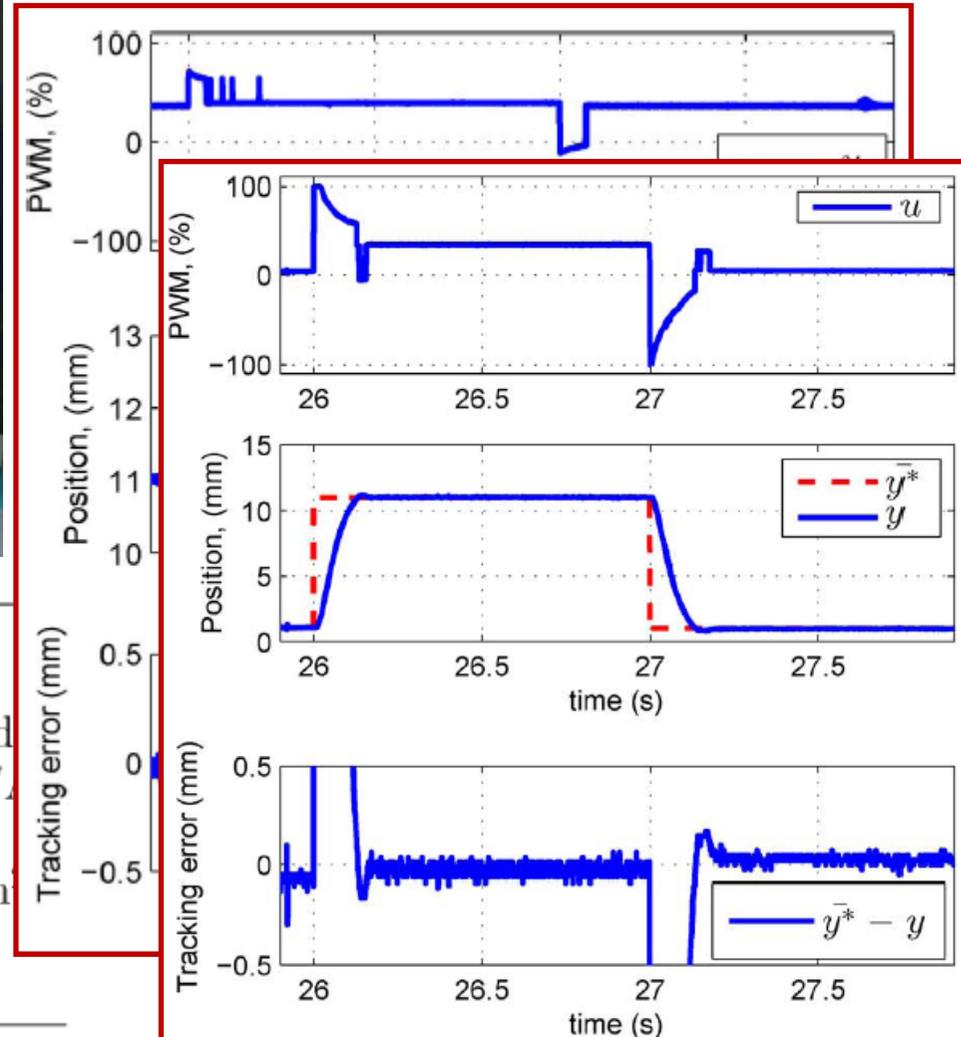
$$u = \underbrace{\left[ \frac{a_3 x_2}{b_3} + \frac{v_a(x_3)}{L_a b_3} \right]}_{\text{稳态控制}} + \underbrace{\left[ \frac{1}{B} \ddot{y}^* - \frac{A_1(x)}{B} \dot{y}^* - \frac{A_2(x)}{B} \ddot{y} \right]}_{\text{参考动态前馈}} + \underbrace{\left[ \frac{-k_0 k_3}{B} \chi + \frac{-(k_0 + k_1 k_3)}{B} e_1 + \frac{-(k_1 - A_1 + k_2 k_3)}{B} \dot{e}_1 + \frac{-(k_2 - A_2 - k_3)}{B} \ddot{e}_1 \right]}_{\text{PIDD}}$$

