

两轴快速反射镜视轴指向与速率补偿分析

杜言鲁^{1,2}, 丁亚林¹, 许永森¹, 李 军¹

(1. 中国科学院长春光学精密机械与物理研究所, 吉林 长春 130033;
2. 中国科学院大学, 北京 100049)

摘 要: 为精确控制两轴快速反射镜的视轴指向, 根据矢量形式斯涅尔定律建立了反射镜转角与视轴指向角间的运动学耦合方程。通过非线性校正实现视轴指向方程解耦, 对于行程为 ± 20 mrad 的两轴快速反射镜在入射角为 45° 时视轴指向误差小于 $8 \mu\text{rad}$, 相比线性近似, 视轴指向精度提高 75 倍。为保证视轴稳定, 根据矢量速率方程推导出补偿基座扰动角速率的反射镜转动角速率方程, 通过对三角函数进行泰勒展开, 舍去高阶项, 得到快反镜转动角速率近似计算公式, 分析了不同入射角下的残余视轴转动角速率, 得出视轴转动角速率 ω_{L_y} 残差远大于 ω_{L_x} , 且入射角 β_i 为 45° 时残差最小, 此时残余视轴转动角速率与基座扰动角速率之比小于 0.164%, 可满足计算精度要求。为快速反射镜伺服控制系统位置、速度指令生成提供理论依据。

关键词: 两轴快速反射镜; 运动耦合; 视轴指向; 速率补偿; 非线性校正

中图分类号: TP70 **文献标志码:** A **DOI:** 10.3788/IRLA201746.0918001

Analysis of LOS pointing and rate compensation for two-axis FSM

Du Yanlu^{1,2}, Ding Yalin¹, Xu Yongsen¹, Li Jun¹

(1. Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: In order to control line-of-sight(LOS) pointing with two-axis fast-steering mirror(FSM) accurately, kinematic equations was set to describe the relationship between LOS pointing and angular displacement of FSM deriving from Snell's law of reflection. LOS pointing equations were decoupled with non-linear correction. LOS pointing error was less than $8 \mu\text{rad}$ for two-axis FSM whose tilt angles were both ± 20 mrad with beam incidence angle equaling to 45° . LOS pointing accuracy rose 75 times compared with linear approximation. To hold the LOS stationary, rate equations were established in terms of vector rate synthesis to compensate the angular rate of the mounted vehicle in inertial space. Angular rate equations for FSM were simplified via Taylor expansion and high order truncation. The residual angular rate of LOS with different beam incidence angles was calculated, which indicated that the residual error of ω_{L_y} was far greater than ω_{L_x} . The ratio between residual LOS angular rate and angular rate of mounted vehicle was minimal and less than 0.164% when beam incidence angle was 45° , which satisfied the accuracy requirements. The equations deduced supply theoretic reference of position and velocity command generation for FSM control system.

Key words: two-axis FSM; kinematics couple; LOS pointing; rate compensation; non-linear correction

收稿日期: 2017-01-05; 修订日期: 2017-02-03

基金项目: 国家 863 计划(Y3471SR140); 国家自然科学基金青年科学基金(61405192)

作者简介: 杜言鲁(1988-), 男, 博士生, 主要从事航空相机稳定成像技术方面的研究。Email: yanlu08@mail.ustc.edu.cn

导师简介: 丁亚林(1964-), 男, 研究员, 博士生导师, 主要从事航空相机总体设计等方面的研究。Email: dingyl_1964@126.com

0 引言

快速反射镜(Fast-Steering Mirror, FSM)作为精密控制光束传播方向的光学元件,具有响应快、精度高等突出优点^[1-2],通常与大惯量跟踪框架构成复合轴系统,用于校正主轴系统的跟踪误差以及由基座、大气等干扰引起的视轴抖动^[3-5]。

建立快速反射镜转动角度与光电系统视轴指向角间的关系,分析光电系统视轴速率稳定方程,对精确控制复合轴系统中的快速反射镜,提高光电系统视轴指向精度和稳定精度具有重要意义。James M. B.Royalty、宋江鹏、吴超等人^[6-9]建立了传统框架式扫描反射镜的视轴指向和速率稳定方程, Satyam Satyarathi^[10]对不同结构形式的框架式扫描反射镜的转角和速率补偿公式进行了总结。陈强等人^[10-11]对二维指向镜的成像特性和扫描特性进行了分析,指出指向镜旋转导致像旋,图像产生畸变,视轴扫描轨迹出现非线性。以上学者均是针对大角度框架式扫描反射镜进行分析,而对小角度柔性无轴式快速反射镜的视轴指向与速率方程缺少分析。J.M.Hilkert、彭树萍、李红光等人^[12-14]推导出小角度柔性无轴式快速反射镜的视轴指向运动学方程,分析了线性近似下的视轴指向误差。

