

基于界栅的日地平动点编队飞行碰撞规避控制研究

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摘要:在航天器编队任务时,某颗航天器发生故障或者编队任务发生改变就需要对编队进行重构。在重构过程中,如何进行航天器防碰已经受到了广泛关注。采用界栅理论(barrier),通过建立 Hamilton 函数,并取得最优控制律,再根据界栅构造理论构造出界栅轨迹,将对策区分为碰撞区与非碰撞区,从而实现日地平动点编队飞行防碰撞设计。经过仿真实验表明,该方法可避开摄动影响,并对飞行器编队队形重构过程航天器间防碰具有一定的意义。

关键词:编队飞行;界栅理论;日地平动点;微分对策;Hamilton

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航天器编队飞行的研究工作从 20 世纪 90 年代末开始就没有间断过,特别是近些年随着小卫星技术的发展,成为了研究热点。目前国际上已经有不少的空间科学实验任务采用航天器编队飞行来实现,比较典型的有美国 NASA 的 A-Train 计划、MMS 计划^[1-2]等。

航天器编队飞行技术的一大特点是多颗小航天器在空间组成特定的构形协同工作,密切联系,以分布方式构成一颗大的“虚拟航天器”(或称为“分布式卫星系统”)^[3-5],从而产生系统理论中的“涌现”现象^[3-5],在性能上超越单颗航天器系统。

在编队飞行中,由于各种摄动的影响,将会使编队构型产生漂移,而且由于各种硬件、软件故障的问题,都会增加编队飞行过程中航天器碰撞概率。如何避免编队航天器之间的碰撞成为卫星编队飞行设计中必须考虑的重要问题。本文通过微分对策中的界栅理论^[4]把相邻 2 个飞行器的最小距离作为约束集,建立 Hamilton 函数并得到最优控制律^[6-8],构造界栅理论及相应界栅轨迹,划分碰撞区与非碰撞区^[6-8],从而实现编队航天器防碰策略设计研究。

1 建立微分对策系统状态方程

假设仅考虑 2 颗卫星在同一平面内相对运动,即目标星为 E , 追赶星为 P , 则多颗卫星以此类推。图 1 为编队飞行追逃关系模型示意图。

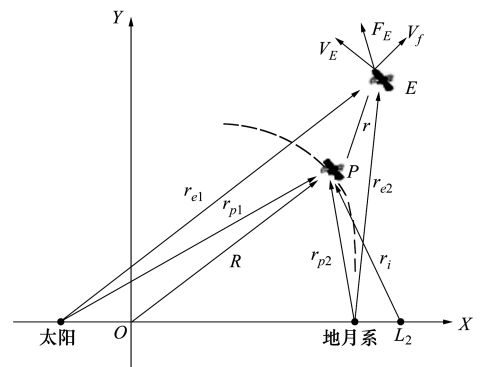


图 1 飞行器编队飞行追逃关系模型示意图

$$\begin{cases} \dot{X}_p = V_{xp} \\ \dot{Y}_p = V_{yp} \\ \dot{X}_e = V_{xe} \\ \dot{Y}_e = V_{ye} \\ \dot{V}_{xp} = -\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)X_p + \frac{F_p}{M_p}\cos v \\ \dot{V}_{yp} = -\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)Y_p + \frac{F_p}{M_p}\sin v \\ \dot{V}_{xe} = -\left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3}\right)X_e + \frac{F_e}{M_e}\cos u \\ \dot{V}_{ye} = -\left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3}\right)Y_e + \frac{F_e}{M_e}\sin u \end{cases} \quad (1)$$

式中, μ_1 为太阳开普勒常数, μ_2 为地月系开普勒常数, \mathbf{r}_{p1} 是由太阳质心指向航天器 P 的矢量, \mathbf{r}_{p2} 是由地月系质心指向航天器 P 的矢量, \mathbf{r}_{e1} 是由太阳质心指向航天器 E 的矢量, \mathbf{r}_{e2} 是由地月系质心指向航天器 E 的矢量。 F 为航天器轨控发动机推力, u 和 v 分别为推力 F_p 和 F_e 与 X 轴的夹角, M_p 与 M_e 分别为航天器 P 与航天器 E 的质量。

