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状态反馈控制及观测器在多桥车辆转向中的应用

王欢¹,高秀华¹,张小江¹,黄大巍²,陈淑清³

(1. 吉林大学机械科学与工程学院,吉林 长春 130022;

2. 机械工业第九设计研究院,吉林 长春 130011;

3. 空军航空大学,吉林 长春 130022)

摘要:建立了多桥车辆的 3 自由度动力学模型,针对质心侧偏角、车身侧倾角及侧倾角速度难以测量问题,设计了 Luenberger 观测器,并对 Luenberger 观测器进行仿真分析,分析结果表明:观测器跟踪性能良好、速度快且误差小。基于 Luenberger 观测器设计了状态反馈控制器,并对某多桥车辆进行仿真研究,与只前轮转向对比分析,结果表明:采用状态反馈控制器进行转向的多桥车辆各性能指标都显著优于只前轮转向,且具有良好的动态性能和鲁棒性,提高多桥车辆的操纵稳定性及安全性。

关键词:多桥转向;Luenberger 观测器;状态反馈;操纵稳定性

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Application of state feedback and observer in multi-axle vehicle steering system

WANG Huan¹, GAO Xiu-hua¹, ZHANG Xiao-jiang¹, HUANG Da-wei², CHEN Shu-qing³

(1. College of Mechanical Science and Engineering, Jilin University, Changchun 130022, Jilin, P. R. China;

2. MMI Planning & Engineering Institute IX, Changchun 130011, Jilin, P. R. China;

3. The Second Aeronautical Institute of the Airforce, Changchun 130022, Jilin, P. R. China)

Abstract: A 3-degrees of freedom multi-axle vehicle dynamic model is established. Taking account of the practical difficulties for measuring the sideslip, rolling angles and rolling angle speed, a Luenberger observer is designed, and the simulation and analysis of the Luenberger observer are performed. The results show that the Luenberger observer has excellent characteristics in the considered speed range in tracking path. Then, a state feedback controller is designed on the basis of the Luenberger observer, and simulation of a multi-axle vehicle is also carried out. The results show that the performances of a multi-axle vehicle with the proposed control strategy is better than a multi-axle vehicle with front wheel steering strategy, and its control system has fine dynamic characteristic and strong robustness, so multi-axle vehicle with the proposed control strategy can improve vehicle handling stability and security.

Key words: multi-axle steering; Luenberger observer; state feedback; handling stability

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作者简介:王欢(1982-),男,吉林大学博士研究生,研究方向为多桥车辆智能控制,(E-mail)wanghuan0809@163.com。

高秀华(联系人),女,吉林大学教授,博士生导师,研究方向为机械控制和特种车辆,(E-mail)xhgao@jlu.edu.cn。

多桥转向技术在工程车辆上应用越来越普遍,不仅能增加车辆低速行驶的机动灵活性,而且当车速较高时也能为车辆提供较好的操纵稳定性;改善横摆角速度和侧向加速度的瞬态性能指标。对于重型车辆来说,应用这种多桥转向技术意义重大^[1]。多桥转向控制器的设计需要采集若干输出变量或状态变量,但在实际中有一些物理量是目前无法测得或难以通过传感器来测量,或测量成本太高。信息的不完全性为实现车辆主动安全性控制带来了很大的困难^[2]。

由于技术保密的原因,国内外多桥转向技术资料还很匮乏,可检索到的相关资料都是以四轮转向为主,且都是基于各变量可测的情况下进行研究的。比如文献[3-13],对四轮转向有较深入的研究,但都假设所有需采集变量都是可测的,控制器在理论上可以实现,但运用到实际车辆上实现起来就比较困难;可见,对难以测量的变量进行估计显得尤为重要。针对这一问题,笔者在建立多桥车辆动力学模型的基础上,采用状态反馈对多桥转向进行控制,并针对相关状态变量难测这一现象设计 Luenberger

观测器来进行状态变量估计,最后进行仿真分析,分析结果表明:多桥转向控制器采用 Luenberger 观测器来进行状态变量估计,从而进行状态反馈控制器设计,车辆控制反应敏捷、控制结果精确,显著改善车辆的动态性能和鲁棒性,从而提高车辆的行驶稳定性和安全性。