文中结合实验室在研的两轴快速反射镜,根据矢量形式斯涅尔定律建立两轴快反镜转角与视轴指向角间的运动学方程,着重分析了非线性和两轴间的耦合特性。通过非线性校正实现视轴指向高精度计算。以视轴指向运动学方程为基础,根据矢量速率方程推导出视轴稳定方程,为光电系统视轴稳定提供理论依据。

1 快反镜视轴指向运动学方程

为分析两轴快速反射镜入射光线与出射光线间

$$\vec{P}_{ol} = \begin{pmatrix} -\cos^2\beta_i(1-2\cos^2\psi_m\cos^2\theta_m)+\sin^2\beta_i(1-2\cos^2\psi_m\sin^2\theta_m) \\ \cos\beta_i(2\cos\psi_m\sin\psi_m\cos^2\theta_m)+\sin\beta_i(2\cos\psi_m\sin\psi_m\cos\theta_m\sin\theta_m) \\ -2\cos^2\psi_m\cos\theta_m\sin\theta_m+2\cos\beta_i\sin\beta_i\sin^2\psi_m \end{pmatrix} \quad (8)$$

由此可计算出视轴指向角为:

$$\theta_{lx} = -\arctan \frac{P_{ol}(z)}{P_{ol}(x)} \approx \frac{2\cos^2\psi_m\cos\theta_m\sin\theta_m-2\cos\beta_i\sin\beta_i\sin^2\psi_m}{-\cos^2\beta_i(1-2\cos^2\psi_m\cos^2\theta_m)+\sin^2\beta_i(1-2\cos^2\psi_m\sin^2\theta_m)} \quad (9)$$

$$\psi_{lx} = \arctan \frac{P_{ol}(y)}{P_{ol}(x)} \approx \frac{\cos\beta_i(2\cos\psi_m\sin\psi_m\cos^2\theta_m)+\sin\beta_i(2\cos\psi_m\sin\psi_m\cos\theta_m\sin\theta_m)}{-\cos^2\beta_i(1-2\cos^2\psi_m\cos^2\theta_m)+\sin^2\beta_i(1-2\cos^2\psi_m\sin^2\theta_m)} \quad (10)$$

可见,视轴指向角是反射镜两轴转动角度的非线性函数,且两轴间存在运动耦合,为精确控制视轴

的变换关系,建立如图 1 所示的坐标系,其中两轴快反镜的旋转轴为 y、z 轴, θ_m 、 ψ_m 为相应的旋转角度, \vec{P}_i 、 \vec{P}_o 分别为入射光线和出射光线矢量, β_i 、 β_o 为对应的入射角和出射角。假设无转动时,反射镜法线方向与坐标系 x 轴共线。

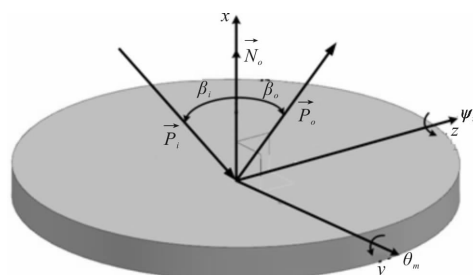


图 1 两轴快反镜坐标系

Fig.1 Reference coordinate of two-axis FSM

对于入射光线矢量,在反射镜坐标系下表示为:

$$\vec{P}_i = (-\cos\beta_i \ 0 \ \sin\beta_i)^T \quad (1)$$

当快反镜旋转一定角度后,其法线方向变为:

$$\vec{N} = M_y \times M_z \quad (2)$$

其中

$$M_y = (-\sin\psi_m \ \cos\psi_m \ 0)^T \quad (3)$$

$$M_z = (\sin\theta_m \ 0 \ \cos\theta_m)^T \quad (4)$$

由入射光线矢量到出射光线矢量的转换矩阵可写为:

$$T = 1 - 2\vec{N} \cdot \vec{N}^T \quad (5)$$

根据矢量形式的斯涅尔定律,可得出射光线矢量在反射镜坐标系下的表示为:

$$\vec{P}_o = T \cdot \vec{P}_i \quad (6)$$

将出射光线矢量转换到视轴坐标系表示为:

$$\vec{P}_{ol} = \begin{pmatrix} \cos\beta_o & 0 & \sin\beta_o \\ 0 & 1 & 0 \\ -\sin\beta_o & 0 & \cos\beta_o \end{pmatrix} \vec{P}_o \quad (7)$$

整理后得,出射光线矢量在视轴坐标系下表示为:

指向,求解快反镜转动角度,需要对该运动学耦合方程进行解耦。

2 视轴指向非线性校正

通常快速反射镜行程比较小,可对公式(9)、(10)中的三角函数进行线性近似,可得快反镜转角与视轴指向角间的关系为:

$$\psi_m \approx \frac{\psi_{Lz}}{2\cos\beta_i} \quad (11)$$

$$\theta_m \approx \frac{\theta_{Ly}}{2} \quad (12)$$

上述近似实现了运动方程解耦,但导致视轴指向角计算时,存在较大的计算误差,误差大小为:

$$\Delta\theta_{Ly} = -\arctan \frac{P_{ol}(z)}{P_{ol}(x)} - 2\theta_m \quad (13)$$

$$\Delta\psi_{Lz} = \arctan \frac{P_{ol}(y)}{P_{ol}(x)} - 2\psi_m \cos\beta_i \quad (14)$$

以行程为±20 mrad 的两轴快反镜为例,仿真分析了在入射角为 45°时,线性近似下视轴指向角计算误差,仿真结果如图 2 所示。可见视轴指向误差最大

为 0.6 mrad,对于高精度视轴指向系统,线性近似已不能满足使用要求。

为得到高精度视轴指向计算公式,可通过对三角函数采用高阶近似,此时快反镜转角非线性校正公式:

$$\psi_m \approx \frac{\psi_{Lz}}{2\cos\beta_i + \theta_{Ly}\sin\beta_i} \quad (15)$$

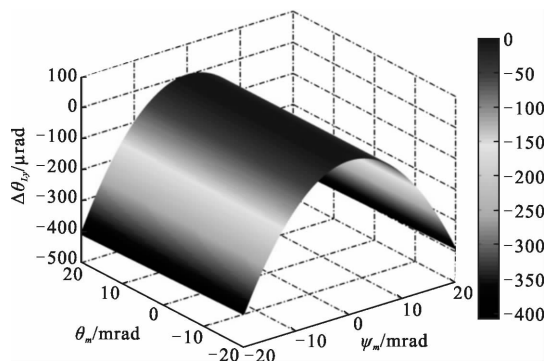
$$\theta_m \approx \frac{\psi_m^2 \sin 2\beta_i + \theta_{Ly}}{2} \quad (16)$$

经非线性校正后的视轴指向误差为:

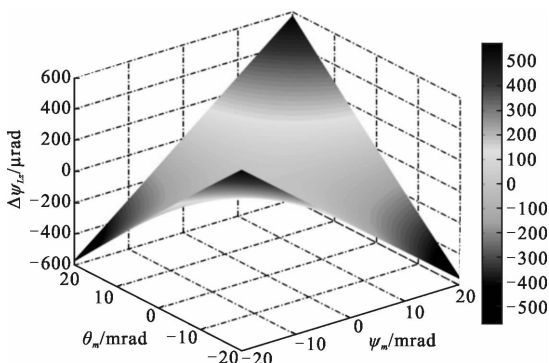
$$\Delta\theta_{Ly} = -\arctan \frac{P_{ol}(z)}{P_{ol}(x)} - 2\theta_m + \psi_m^2 \sin 2\beta_i \quad (17)$$

$$\Delta\psi_{Lz} = \arctan \frac{P_{ol}(y)}{P_{ol}(x)} - \psi_m \sin 2\beta_i - 2\theta_m \psi_m \sin\beta_i \quad (18)$$

同样以行程为±20 mrad 的两轴快反镜为例,分析了入射角为 45°时的视轴指向角计算误差,仿真结果如图 3 所示,视轴指向误差小于 8 μrad,相比线性近似,视轴指向计算精度提高 75 倍,可满足视轴指向精度为 μrad 量级的高精度光束指向系统。



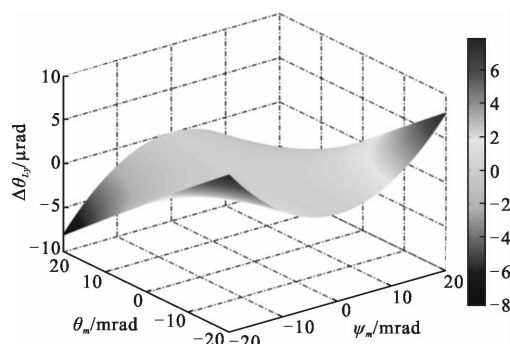
(a) θ_{Ly} 计算误差
(a) Calculation error of θ_{Ly}