# AMT离合器执行机构控制

## 实验验证

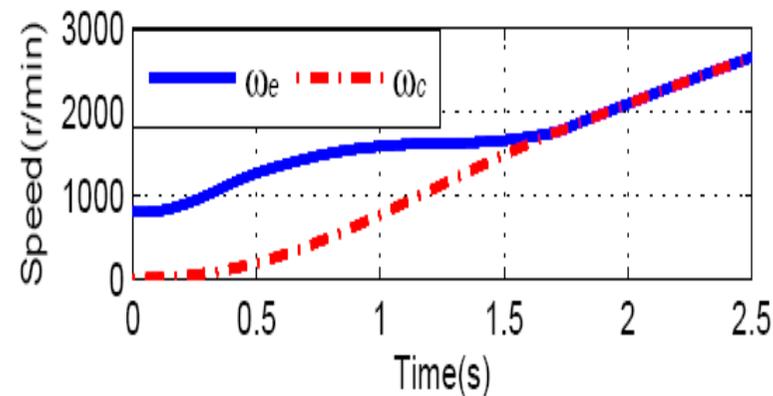
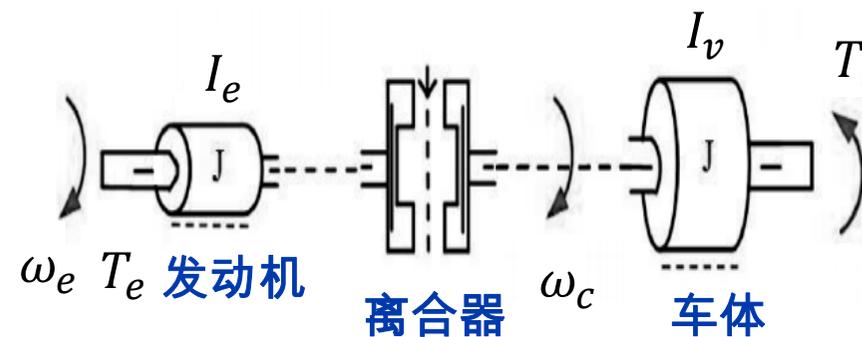
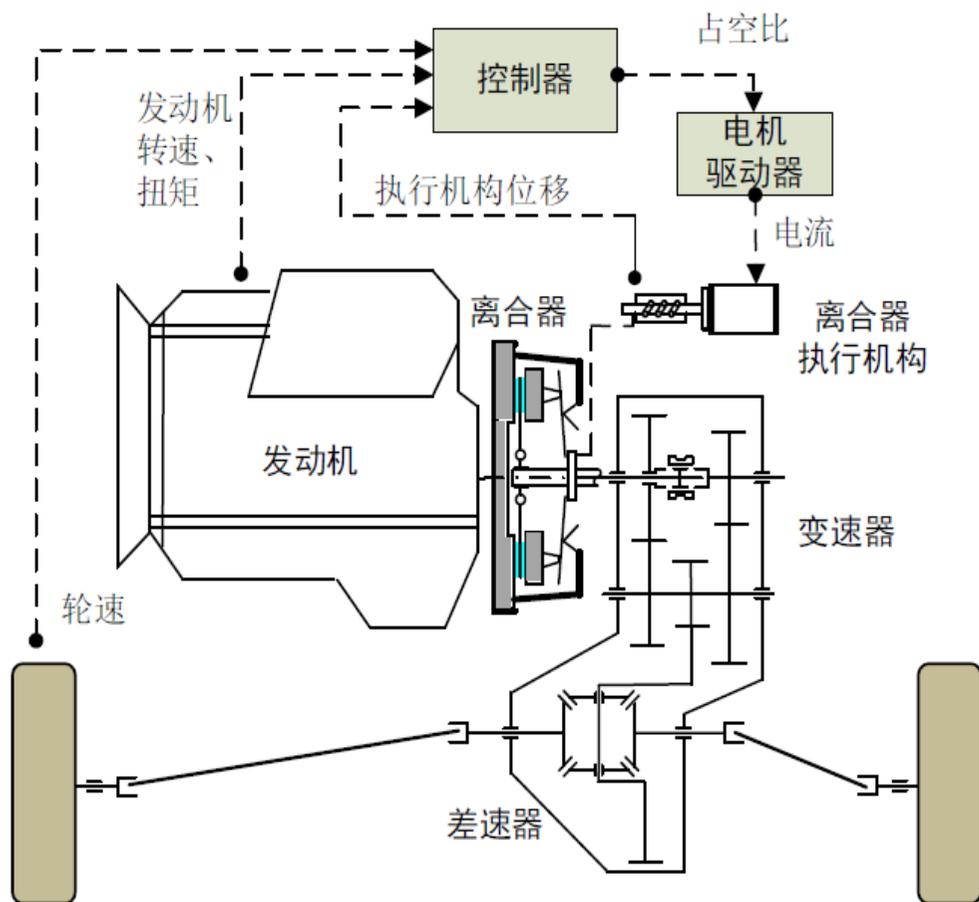