1 多桥转向车辆动力学模型

为了方便建立车辆三自由度数学模型,本文取车身质心的位置为坐标原点,车辆行驶方向为 x 轴正方向,垂直地面向上方向为 z 轴正方向, y 轴方向根据右手定则确定,如图 1 所示。^[14]

为了全面反映多桥转向车辆转向性能,根据图 1 采用拉格朗日能量法建立包括横摆、侧倾和侧向三个方向的多桥转向车辆的三自由度动力学模型。拉格朗日表达式如下:

$$\frac{d}{dt} \left(\frac{\partial E_T}{\partial \dot{q}_i} \right) - \frac{\partial E_T}{\partial q_i} + \frac{\partial E_V}{\partial q_i} + \frac{\partial E_D}{\partial \dot{q}_i} = Q_i. \quad (1)$$

建立多桥车辆动力学三自由度模型为:

$$\left. \begin{aligned} & \sum_{i=1}^n m_i L_i \dot{\varphi} + m_b h \ddot{\phi} + (m_b + \sum_{i=1}^n m_i + \frac{\sum_{i=1}^n C'_i L_i}{V^2}) V \dot{\varphi} + (m_b + \sum_{i=1}^n m_i) V \dot{\beta} + \sum_{i=1}^n C'_i \dot{\beta} = \sum_{i=1}^n C'_i H_i \delta_1, \\ & (I_{zz} + \sum_{i=1}^n m_i L_i^2 + \sum_{i=1}^n I_{zi}) \dot{\varphi} - I_{xzb} \ddot{\phi} + \left[\frac{\sum_{i=1}^n C'_i L_i^2}{V^2} + \sum_{i=1}^n m_i L_i \right] V \dot{\varphi} - m_b h V \dot{\phi} + \sum_{i=1}^n m_i L_i V \dot{\beta} + \sum_{i=1}^n C'_i L_i \dot{\beta} = \\ & \sum_{i=1}^n L_i C'_i H_i \delta_1, \\ & -I_{xzb} \dot{\varphi} + (m_b h^2 + I_{xx}) \ddot{\phi} + \frac{\sum_{i=1}^n C'_i L_i d_{yi}}{V} \dot{\varphi} + C_\phi \dot{\phi} + (K_\phi - m_b g h) \phi + m_b h V \dot{\beta} + \sum_{i=1}^n C'_i d_{yi} \beta = \sum_{i=1}^n d_{yi} C'_i H_i \delta_1. \end{aligned} \right\} \quad (2)$$

定义各变量如下:

V 为车辆行驶速度; δ_1 为 1 轴车轮的转角; β 质心处的侧偏角; L_i 为 i 轴到车辆瞬时转向中心的距离。 m_b 为车身的质量; m_i 为第 i 个车轴的质量; I_{xzb} 为车身绕侧倾中心 x 轴和 z 轴的惯性积; I_{zz} 为车身绕侧倾中心 z 轴的转动惯量; I_{zi} 为第 i 轴绕 z 轴的转动惯量; I_{xx} 为车身绕侧倾中心 x 轴的转动惯量; d_{yi} 为第 i 轮胎印迹侧向位移导数; h 为车身质心到侧倾轴线的高度; K_ϕ 为车辆侧倾刚度; C_ϕ 为车辆侧倾阻尼系数; p 为车身的侧倾角速度; ϕ 为车身的侧

倾角; φ 为车身的横摆角; H_i 为第 i 桥转角与第 1 桥转角比。

写成状态方程的形式如下:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}, \quad (3)$$

$$\mathbf{y} = \mathbf{Cx}. \quad (4)$$

式中

系统的状态变量 $\mathbf{x} = [\beta \ \varphi \ \phi \ p]^T$;

$\mathbf{A} = -\mathbf{M}^{-1}\mathbf{N}$; $\mathbf{B} = \mathbf{M}^{-1}\mathbf{R}$ 。