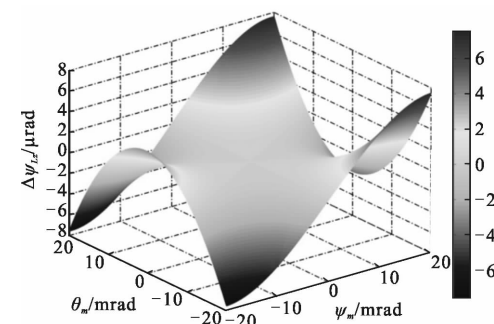
(b) ψ_{Lz} 计算误差
(b) Calculation error of ψ_{Lz}

图 2 线性近似下视轴指向计算误差

Fig.2 Calculation error of LOS pointing with linear model



(a) θ_{Ly} 计算误差
(a) Calculation error of θ_{Ly}



(b) ψ_{Lz} 计算误差
(b) Calculation error of ψ_{Lz}

图 3 非线性校正下视轴指向计算误差

Fig.3 Calculation error of LOS pointing with non-linear correction

以上仅是对入射角为 45°时的视轴指向计算误差进行了分析,而根据公式(17)、(18)可知,视轴指向计算误差还是光线入射角的非线性函数,下面分析了在给定快反镜转角下,入射角从 0°~90°时,经非线性校正后的视轴指向计算误差,分析结果如图 4 所示。可见对于配置不同入射角的光束指向系统,指向误差也会有所不同,在入射角为 45°时,指向误差最小。

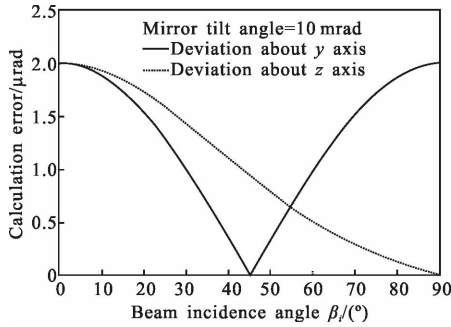


图 4 不同入射角 β 非线性校正下视轴指向计算误差

Fig.4 Calculation error of LOS pointing with non-linear correction of different β ,

$$\vec{P}_{ol} = \begin{pmatrix} -\sin 2\psi_m (\cos 2\theta_m + \cos 2\beta_i) \dot{\psi}_m - 2\cos^2 \psi_m \sin 2\theta_m \dot{\theta}_m \\ \cos 2\psi_m [\cos (2\theta_m - \beta_i) + \cos \beta_i] \dot{\psi}_m - \sin 2\psi_m \sin (2\theta_m - \beta_i) \dot{\theta}_m \\ \sin 2\psi_m (\sin 2\theta_m + \sin 2\beta_i) \dot{\psi}_m - 2\cos 2\psi_m \cos 2\theta_m \dot{\theta}_m \end{pmatrix} \quad (21)$$

根据矢量速率方程,由安装基座扰动和快反镜转动共同引起的出射光线端点速度矢量为:

$$\vec{V}_{ol} = \vec{P}_{ol} + \vec{\omega}_{bl} \times \vec{P}_{ol} \quad (22)$$

将视轴坐标系下的出射光线端点速度矢量转换到动视轴坐标系下:

$$\vec{V}_{olm} = E(\lambda_i) E(\lambda_o) \vec{V}_{ol} \quad (23)$$

其中

$$E(\lambda_i) = \begin{pmatrix} \cos \lambda_i & 0 & -\sin \lambda_i \\ 0 & 1 & 0 \\ \sin \lambda_i & 0 & \cos \lambda_i \end{pmatrix} \quad (24)$$

$$E(\lambda_o) = \begin{pmatrix} \cos \lambda_o & \sin \lambda_o & 0 \\ -\sin \lambda_o & \cos \lambda_o & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (25)$$

对转换矩阵中欧拉角可通过图 5 中坐标系构造,其中 $O-x_L y_L z_L$ 为视轴坐标系,无转动时视轴与 Ox_L 轴共线,经反射镜转动后视轴矢量变为 \vec{OP}_{ol} 。其中欧拉角 λ_o 、 λ_i 可由以下公式确定:

3 快反镜视轴角速率补偿分析

在实际应用中,快速反射镜一方面与稳定框架结构配合实现高精度视轴指向,另一方面用于补偿基座或稳定框架残余的角速率,提高视轴稳定精度。为此,根据矢量速率方程,推导出快反镜转动角速率方程,以补偿安装基座扰动角速率,实现视轴稳定。