2 最优控制量的求解及界栅的构造

假设航天器 P 域与航天器 E 在同一平面内组成追逃模型, 星间临界碰撞距离为 l , 则对策目标约束集 D 为圆域^[9]:

$$(X_e - X_p)^2 + (Y_e - Y_p)^2 - l^2 \leq 0 \quad (2)$$

当编队航天器间相对距离大于 l , 则不会发生碰撞, 反之则发生碰撞。

根据微分对策理论, Hamilton 函数可表示如下:

$$\begin{aligned} H(X_p, X_e, Y_p, Y_e, u, v, \gamma) &= \gamma_1 V_{xp} + \gamma_2 V_{yp} + \\ &\gamma_3 \left[-\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)X_p + \frac{F_p}{M_p}\cos v \right] + \\ &\gamma_4 \left[-\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)Y_p + \frac{F_p}{M_p}\sin v \right] + \\ &\gamma_5 V_{xe} + \gamma_6 V_{ye} + \\ &\gamma_7 \left[-\left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3}\right)X_e + \frac{F_e}{M_e}\cos u \right] + \\ &\gamma_8 \left[-\left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3}\right)Y_e + \frac{F_e}{M_e}\sin u \right] = \\ &H_p + H_e + H_0 \end{aligned} \quad (3)$$

式中: $\boldsymbol{\gamma} = [\gamma_1 \ \gamma_2 \ \gamma_3 \ \gamma_4 \ \gamma_5 \ \gamma_6 \ \gamma_7 \ \gamma_8]^T \in \mathbf{R}^8$ 是任意向量; 且

$$H_p(v) = \gamma_3 \frac{F_p}{M_p} \cos v + \gamma_4 \frac{F_p}{M_p} \sin v$$

$$H_e(u) = \gamma_7 \frac{F_e}{M_e} \cos u + \gamma_8 \frac{F_e}{M_e} \sin u$$

$$H_0 = \gamma_1 V_{xp} + \gamma_2 V_{yp} - \gamma_3 \left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3} \right) X_p -$$

$$\gamma_4 \left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3} \right) Y_p + \gamma_5 V_{xe} + \gamma_6 V_{ye} -$$

$$\gamma_7 \left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3} \right) X_e -$$

$$\gamma_8 \left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3} \right) Y_e$$

因此:

$$\begin{aligned} \max_u \min_v H(X_p, X_e, Y_p, Y_e, u, v, \boldsymbol{\gamma}) &= \\ \min_v H_p(v) + \max_u H_e(u) + H_0 \end{aligned} \quad (4)$$

$$\text{令 } \frac{dH_p(v)}{dv} = 0, \text{ 即}$$

$$\frac{F_p}{M_p} (-\gamma_3 \sin v + \gamma_4 \cos v) = 0 \quad (5)$$

解得

$$\begin{cases} \sin v^* = \frac{-\gamma_4}{\sqrt{\gamma_3^2 + \gamma_4^2}} \\ \cos v^* = \frac{-\gamma_3}{\sqrt{\gamma_3^2 + \gamma_4^2}} \end{cases} \quad (6)$$

显然有

$$\frac{d^2 H_p(v^*)}{dv^2} = -(\gamma_3 \sin v^* + \gamma_4 \cos v^*) > 0 \quad (7)$$

由(6)式、(7)式确定 v^* 是航天器 P 的最优策略。类似可求得航天器 E 的最优策略 u^* , 其满足

$$\begin{cases} \sin u^* = \frac{-\gamma_8}{\sqrt{\gamma_7^2 + \gamma_8^2}} \\ \cos u^* = \frac{-\gamma_7}{\sqrt{\gamma_7^2 + \gamma_8^2}} \end{cases} \quad (8)$$