$v_{bat}$	battery voltage	12 V
$L_a$	armature inductance	$5 \times 10^{-4} \text{H}$
$k_v$	EMF coefficient	$40.5 \times 10^{-3} \text{V}/(\text{rad})$
$k_t$	torque coefficient	$40.5 \times 10^{-3} \text{Nm}/\text{A}$
$T_{mf}$	motor friction torque	0.01Nm
$J_m$	motor inertia	$1.0 \times 10^{-4} \text{kg} \cdot \text{m}^2$
$m$	mass of moving parts	0.75kg
$h$	lead of screw	5mm



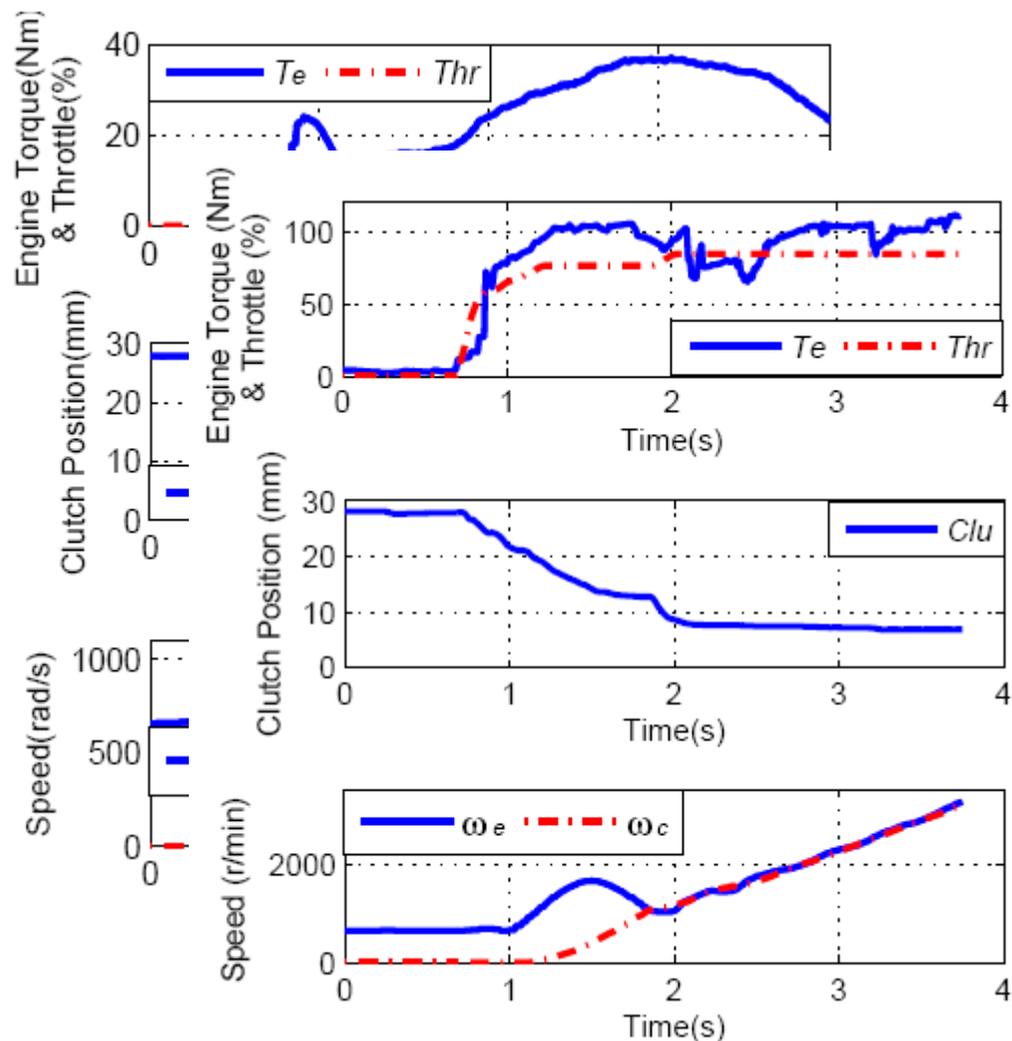
# AMT离合器执行机构控制

## ● 电控机械式自动变速器AMT



# AMT离合器执行机构控制

## 实车试验验证