假设快反镜安装基座坐标系与无转动时反射镜坐标系重合,基座角速率矢量为:

$$\vec{\omega}_b = (\omega_{bx} \ \omega_{by} \ \omega_{bz})^T \quad (19)$$

基座角速率在视轴坐标系下的表示为:

$$\vec{\omega}_{bl} = \begin{pmatrix} \cos \beta_o & 0 & \sin \beta_o \\ 0 & 1 & 0 \\ -\sin \beta_o & 0 & \cos \beta_o \end{pmatrix} \vec{\omega}_b \quad (20)$$

在视轴坐标系下,由快反镜转动 $(\dot{\psi}_m, \dot{\theta}_m)^T$ 引起的出射光线端点速度矢量为:

$$\cos \lambda_o = \frac{P_{ol}(x)}{\sqrt{P_{ol}^2(x) + P_{ol}^2(y)}} \quad (26)$$

$$\sin \lambda_o = \frac{P_{ol}(y)}{\sqrt{P_{ol}^2(x) + P_{ol}^2(y)}} \quad (27)$$

$$\cos \lambda_i = \sqrt{P_{ol}^2(x) + P_{ol}^2(y)} \quad (28)$$

$$\sin \lambda_i = -P_{ol}(z) \quad (29)$$

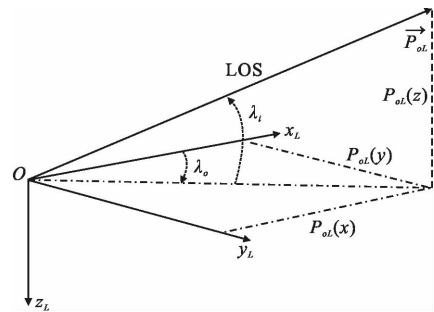


图 5 视轴坐标系

Fig.5 Reference coordinate of LOS

设视轴转动角速率为:

$$\vec{\omega}_{ol} = (\omega_{Lx} \ \omega_{Ly} \ \omega_{Lz})^T \quad (30)$$

此时出射光线端点速度矢量还可表示为:

$$\vec{V}_{oLm} = (\omega_{Lx} \ \omega_{Ly} \ \omega_{Lz})^T \times (1 \ 0 \ 0)^T = (0 \ \omega_{Lz} \ -\omega_{Ly})^T \quad (31)$$

于是视轴转动角速率为:

$$\omega_{Ly} = -\sin\lambda_i [\cos\lambda_o V_{ol}(x) + \sin\lambda_o V_{ol}(y)] - \cos\lambda_i V_{ol}(z) \quad (32)$$

$$\omega_{Lz} = -\sin\lambda_o V_{ol}(x) + \cos\lambda_o V_{ol}(y) \quad (33)$$

为保证视轴稳定,即要求:

$$\omega_{Ly} = 0$$

$$\omega_{Lz} = 0$$

写成求解快反镜转动角速率的矩阵形式为:

$$\begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} \dot{\psi}_m \\ \dot{\theta}_m \end{pmatrix} = \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \quad (34)$$

其中矩阵中各元素分别为:

$$A_{11} = S\lambda_i \{ C\lambda_o S2\psi_m (C2\theta_m + C2\beta_i) - S\lambda_o C2\psi_m [C(2\theta_m - \beta_i) + C\beta_i] \} - C\lambda_i S2\psi_m (S2\theta_m + S2\beta_i) \quad (35)$$

$$A_{12} = 2S\lambda_i C\lambda_o C^2\psi_m S2\theta_m + S\lambda_i S\lambda_o S2\psi_m S(2\theta_m - \beta_i) + 2C\lambda_i C^2\psi_m C2\theta_m \quad (36)$$

$$A_{21} = S\lambda_o S2\psi_m (C2\theta_m + C2\beta_i) + C\lambda_o C2\psi_m [C(2\theta_m - \beta_i) + C\beta_i] \quad (37)$$

$$A_{22} = 2S\lambda_o C^2\psi_m S2\theta_m - C\lambda_o S2\psi_m S(2\theta_m - \beta_i) \quad (38)$$

$$B_1 = \{ S\lambda_i [-S\lambda_o S\beta_i P_{ol}(x) + C\lambda_o S\beta_i P_{ol}(y) - S\lambda_o C\beta_i P_{ol}(z)] + C\lambda_i C\beta_i P_{ol}(y) \} \omega_{bx} + [-C\lambda_i P_{ol}(x) + S\lambda_i C\lambda_o P_{ol}(z)] \omega_{by} - \{ S\lambda_i [C\lambda_o C\beta_i P_{ol}(y) + S\lambda_o S\beta_i P_{ol}(z)] - S\lambda_o C\beta_i P_{ol}(x) \} - C\lambda_i S\beta_i P_{ol}(y) \} \omega_{bz} \quad (39)$$