于是, 可得

$$\begin{aligned} H(X_p^*, X_e^*, Y_p^*, Y_e^*, u^*, v^*, \boldsymbol{\gamma}) &= \\ &-\frac{F_p}{M_p} \sqrt{\gamma_3^2 + \gamma_4^2} - \frac{F_e}{M_e} \sqrt{\gamma_7^2 + \gamma_8^2} + H_0 \end{aligned} \quad (9)$$

将目标集

$$\partial D = \{ (X_p, X_e, Y_p, Y_e) \mid (X_e - X_p)^2 + (Y_e - Y_p)^2 - l^2 = 0 \}$$

写成参数形式:

$$\begin{aligned} X_p(\tilde{t}) &= \phi_1(\mathbf{s}) = s_1, Y_p(\tilde{t}) = \phi_2(\mathbf{s}) = s_2, \\ V_{xp}(\tilde{t}) &= \phi_3(\mathbf{s}) = s_3, V_{yp}(\tilde{t}) = \phi_4(\mathbf{s}) = s_4, \\ X_e(\tilde{t}) &= \phi_5(\mathbf{s}) = s_1 + l \cos s_5, \\ Y_e(\tilde{t}) &= \phi_6(\mathbf{s}) = s_2 + l \cos s_5, \\ V_{xe}(\tilde{t}) &= \phi_7(\mathbf{s}) = s_3, V_{ye}(\tilde{t}) = \phi_8(\mathbf{s}) = s_4 \end{aligned}$$

式中, $\mathbf{s} = (s_1, s_2, s_3, s_4)^T$; s_5 为与 x 轴正方向的夹角, $-\pi \leq s_5 \leq \pi$; \tilde{t} 为捕获时间。

由界栅构造理论:

$$\begin{cases} \sum_{i=1}^m \gamma_i \frac{\partial \phi_i(s_1, s_2, \dots, s_{m-2})}{\partial s_j} = 0, (j = 1, 2, \dots, m - 2) \\ \boldsymbol{\gamma}^T \cdot \boldsymbol{\gamma} \mid_{\partial D} = 1 \end{cases} \quad (10)$$

由方程组 (10) 中第一个式子可得:

$$\gamma_1(\tilde{t}) + \gamma_5(\tilde{t}) = 0$$

$$\begin{aligned} \gamma_2(\tilde{t}) + \gamma_6(\tilde{t}) &= 0 \\ \gamma_3(\tilde{t}) + \gamma_7(\tilde{t}) &= 0 \\ \gamma_4(\tilde{t}) + \gamma_8(\tilde{t}) &= 0 \\ -\gamma_5(\tilde{t})l \cos s_5 + \gamma_6(\tilde{t})l \cos s_5 &= 0 \\ \gamma_1^2(\tilde{t}) + \gamma_2^2(\tilde{t}) + \gamma_3^2(\tilde{t}) + \gamma_4^2(\tilde{t}) &= \frac{1}{2} \end{aligned} \quad (11)$$

再结合方程组 (10) 中第二个式子可得 ∂D 上的单位法线向量为

$$\boldsymbol{\gamma} \mid_{\partial D} = \left(\frac{\cos s_5}{\sqrt{8}}, \frac{\sin s_5}{\sqrt{8}}, \frac{\cos s_5}{\sqrt{8}}, \frac{\sin s_5}{\sqrt{8}}, -\frac{\cos s_5}{\sqrt{8}}, -\frac{\sin s_5}{\sqrt{8}}, -\frac{\cos s_5}{\sqrt{8}}, -\frac{\sin s_5}{\sqrt{8}} \right)^T$$

显然 Hamilton 函数可写成:

$$\begin{aligned} H(X_p^*, X_e^*, Y_p^*, Y_e^*, u, v, \boldsymbol{\gamma}) &= \\ \frac{1}{\sqrt{8}} \left[Q \sin(s_5 + a) - \left(\frac{F_p}{M_p} + \frac{F_e}{M_e} \right) \right] \end{aligned} \quad (12)$$