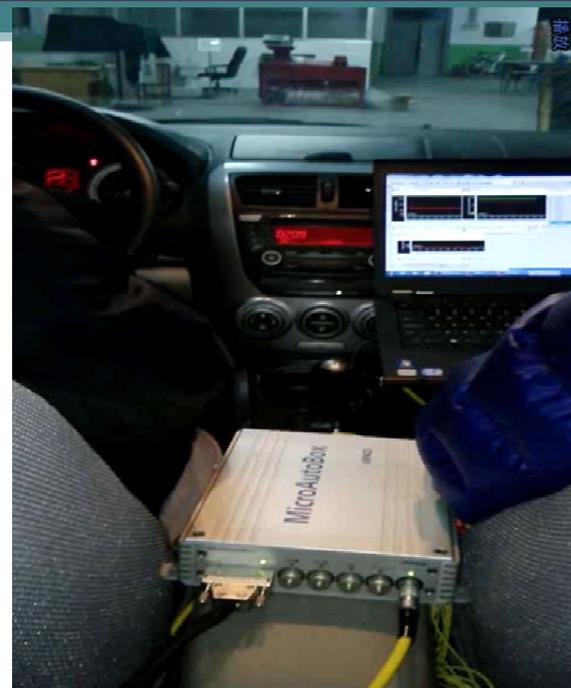
大油门试验结果

# AMT离合器执行机构控制

## 试验场景



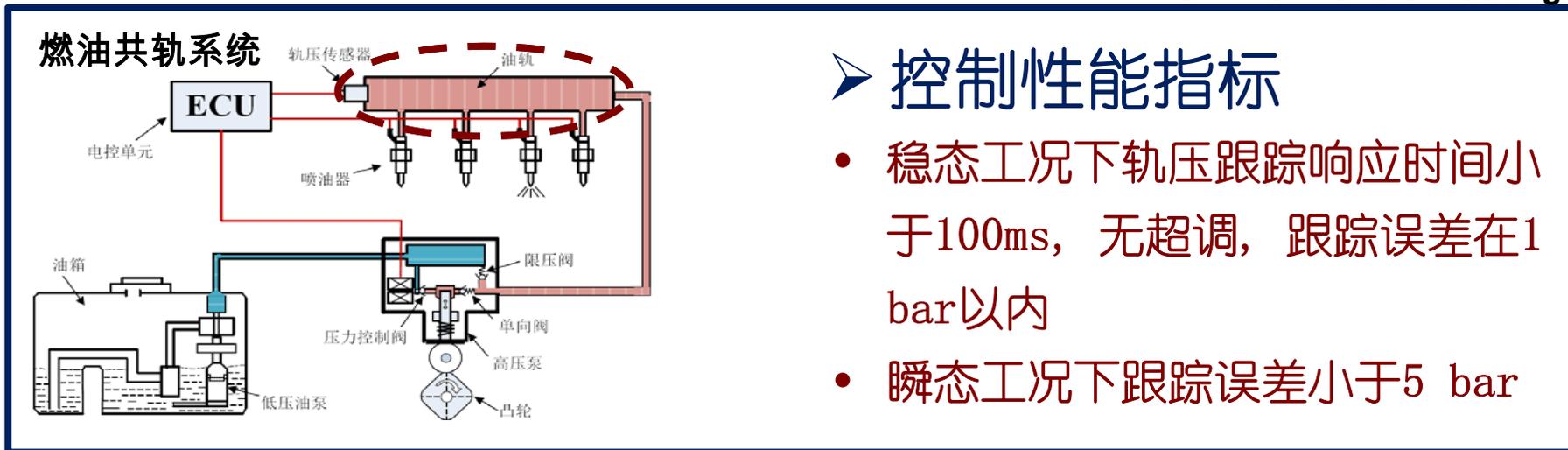
一汽轿车奔腾B50



吉利汽车熊猫微型车

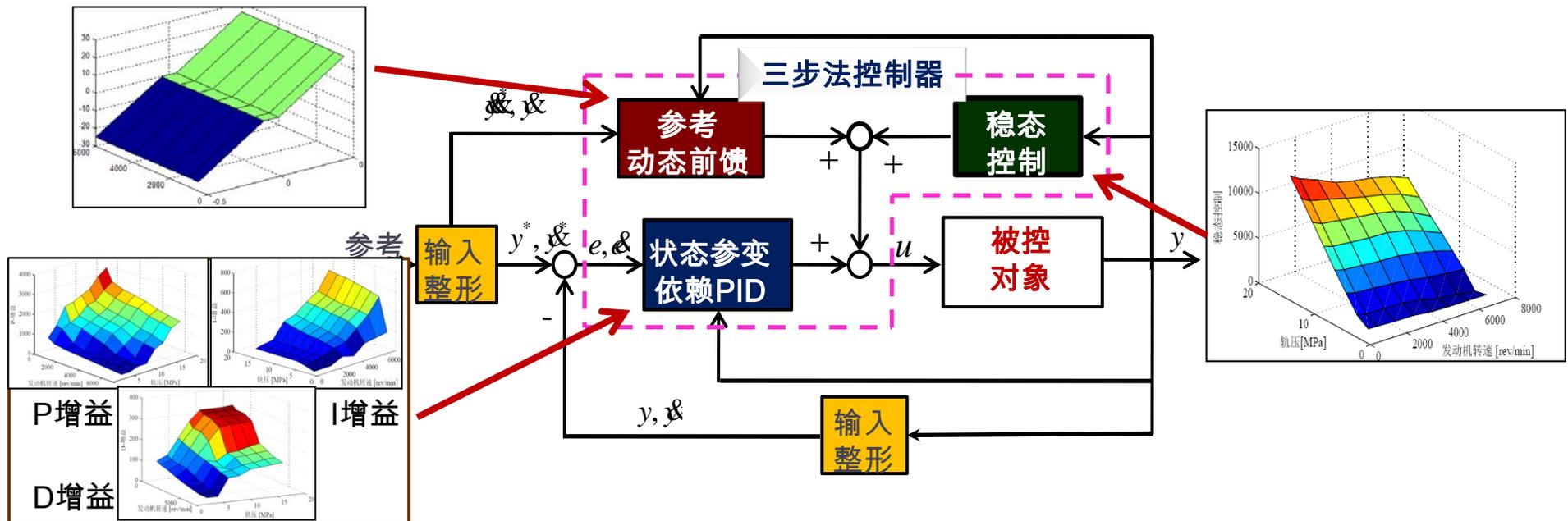


# 直喷发动机轨压控制

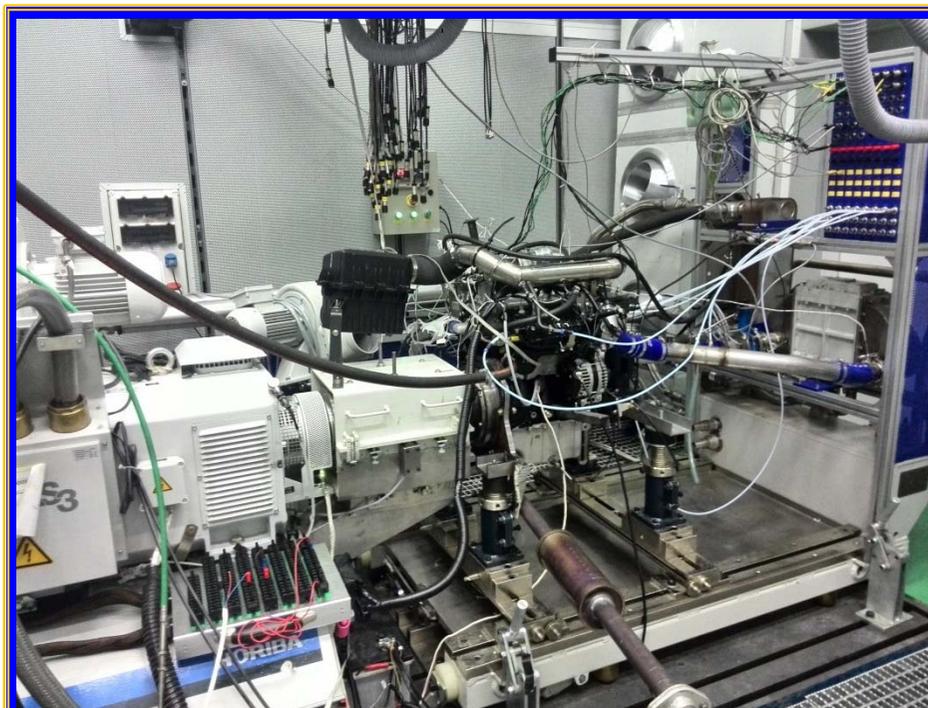