$$B_2 = [C\lambda_o S\beta_i P_{ol}(x) + S\lambda_o S\beta_i P_{ol}(y) + C\lambda_o C\beta_i P_{ol}(z)] \omega_{bx} + S\lambda_o P_{ol}(z) \omega_{by} + [-C\lambda_o C\beta_i P_{ol}(x) - S\lambda_o S\beta_i P_{ol}(y) + C\lambda_o S\beta_i P_{ol}(z)] \omega_{bz} \quad (40)$$

$$\dot{\psi}_m \approx \frac{(S\beta_i - 2\theta_m C\beta_i + \psi_m^2 S\beta_i C2\beta_i) \omega_{bx} + (S\beta_i - 2\theta_m C\beta_i) \psi_m \omega_{by} - [C\beta_i + 2\theta_m S\beta_i - \psi_m^2 C\beta_i (4 - C2\beta_i - 2S2\beta_i)]}{2[C\beta_i + \theta_m S\beta_i + \theta_m^2 C\beta_i - \psi_m^2 C\beta_i (2 - S2\beta_i - 3C2\beta_i)]} \quad (43)$$

$$\dot{\theta}_m \approx \frac{[C\beta_i (S2\beta_i + 2C2\beta_i) + 2\theta_m S\beta_i - \theta_m C\beta_i (1 + 3C2\beta_i - 2S2\beta_i)] \psi_m \omega_{bx} - (C\beta_i + \theta_m S\beta_i + \theta_m^2 C\beta_i - 2\psi_m^2 S^2 C\beta_i) \omega_{by} - \frac{\psi_m C\beta_i [2C^2\beta_i - (2C2\beta_i - 3S2\beta_i) \theta_m] \omega_{bz}}{2[C\beta_i + \theta_m S\beta_i + \theta_m^2 C\beta_i - \psi_m^2 C\beta_i (2 - S2\beta_i - 3C2\beta_i)]}}{2[C\beta_i + \theta_m S\beta_i + \theta_m^2 C\beta_i - \psi_m^2 C\beta_i (2 - S2\beta_i - 3C2\beta_i)]} \quad (44)$$

同样公式(43)、(44)中的 S、C 分别为 sin、cos 的简写。由于采用近似公式计算快反镜转动角速率,此时反射镜转动不能完全补偿基座角速率,视轴转动角速率不为 0。定义残余视轴转动角速率与基座扰动角速率之比为:

$$\Delta\omega_{Ly} = \frac{\omega_{Ly}}{\sqrt{\omega_{bx}^2 + \omega_{by}^2 + \omega_{bz}^2}} \times 100\% \quad (45)$$

式中:S、C 分别为函数 sin、cos 的简写。线性方程组系数矩阵 A 的行列式值可写为:

$$\det(A) = \begin{vmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{vmatrix} \quad (41)$$

以行程为±20 mrad 的两轴快反镜为例,矩阵 A 在反射镜行程范围内行列式的最小值与最大值随入射角 β_i 的变化曲线如图 6 所示。可见当 β_i ∈ [0°, 90°) 时,系数矩阵 A 的行列式的最小值和最大值均小于 0,于是行列式值不为 0,矩阵 A 可逆。因此为补偿基座扰动角速率,保证视轴稳定,快反镜转动角速率可写为:

$$\begin{pmatrix} \dot{\psi}_m \\ \dot{\theta}_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}^{-1} \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \quad (42)$$

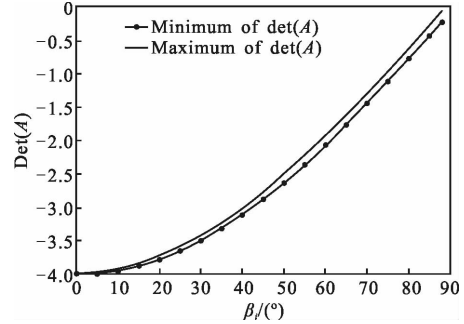


图 6 系数矩阵 A 行列式数值

Fig.6 Determinant of the calculation matrix A

为避免对矩阵求逆,同时简化计算公式,将公式(42)中的三角函数进行泰勒级数展开,保留至二次项,得出快反镜转动角速率的近似计算公式:

$$\Delta\omega_{Lz} = \frac{\omega_{Lz}}{\sqrt{\omega_{bx}^2 + \omega_{by}^2 + \omega_{bz}^2}} \times 100\% \quad (46)$$

4 视轴角速率补偿仿真分析

以基座扰动角速率矢量 $\vec{\omega}_b = (0.1 \ 0.1 \ 0.1)^T$, 入射角 β_i 为 30°、45°、60° 为例,分析采用公式(43)、(44)