式中:

$$\begin{aligned} Q &= \left\{ \left[V_{xp} - V_{xe} + \left(\frac{\mu_1}{\| \mathbf{r}_{e1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{e2} \|^3} \right) X_e - \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^3} \right) X_p \right]^2 + \right. \\ &\quad \left. \left[V_{yp} - V_{ye} + \left(\frac{\mu_1}{\| \mathbf{r}_{e1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{e2} \|^3} \right) Y_e - \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^3} \right) Y_p \right]^2 \right\}^{\frac{1}{2}} \\ a &= \arctan \frac{V_{xp} - V_{xe} + \left(\frac{\mu_1}{\| \mathbf{r}_{e1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{e2} \|^3} \right) X_e - \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^3} \right) X_p}{V_{yp} - V_{ye} + \left(\frac{\mu_1}{\| \mathbf{r}_{e1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{e2} \|^3} \right) Y_e - \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^3} \right) Y_p} \end{aligned}$$

以下有 3 种情况:

1) 当 $\sin(s_5 + a) > \left(\frac{F_p}{M_p} + \frac{F_e}{M_e} \right) / Q$ 时, 则整个目标边界集 ∂D 是 NUP, 不存在界栅, 航天器 P 与航天器 E 总可以发生碰撞, 整个对策空间都是碰撞区。

2) 当 $\sin(s_5 + a) < \left(\frac{F_p}{M_p} + \frac{F_e}{M_e} \right) / Q$ 时, 则整个目标边界集 ∂D 是 UP, 不存在界栅, 航天器 P 与航天器 E 总可以避开碰撞, 整个对策空间都是躲避区。

3) 当 $\sin(s_5 + a) = \left(\frac{F_p}{M_p} + \frac{F_e}{M_e} \right) / Q$ 时, 则整个目标边界集 ∂D 是 BUP, 在这种情况下, 一定存在界栅 B 。下面以对应于 BUP 上任意一点 s 为初始点倒向

构造界栅 B 。

易于得到倒向协态方程组为:

$$\begin{aligned} \frac{d\gamma_1}{d\tau} &= \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^3} \right) \cos s_5 - \\ &\quad (\cos s_5 X_p + \sin Y_p) \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^{\frac{9}{2}}} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^{\frac{9}{2}}} \right) X_p \\ \frac{d\gamma_2}{d\tau} &= \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^3} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^3} \right) \sin s_5 - \\ &\quad (\cos s_5 X_p + \sin Y_p) \left(\frac{\mu_1}{\| \mathbf{r}_{p1} \|^{\frac{9}{2}}} + \frac{\mu_2}{\| \mathbf{r}_{p2} \|^{\frac{9}{2}}} \right) Y_p \\ \frac{d\gamma_3}{d\tau} &= -\cos s_5 \end{aligned}$$

$$\begin{aligned}
 \frac{d\gamma_4}{d\tau} &= -\sin s_5 \\
 \frac{d\gamma_5}{d\tau} &= -\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)\cos s_5 - \\
 &\quad (\cos s_5 X_e + \sin Y_e)\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^{\frac{9}{2}}} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^{\frac{9}{2}}}\right)X_e \\
 \frac{d\gamma_6}{d\tau} &= -\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)\sin s_5 - \\
 &\quad (\cos s_5 X_e + \sin Y_e)\left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^{\frac{9}{2}}} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^{\frac{9}{2}}}\right)Y_e \\
 \frac{d\gamma_7}{d\tau} &= \cos s_5 \\
 \frac{d\gamma_8}{d\tau} &= \sin s_5
 \end{aligned} \tag{13}$$

相应的初始条件为:

$$\begin{aligned}
 \gamma_1(0) &= \frac{1}{2}\cos s_5, \gamma_2(0) = \frac{1}{2}\sin s_5, \\
 \gamma_3(0) &= \frac{1}{2}\cos s_5, \gamma_4(0) = \frac{1}{2}\sin s_5, \\
 \gamma_5(0) &= -\frac{1}{2}\cos s_5, \gamma_6(0) = -\frac{1}{2}\sin s_5, \\
 \gamma_7(0) &= -\frac{1}{2}\cos s_5, \gamma_8(0) = -\frac{1}{2}\sin s_5
 \end{aligned}$$