## 控制性能指标

- 稳态工况下轨压跟踪响应时间小于100ms, 无超调, 跟踪误差在1 bar以内
- 瞬态工况下跟踪误差小于5 bar



# 直喷发动机轨压控制

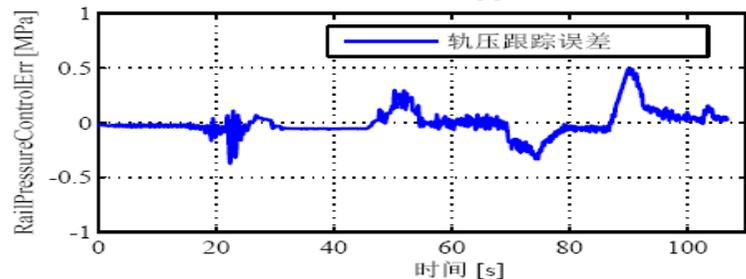
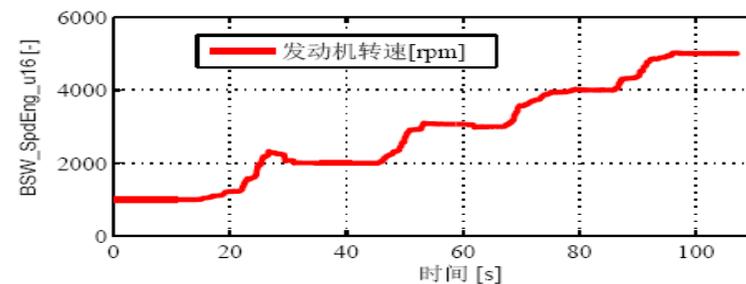
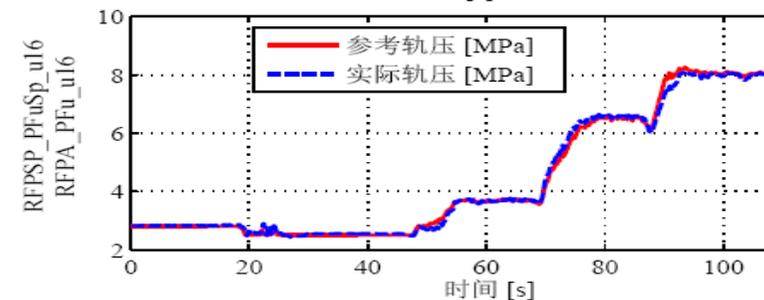
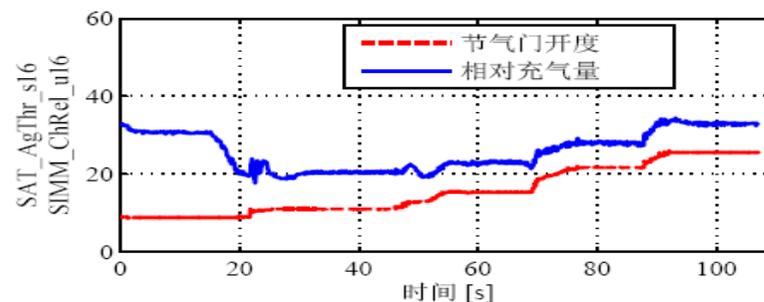