近似计算时的残余视轴转动角速率，仿真结果如图 7 所示。可见，对于同一入射角，视轴转动角速率 ω_{ly} 的残差远大于 ω_{lz} 的残差；而对于不同入射角，残余视轴转动角速率存在较大差异。为分析不同入射角情况下的残余视轴转动角速率的变化情况，同样以行程为 ± 20 mrad 的两轴快反镜为例，绘制了反射镜行

程范围内最大视轴转动角速率残差随入射角的变化曲线，分析结果如图 8 所示。残差主要体现在视轴转动角速率 ω_{ly} 上，相比之下 ω_{lz} 的残差小很多；视轴转动角速率 ω_{ly} 的残差在入射角为 45° 时最小，此时视轴转动角速率 ω_{ly} 残差与基座扰动角速率之比小于 0.164%，同时视轴转动角速率 ω_{lz} 残差与基座扰

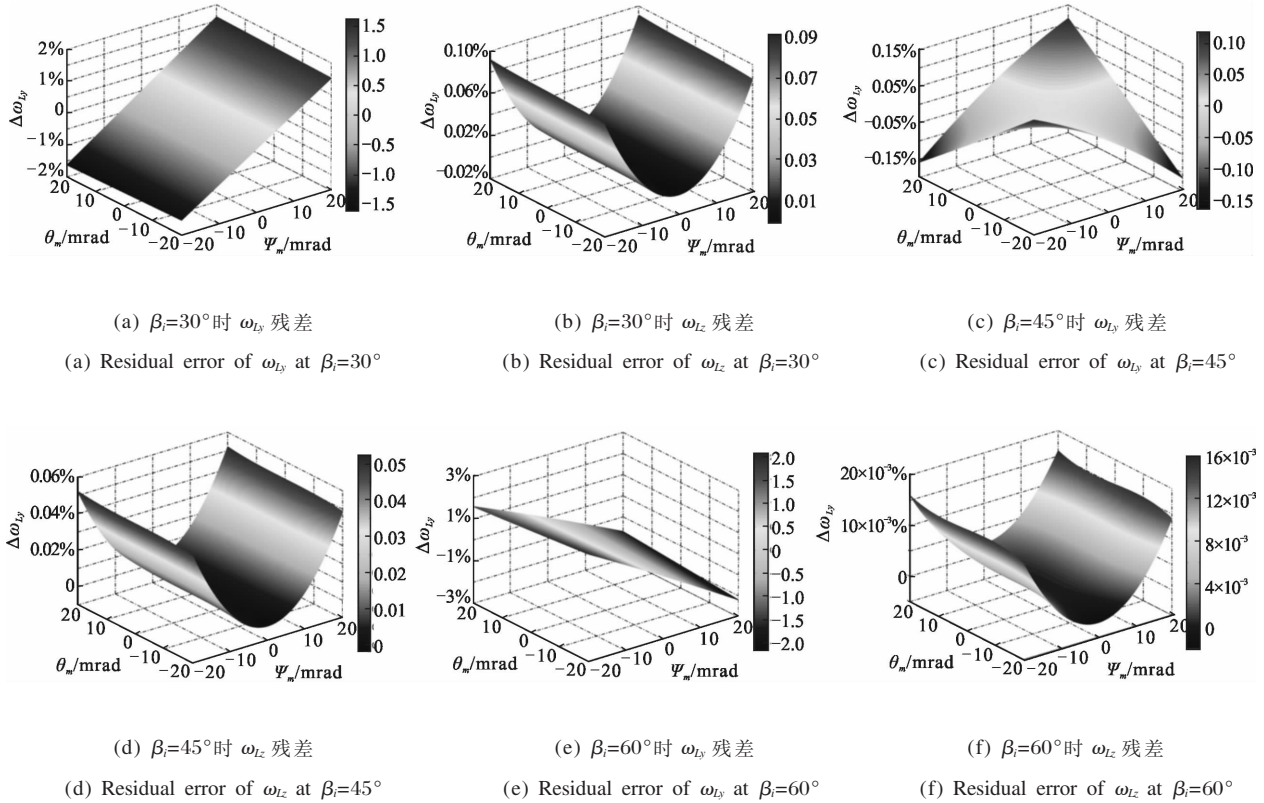


图 7 β_i 为 30° 、 45° 、 60° 时非线性补偿下视轴转动角速率残差

Fig.7 Residual error of LOS rate with non-linear model when β_i is 30° , 45° , 60°