其中

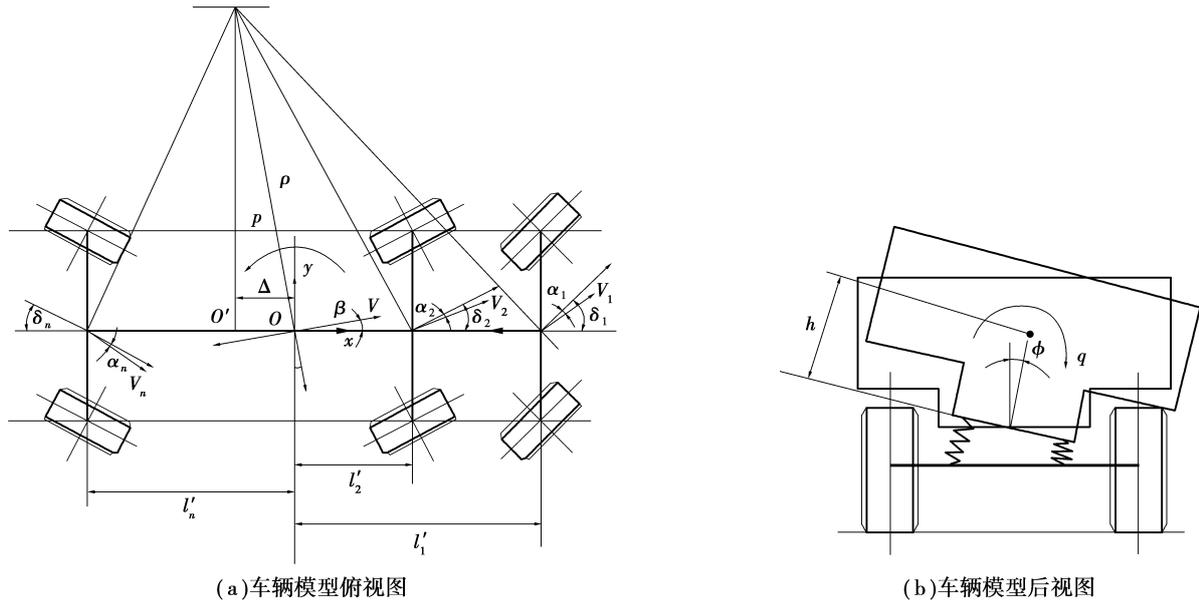


图 1 多桥转向车辆三自由度动力学模型

$$\begin{aligned}
 \mathbf{M} &= \begin{bmatrix} (m_b + \sum_{i=1}^n m_i)V & 0 & \sum_{i=1}^n m_i L_i & m_b h \\ \sum_{i=1}^n m_i L_i V & 0 & I_{zz} + \sum_{i=1}^n m_i L_i^2 + \sum_{i=1}^n I_{zi} & -I_{xzb} \\ m_b h V & C_\phi & -I_{xzb} & m_b h^2 + I_{xx} \\ 0 & -1 & 0 & 0 \end{bmatrix}, \\
 \mathbf{N} &= \begin{bmatrix} \sum_{i=1}^n C'_i & 0 & m_b + \sum_{i=1}^n m_i + \frac{\sum_{i=1}^n C'_i L_i}{V^2} & 0 \\ \sum_{i=1}^n C'_i L_i & 0 & \sum_{i=1}^n m_i L_i V + \frac{\sum_{i=1}^n C'_i L_i}{V} & -m_b h \\ \sum_{i=1}^n C'_i d_{yi} & k_\phi - m_b g h & \frac{\sum_{i=1}^n C'_i L_i d_{yi}}{V} & m_b h^2 + I_{xx} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \\
 \mathbf{R} &= \begin{bmatrix} \sum_{i=1}^n C'_i H_i \\ \sum_{i=1}^n L_i C'_i H_i \\ \sum_{i=1}^n d_{yi} C'_i H_i \\ 0 \end{bmatrix}, \mathbf{C} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}^T.
 \end{aligned}$$