式中, $\tau = \tilde{t} - t_0$, 倒向状态微分方程组为:

$$\begin{cases}
 \frac{dX_p^*}{d\tau} = -V_{xp}^* \\
 \frac{dY_p^*}{d\tau} = -V_{yp}^* \\
 \frac{dV_{xp}^*}{d\tau} = \left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)X_p^* - \frac{F_p}{M_p}\cos v^* \\
 \frac{dV_{yp}^*}{d\tau} = \left(\frac{\mu_1}{\|\mathbf{r}_{p1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{p2}\|^3}\right)Y_p^* - \frac{F_p}{M_p}\sin v^* \\
 \frac{dX_e^*}{d\tau} = -V_{xe}^* \\
 \frac{dY_e^*}{d\tau} = -V_{ye}^* \\
 \frac{dV_{xe}^*}{d\tau} = \left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3}\right)X_e^* - \frac{F_e}{M_e}\cos u^* \\
 \frac{dV_{ye}^*}{d\tau} = \left(\frac{\mu_1}{\|\mathbf{r}_{e1}\|^3} + \frac{\mu_2}{\|\mathbf{r}_{e2}\|^3}\right)Y_e^* - \frac{F_e}{M_e}\sin u^*
 \end{cases} \tag{14}$$

以及倒向初值条件为:

$$\begin{cases}
 X_p^*(0) = s_1 \\
 Y_p^*(0) = s_2 \\
 V_{xp}^*(0) = s_3 \\
 V_{yp}^*(0) = s_4 \\
 X_e^*(0) = s_1 + l\cos s_5 \\
 Y_e^*(0) = s_2 + l\sin s_5 \\
 V_{xe}^*(0) = s_3 \\
 V_{ye}^*(0) = s_3
 \end{cases} \tag{15}$$

简单的积分可得:

$$\begin{cases}
 X_p^*(\tau) = s_1 - \tau V_{xp}^* \\
 Y_p^*(\tau) = s_2 - \tau V_{yp}^* \\
 X_e^*(\tau) = s_1 + l\cos s_5 - \tau V_{xe}^* \\
 Y_e^*(\tau) = s_2 + l\sin s_5 - \tau V_{ye}^*
 \end{cases} \tag{16}$$

则所求的界栅 \mathbf{B} 为:

$$(x_p^*(\tau) - x_e^*(\tau))^2 + (y_p^*(\tau) - y_e^*(\tau))^2 = l^2 \tag{17}$$

即为一个圆, 界栅 \mathbf{B} 把对策空间 \mathbf{R}^2 分为 2 个部分, 由 \mathbf{B} 围成的圆域(包括 \mathbf{B} 本身)为捕获区, 圆域之外的区域为躲避区。

3 实例仿真与分析

文本仿真实例的初始条件如下:

假设航天器 P 与航天器 E 的质量及大小相同, 质量均为 2 000 kg; 航天器 P 处于幅值为 900 000 km 的运行轨道上, 捕获半径为 5 km, 以日地平动点 L_2 点附近编队飞行为例, 具体的 L_2 点基本常数^[10] 如表 1 所示:

表 1 日地系统 L_2 点基本常数

类别	值
太阳开普勒常数 $\mu_1 / (\text{km}^3 \cdot \text{s}^{-2})$	1.327 124 4 × 10 ¹¹
地月系开普勒常数 $\mu_2 / (\text{km}^3 \cdot \text{s}^{-2})$	3.986 004 4 × 10 ⁵
太阳到坐标原点的距离 D_1 / km	4.902 777 9 × 10 ³
地月系到坐标原点的距离 D_2 / km	4.548 408 5 × 10 ⁸
轨道偏心率 e	0.016 708 62
平动点 L_2 点到月亮的距离 x_c / km	1.511 051 5 × 10 ⁸