GDI发动机实验台架

发动机转速：1000 - 5000 rpm

发动机负荷：20-75 (%)

综合选取工况点



# 电动汽车稳定性控制

轮毂电机电动汽车稳定性控制, MIMO非仿射系统

参考目标

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

$$\beta^* = 0.$$

$$y = \begin{bmatrix} \beta \\ \gamma \end{bmatrix}, u = \begin{bmatrix} \delta_f \\ M_z \end{bmatrix}$$

车辆侧偏角

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

横摆角速度

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

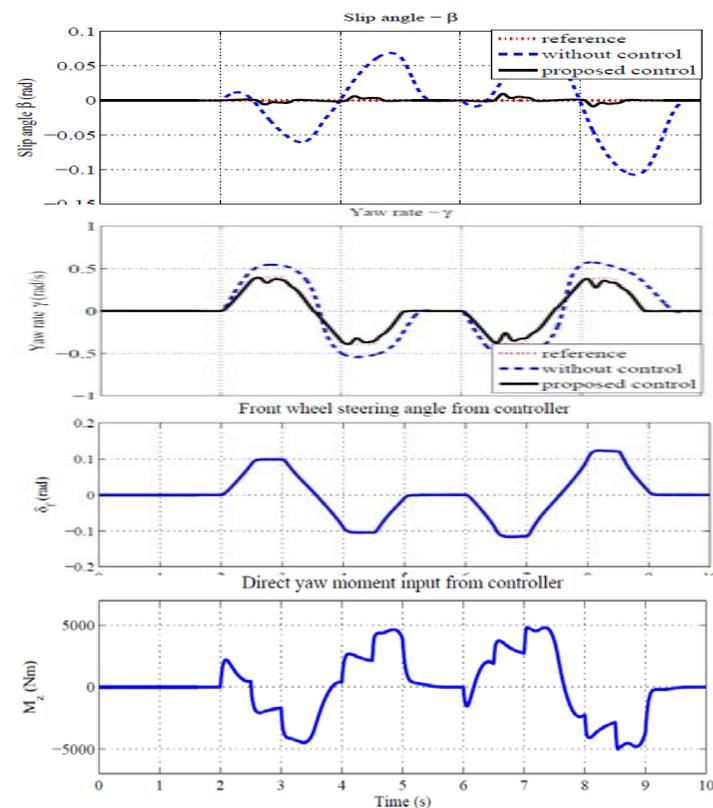
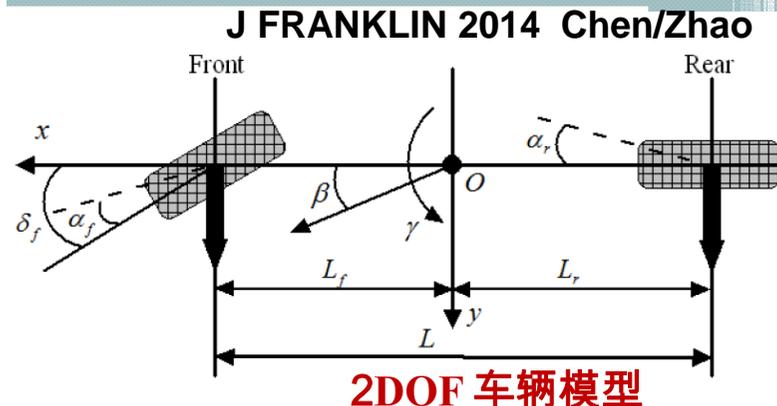
控制律

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

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

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

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



---

**谢谢！**  
**欢迎批评指正！**