2 Luenberger 观测器设计

根据多桥车辆系统动力学方程可知,系统可观测。由系统的状态变量 $\mathbf{x} = [\beta \ \phi \ \varphi \ p]^T$ 可知横摆角速度信号最容易测得,假设其可测,而质心侧偏角、车身侧倾角及侧倾角速度难以测得,可通过观测

器估计出这三个状态变量以实现状态反馈。根据文献[15]相关知识设计 Luenberger 观测器过程如下。

2.1 构造 Q 矩阵

构造 Q 矩阵

$$Q = \begin{bmatrix} \mathbf{D} \\ \mathbf{C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

$$\bar{\mathbf{y}} = \bar{\mathbf{C}}\bar{\mathbf{x}}. \quad (6)$$

式中

$$\bar{\mathbf{x}} = \begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \end{bmatrix}, \bar{\mathbf{A}} = \mathbf{Q}\mathbf{A}\mathbf{Q}^{-1} = \begin{bmatrix} \bar{\mathbf{A}}_{11} & \bar{\mathbf{A}}_{12} \\ \bar{\mathbf{A}}_{21} & \bar{\mathbf{A}}_{22} \end{bmatrix},$$

2.2 被控系统动态方程的变换

$\mathbf{x} = \mathbf{Q}^{-1}\bar{\mathbf{x}}$ 变换后被控系统动态方程为:

$$\bar{\mathbf{B}} = \mathbf{Q}\mathbf{B} = \begin{bmatrix} \bar{\mathbf{B}}_1 \\ \bar{\mathbf{B}}_2 \end{bmatrix}, \bar{\mathbf{C}} = [0 \quad 0 \quad 0 \quad 1]$$

$$\dot{\bar{\mathbf{x}}} = \bar{\mathbf{A}}\bar{\mathbf{x}} + \bar{\mathbf{B}}\mathbf{u}, \quad (5)$$

其中

$$\bar{\mathbf{A}}_{11} = \begin{bmatrix} \frac{a}{\sum C'_i} + \frac{b}{\sum C'_i L_i} + \frac{c}{\sum C'_i d_{yi}} & \frac{c}{K_\phi - m_b g h} & \frac{b}{-m_b h} + \frac{c}{m_b h^2 + I_{xx}} + cC_\phi \\ 0 & 0 & 1 \\ \frac{cV}{\sum C'_i} + \frac{dV}{\sum C'_i L_i} + \frac{fV}{\sum C'_i d_{yi}} & \frac{fV}{K_\phi - m_b g h} & \frac{dV}{-m_b h} + \frac{fV}{m_b h^2 + I_{xx}} + fVC_\phi \end{bmatrix},$$

$$\bar{\mathbf{A}}_{12} = \begin{bmatrix} \frac{a}{\xi} + \frac{b}{\zeta} + \frac{cV}{\sum C'_i L_i d_{yi}} \\ 0 \\ \frac{cV}{\xi} + \frac{dV}{\zeta} + \frac{fV^2}{\sum C'_i L_i d_{yi}} \end{bmatrix}, \bar{\mathbf{A}}_{21} = \begin{bmatrix} \frac{bV}{\sum C'_i} + \frac{mV}{\sum C'_i L_i} + \frac{dV}{\sum C'_i d_{yi}} \\ \frac{dV}{K_\phi - m_b g h} \\ \frac{mV}{-m_b h} + \frac{dV}{m_b h^2 + I_{xx}} + dVC_\phi \end{bmatrix}^T,$$

$$\bar{\mathbf{A}}_{22} = \begin{bmatrix} \frac{bV}{\xi} + \frac{mV}{\zeta} + \frac{dV^2}{\sum C'_i L_i d_{yi}} \\ 0 \\ \frac{-cV}{\sum C'_i H_i} - \frac{dV}{\sum C'_i H_i L_i} - \frac{fV}{\sum C'_i H_i d_{yi}} \end{bmatrix}, \bar{\mathbf{B}}_1 = \begin{bmatrix} -a \\ -cV \\ \frac{b}{\sum C'_i H_i} - \frac{dV}{\sum C'_i H_i L_i} - \frac{fV}{\sum C'_i H_i d_{yi}} \end{bmatrix},$$

$$\bar{\mathbf{B}}_2 = \begin{bmatrix} -bV \\ \frac{mV}{\sum C'_i H_i} - \frac{dV}{\sum C'_i H_i L_i} - \frac{dV}{\sum C'_i H_i d_{yi}} \end{bmatrix}.$$