航天器 P 与航天器 E 在坐标系下的位置与速度^[11-12] 分别为:

$$\begin{aligned}
X_p(0) &= 87\,028.508\,409 \text{ km} \\
X_e(0) &= 87\,028.618\,409 \text{ km} \\
Y_p(0) &= -24\,739.512\,629 \text{ km} \\
Y_e(0) &= -23\,268.613\,245 \text{ km} \\
V_{xp} &= 8.995\,877 \text{ m/s} \\
V_{yp} &= 121.605\,675 \text{ m/s} \\
V_{xe} &= 8.285\,877 \text{ m/s} \\
V_{ye} &= 120.924\,877 \text{ m/s}
\end{aligned}$$

由于编队飞行时,航天器间距较近,可忽略轨道引力,太阳光压等摄动力影响。对 Hamilton 函数进行 Matlab 仿真如图 2 所示:

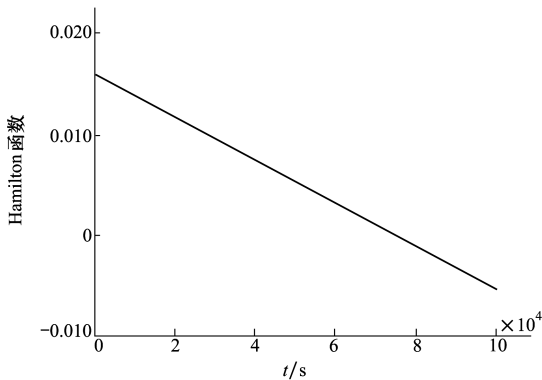


图 2 Hamilton 函数随时间变化曲线

在图 2 中,可以看到 Hamilton 函数存在大于 0、等于 0、小于 0 的情况,也就是航天器间存在非碰撞区、界栅和碰撞区。

对方程(4)做积分 $\frac{dH_p}{dF_p} = 0$ 可得最优控制推力表达式:

$$F_p^* = \frac{\gamma_3}{M_p} \cos v + \frac{\gamma_4}{M_p} \sin v \quad (18)$$

再将(13)式代入(18)式可得:

$$\begin{aligned}
F_p^* &= \frac{\sin s_5}{\sqrt{8} M_p} \cos v - \frac{\cos s_5}{\sqrt{8} M_p} \sin v = \\
&\quad - \frac{1}{\sqrt{8} M_p} \cos(s_5 + v) \quad (19)
\end{aligned}$$

经过 matlab 仿真可得航天器 P 的控制力 F_p 随倒向时间变化如图 3 所示:

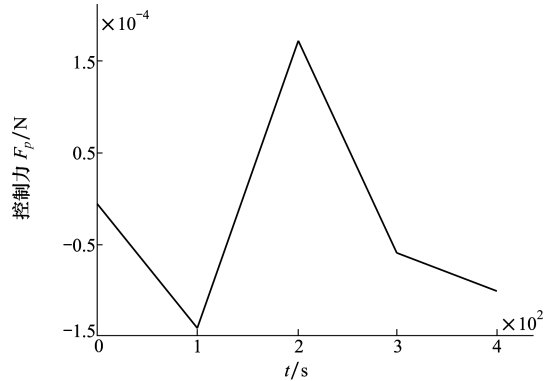


图 3 航天器 P 的控制力 F_p 随倒向时间变化曲线

在图 3 中,首先,控制力 F_p 随倒向时间的变化呈先由小变大再由大变小的循环过程,中间有反向的出现,这是由于航天器 P 在追逃过程中,两航天器的位置发生了改变造成控制力方向的变化。

4 结 论

编队飞行技术是深空探测方向的一个重要研究方向,本文将任意 2 个航天器间的最小距离作为临界距离,运用微分对策中的界栅理论将整个对策空间分为碰撞区与非碰撞区,碰撞区与非碰撞区的重叠部分即为界栅。通过对界栅区域的构造,能够保证航天器间不发生碰撞。经过实例仿真证明该方法简单可行。

参考文献:

[1] Lian Yijun, Gerard Gómez, Josep J Masdemont, et al. Station Keeping of Real Earth-Moon Libration Point Orbits Using Discrete-Time Sliding Mode Control [J]. Communications in Nonlinear Science and Numerical Simulation, 2014, 19(10): 3792-3807

[2] Josep Virgili Llop. Autonomous Optical Navigation for Orbits around Earth-Moon Collinear Libration Points[J]. Acta Astronautica, 2013, 86(5/6): 119-125

- [3] 徐明. 平动点轨道的动力学与控制研究综述[J]. 宇航学报, 2009, 30(4): 1299-1313
Xu Ming. Overview of Orbital Dynamics and Control for Libration Point Orbits[J]. Chinese Journal of Astronautics, 2009, 30(4): 1299-1313 (in Chinese)
- [4] Daren Lee, Krishna Dev Kumar, Manoranjan Sinha, et al. Fault Detection and Recovery of Spacecraft Formation Flying Using Nonlinear Observer and Reconfigurable Controller[J]. Acta Astronautica, 2014, 97(4/5): 58-72
- [5] Lü Jing, Li Junfeng, Lu Qishao, et al. Periodic Orbits Based on Geometric Structure of Center Manifold around Lagrange Points [J]. Astrophys Space, 2012, 340:17-25
- [6] 李登峰. 微分对策及其应用[M]. 北京: 国防工业出版社, 2000
Li Dengfeng. Differential Games and Applications [M]. Beijing, National Defense Industry Press, 2000 (in Chinese)
- [7] Lin W. Distributed UAV Formation Control Using Differential Game Approach[J]. Aerospace Science and Technology, 2014, 35(3): 54-62
- [8] Andrea L'fllitto. Differential Games, Partial-State Stabilization, and Model Reference Adaptive Control [J]. Journal of the Franklin Institute, 2017, 354(1): 456-478
- [9] 张秋华, 孙毅, 黄明明, 等. 近地共面轨道上两飞行器在径向连续小推力下的追逃界栅[J]. 控制与决策, 2007, 22(5): 530-534
Zhang Qiuhua, Sun Yi, Huang Mingming, et al. Pursuit-Evasion Barrier of Two Spacecrafts under Minute Continuous Radial Thrust in Coplanar Orbit[J]. Control and Decision, 2007, 22(5): 530-534 (in Chinese)
- [10] 熊攀. 日地 L2 平动点编队飞行高精度位置保持建模及控制[D]. 哈尔滨: 哈尔滨工业大学, 2011
Xiong Pan. Modeling and Control of High Precision Position Keeping for the Sun Earth L2 Point Formation Flying[D]. Harbin, Harbin Institute of Technology, 2011 (in Chinese)
- [11] Korobtsev Iv, Goryashin Ve, Eseevich Mv. Results of Tracking a Spacecraft in the Vicinity of the L2 Libration Point of the Sun-Earth System[J]. Journal of the Franklin Institute, 2017, 61(2): 153-159
- [12] He Zhenqi, Zhang Ke, Lü Meibai. Research on Control Method of Keeping Flight Formation by Using SDRE on the Sun-Earth Libration Points[J]. Advances in AstronomAdvances in Astronom, 2017, 1(1): 5-16

Research on Flight Collision Avoidance Control on The Sun-Earth Libration Points Based on Barrier Theory

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Abstract: In the spacecraft formation task, a spacecraft failure or formation of the mission to change the need for reconstruction of the formation. In the process of reconstruction, how to carry out spacecraft anti-collision has been widespread concern. In this paper, barrier theory is adopted. By establishing Hamilton function, the optimal control law is obtained. According to the theory of barrier construction, the corresponding barrier trajectory is constructed. Then, the barrier is divided into collision area and non-collision area, so as to realize the formation flight anti-collision design. The simulation results show that the method can avoid the perturbation effect and has a certain theoretical value for the anti-collision between the spacecrafts during the formation process.

Keywords: formation flight; barrier theory; sun-earth libration points, differential games; Hamiltonian