动角速率之比小于 0.05%，可满足计算精度的要求。

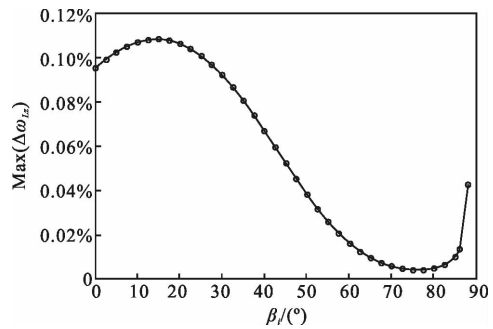
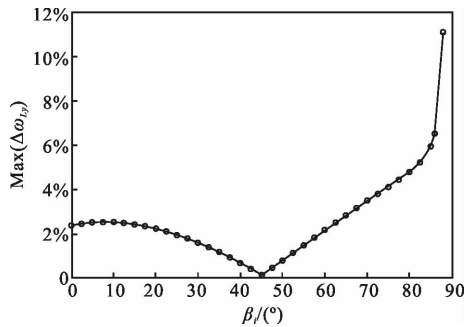


图 8 非线性补偿下视轴转动角速率最大残差

Fig.8 Maximum residual error of LOS rate with non-linear model

5 结论

文中详细推导了两轴快速反射镜转角与视轴指向角间的运动学耦合方程,分析了线性近似、非线性校正下的视轴指向误差。为补偿基座扰动角速率,保证视轴稳定,建立了两轴快反镜转动角速率方程,指出在入射角为 45° 时补偿误差最小,对光路设计中反射镜入射角的选择具有指导意义,同时为快速反射镜伺服控制系统位置、速度指令生成提供理论依据。

参考文献:

- [1] Peng Shuping, Yu Hongjun, Wang Weiguo, et al. Design of servo system for novel fast-steering mirror [J]. *Infrared and Laser Engineering*, 2014, 43(5): 1610–1615. (in Chinese)
- [2] Shi Jingjing, Yao Baidong, Lu Jiaguo. Modeling and transfer function identification of FSM system[J]. *Infrared and Laser Engineering*, 2013, 42(10): 2748–2752. (in Chinese)
- [3] Xu Xinhang, Gao Yunguo, Yang Hongbo, et al. Large-diameter fast steering mirror on rigid support technology for dynamic platform [J]. *Optics and Precision Engineering*, 2014, 22(1): 117–124. (in Chinese)
- [4] Zhou Ziyun, Gao Yunguo, Shao Shuai, et al. Design of fast steering mirror using flexible hinge [J]. *Optics and Precision Engineering*, 2014, 22(6): 1547–1554. (in Chinese)
- [5] Yang Dong, Mao Yao, Ding Ke, et al. Application of model reference adaptive algorithm in fast-steering mirrors [J]. *Infrared and Laser Engineering*, 2013, 42(10): 2790–2795. (in Chinese)
- [6] Royalty J M B. Line-of-sight kinematics for a two-axis hear mirror [C]//SPIE, 2009, 7338: 733804.
- [7] Song Jiangpeng, Sun Guangli, Zhou Di, et al. Line-of-sight stabilization techniques for mirror electro-optical platform [J]. *Infrared and Laser Engineering*, 2015, 44(6): 1904–1911. (in Chinese)
- [8] Song Jiangpeng, Sun Guangli, Zhou Di, et al. Line-of-sight stabilization and modeling analysis of bias shafting mirror platform [J]. *Infrared and Laser Engineering*, 2015, 44(8): 2484–2490. (in Chinese)
- [9] Wu Chunnan, Lin Zhaorong, Wang Zhe. Rate equations for mirror tracking system with unconventional sensor-to-gimbal orientation [J]. *Opto-Electronic Engineering*, 2014, 41(11): 23–28. (in Chinese)
- [10] Lange D A. Optical line-of-sight steering using gimbaledd mirrors [C]//SPIE, 2014, 9076(5): 303–309.
- [11] Wu Fan, Wang Dapeng. Analysis of scanning traces characteristics of the two-axis pointing mirror in the mode of scanning in given area [J]. *Electro-Optic Technology Application*, 2009, 24(4): 16–20. (in Chinese)
- [12] Peng Shuping, Chen Tao, Liu Tingxia, et al. Reflection process of fast-steering mirror of laser launching system[J]. *Optics and Precision Engineering*, 2015, 23(2): 378–386. (in Chinese)
- [13] Hilkert J M. Line-of-sight kinematics and corrections for fast-steering mirror used in precision pointing and tracking systems[C]//SPIE, 2014, 9076: 90760F.
- [14] Li Hongguang, Ji Ming, Shou Shaojun, et al. Complex axes stabilization theory of optics-electricity system with upside mirror [J]. *Infrared and Laser Engineering*, 2016, 45(7): 0731002. (in Chinese)