式中

$$\begin{aligned} a &= -q(m_b h^2 + I_{xx}) + I_{xzb}^2, \\ b &= \sum m_i L_i (m_b h^2 + I_{xx}) + m_b h I_{xzb}, \\ c &= \sum m_i L_i I_{xzb} + m_b h q, \\ d &= -[I_{xzb}(m_b + \sum m_i) + m_b h \sum m_i L_i], \\ f &= -q(m_b + \sum m_i) + (\sum m_i L_i)^2, \\ m &= -(m_b + \sum m_i)(m_b h^2 + I_{xx}) + m_b^2 h^2, \\ q &= I_{zz} + \sum m_i L_i^2 + \sum I_{zi}, \\ r &= -a(m_b h^2 + \sum m_i)V - \\ &\quad b \sum m_i L_i V - c m_b h V, \end{aligned}$$

$$\xi = \left[m_b + \sum m_i + \frac{\sum C'_i L_i}{V^2} \right] V,$$

$$\zeta = \left[\sum m_i L_i + \frac{\sum C'_i L_i^2}{V^2} \right] V.$$

2.3 Luenberger 观测器动态方程

Luenberger 观测器动态方程为:

$$\dot{\mathbf{w}} = (\bar{\mathbf{A}}_{11} - \bar{\mathbf{H}}\bar{\mathbf{A}}_{21})\mathbf{w} + (\bar{\mathbf{B}}_1 - \bar{\mathbf{H}}\bar{\mathbf{B}}_2)\mathbf{u} + [(\bar{\mathbf{A}}_{11} - \bar{\mathbf{H}}\bar{\mathbf{A}}_{21})\mathbf{H} + \bar{\mathbf{A}}_{12} - \bar{\mathbf{H}}\bar{\mathbf{A}}_{22}]\bar{\mathbf{y}}, \quad (7)$$

$$\hat{\bar{\mathbf{x}}}_1 = \mathbf{w} + \bar{\mathbf{H}}\bar{\mathbf{y}}. \quad (8)$$

式中

$$\mathbf{w} = \hat{\bar{\mathbf{x}}}_1 - \bar{\mathbf{H}}\bar{\mathbf{y}}, \mathbf{H} = \begin{bmatrix} h_0 \\ h_1 \\ h_2 \end{bmatrix}.$$

2.4 估计误差

观测器状态向量估计误差为:

$$\dot{\bar{\mathbf{x}}}_1 - \hat{\bar{\mathbf{x}}}_1 = (\bar{\mathbf{A}}_{11} - \bar{\mathbf{H}}\bar{\mathbf{A}}_{21})(\bar{\mathbf{x}}_1 - \hat{\bar{\mathbf{x}}}_1). \quad (9)$$

可见只要适当选择 \mathbf{H} 阵,便可以随意配置 Luenberger 观测器极点,使 $(\bar{\mathbf{x}}_1 - \hat{\bar{\mathbf{x}}}_1)$ 具有满意的衰减

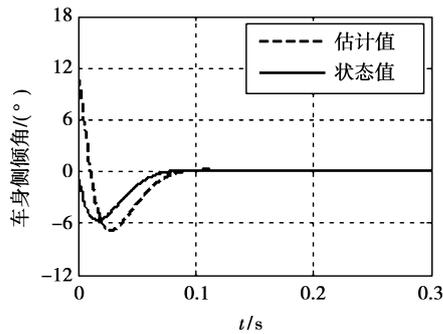


图 5 车身侧倾角状态估计

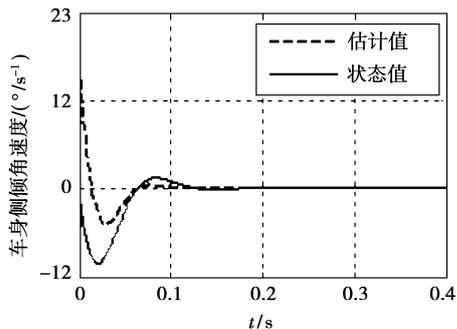


图 6 车身侧倾角速度状态估计

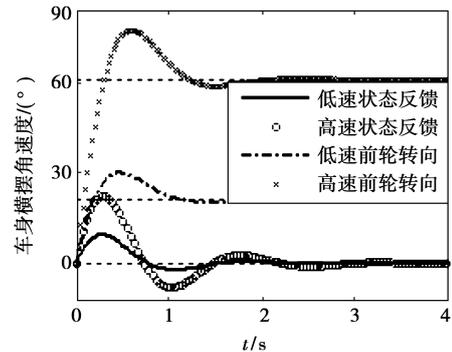


图 8 车身横摆角速度阶跃响应对比

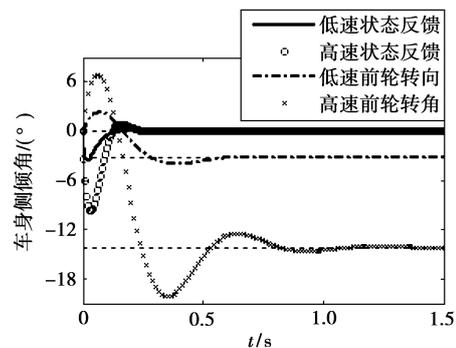


图 9 车身侧倾角阶跃响应对比图

身横摆角速度及车身侧倾角阶跃响应对比结果。从图中可以看出,无论在低速还是高速工况下,采用状态反馈控制的多桥车辆的各项性能指标经过很短的时间后阶跃响应的稳态值基本为零,这样保证了车辆行驶过程中的稳定性;而只前轮转向的多桥车辆各项性能指标很容易使车辆失稳,且随着车速的提高失稳发生的概率明显增高。以上分析结果表明:采用状态反馈控制器进行转向的多桥车辆各性能指标都显著优于只前轮转向,且具有良好的动态性能和鲁棒性,提高多桥车辆的操纵稳定性及安全性。

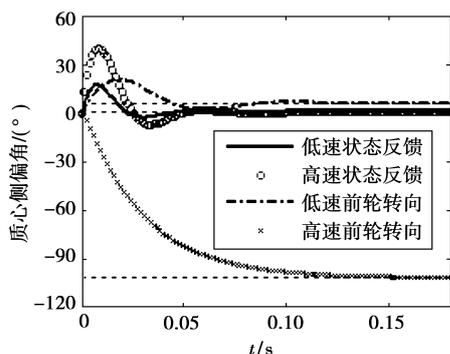


图 7 质心侧偏角阶跃响应对比

5 结 论

多桥转向技术是现今汽车行业的前沿技术,各种车辆,尤其是工程车辆对多桥转向技术要求极为迫切,由于技术保密的原因,能检索到的相关研究资料十分有限,且所涉及到的控制方法都是假设所需采集变量可测的条件建立起来的,而在实际情况中有很多变量不易测得、不可能测得或者测量费用较高等,这就造成了所研究的控制方法停留在理论阶段而不能应用于实际。针对这一问题,本文做了详细研究与分析,具体工作如下:

- 1)建立了包括横摆、侧倾及侧向三个方向的多桥车辆 3 自由度动力学模型;
- 2)针对质心侧偏角、车身侧倾角及侧倾角速度难以测量这一问题,设计 Luenberger 观测器来进行状态变量估计;
- 3)基于 Luenberger 观测器,设计最优状态反馈控制器对多桥转向进行控制;
- 4)针对某一三桥车辆进行仿真分析。

研究及分析结果表明:所设计的 Luenberger 观测器跟踪性能良好、速度快且误差小;采用状态反馈控制器进行转向的多桥车辆各性能指标都显著优于只前轮转向,且具有良好的动态性能和鲁棒性,提高多桥车辆的操纵稳定性及安全性;为多桥车辆技术

的理论研究转化为实际应用打下良好基础,同时对相关课题的研究具有借鉴意义。

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