

充液柔性航天器非线性姿态动力学及再定向姿态机动*

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摘要 研究全充液柔性航天器大角度姿态机动中非线性姿态动力学及姿态再定向问题. 采用 Lagrange 方法推导了液-柔耦合系统动力学方程并对系统进行了相空间动力学研究. 由于能量耗散及柔性附件振动对系统产生扰动并由此引起混沌姿态运动, 经历姿态转换后的航天器最终姿态定向不能预先确定. 本文研究表明, 通过一对互为反向的脉冲推进可以完成预期的姿态再定向机动. 给出了实现姿态再定向机动的控制策略, 并对控制前后的姿态本体轨迹及主角动量分量时间响应历程进行了数值仿真.

关键词 非线性姿态机动, 姿态再定向, 控制策略, 充液航天器

引言

姿态预测及控制是航天器姿态动力学的重要研究课题. 数值仿真结果及 Melnikov 解析预测准则表明, 由于受液体燃料晃动及柔性附件振动的影响, 当系统参数在一定范围内取值时, 充液柔性航天器姿态运动表现出随机姿态运动及拟周期姿态运动甚至混沌姿态运动特性^[1-21]. 这样, 人们就无法事先确定航天器在完成姿态机动后的姿态定向. Gray 等学者在他们的近期研究中采用 Melnikov 方法研究了带有周期往返运动的质量块、浸没于粘性液体中的转子动量轮及柔性扭转振动的太阳帆这种复杂航天器在姿态转换机动过程中的混沌行为^[2,3]. 有大量文献报道了对充液航天器非线性姿态动力学方面的研究成果, 但有待进一步加强对航天器姿态动力学建模中液体燃料晃动动力学因素的研究^[6-9]. 许多航天器对姿态定向有一定的要求和限制. 姿态控制的目的是采取主动或被动控制策略实现这种预期的姿态定向. Barta 等许多学者对单刚体模型航天器的姿态定向控制进行了研究^[10]. Rahn 等学者对充液航天器姿态再定向进行了研究并推导了脉冲推进控制策略^[11].

本文重点研究全充液柔性自旋航天器在姿态转换机动过程中的非线性姿态动力学及姿态再定向问题. 采用 Lagrange 方法推导了耦合系统动力学方程并对其进行了无量纲化处理, 在相空间中对耦

合系统非线性动力学特性进行了研究. 为实现航天器的预期姿态定向, 推导了双脉冲推进控制策略, 并对受控本体轨迹及主角动量分量时间响应历程进行了数值仿真.

1 系统动力学方程

1.1 航天器模型描述

航天器模型含一主刚体平台 b 并携带一全充液体燃料球形贮腔和一柔性附件 (图 1 所示), 暂不考虑重力梯度及大气阻尼效应. 以整个系统的质心 c 为坐标原点建立一正交坐标架 e_1, e_2 和 e_3 . 主刚体及液体燃料关于最小惯量主轴, 中间惯量主轴及最大惯量主轴的三个转动惯量分量分别为 I_1, I_2 和 I_3 . 液体燃料简化为被粘性边界层所包围的球形刚性块, 其转动惯量用来表示. 柔性附件简化模型为一通过长度为 L 、无质量弹性杆连接于主刚体的端部集中质量 m , 其质心 c_1 的位置在沿 e_1 坐标轴方向与坐标原点距离为 d 处. 以为坐标原点建立另一附件坐标系, 其三个正交坐标轴为 ζ_1, ζ_2 和 ζ_3 , 并且 e_1 和 ζ_1 两个坐标轴共线. 在附件坐标系下, 设附件关于坐标轴 ζ_1, ζ_2 和 ζ_3 的惯量矩阵为 $\text{diag}\{A, B, C\}$. 假设燃料块相对于航天器的相对角速度为 σ_1, σ_2 和 σ_3 , 在随体坐标架中航天器主刚体 b 的角速度 ω 定义为 $\omega = \omega_1 e_1 + \omega_2 e_2 + \omega_3 e_3$. 假设柔性附件仅限于绕 e_1 轴做扭转振动并用 α 表示扭转角, 暂不考虑连接杆的弯曲及翘曲变形. 以上关于柔性附件的假设

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相当于当太阳帆受张索限制时的简化模型^[3], 此时附件的质心在航天器姿态机动时不发生变化。假定具有圆形截面的连接杆具有抗扭刚度 $K = SG/L$, 其中 S 表示面积惯性矩, G 表示剪切模量。

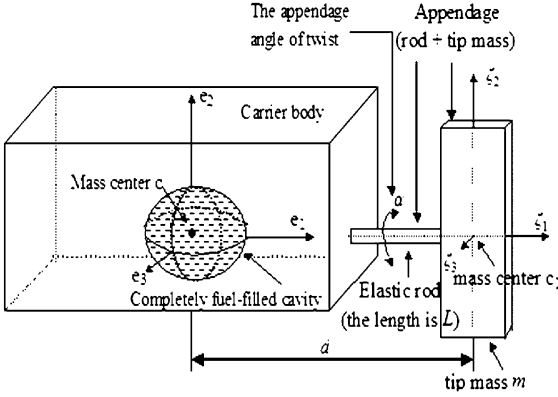


图1 带柔性附件充液航天器模型

Fig. 1 The model of liquid-filled spacecraft with flexible appendage

1.2 系统动力学方程

由 Lagrange 方程可推导出主刚体的姿态方程

$$\dot{h}_1 = \frac{1}{D_3} \{ 2(D_1 - D_2)h_2h_3 - (h_3^2 - h_2^2)(B - C) \sin 2\alpha + [2J\sigma_2(B - C) \sin 2\alpha - 2D_1J\sigma_3]h_2 + [2D_2J\sigma_2 - 2J\sigma_3(B - C) \sin 2\alpha] \} \quad (1)$$

$$\dot{h}_2 = \frac{h_1h_3 - A\dot{\alpha}h_3 - J\sigma_1h_3}{I_1 + A} - \frac{1}{D_3} \{ 2D_1h_3h_1 - 2(B - C)h_2h_1 \sin 2\alpha + [2D_2J\sigma_2 - 2J\sigma_3(B - C) \sin 2\alpha] \} \quad (2)$$

$$\dot{h}_3 = \frac{h_1h_3 - A\dot{\alpha}h_2 - J\sigma_1h_2}{I_1 + A} + \frac{1}{D_3} \{ 2D_1h_2h_1 - 2(B - C)h_3h_1 \sin 2\alpha + [2J\sigma_3(B - C) \sin 2\alpha - 2D_2J\sigma_2]h_1 \} \quad (3)$$

其中 D_1 , D_2 和 D_3 分别定义如下

$$D_1 = B + C + 2I_2 + 2md^2 + (B - C) \cos 2\alpha \quad (4)$$

$$D_2 = B + C + 2I_3 + 2md^2 - (B - C) \cos 2\alpha \quad (5)$$

$$D_3 = [(B - C) \sin 2\alpha]^2 - D_1D_2 \quad (6)$$

柔性附件的动力学方程为

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\alpha}} - \frac{\partial L}{\partial \alpha} = 0 \quad (7)$$

展开方程(15)得到

$$A(\ddot{\alpha} + \dot{\omega}_1) - B(\omega_3 \cos \alpha - \omega_2 \sin \alpha)(\omega_2 \cos \alpha + \omega_3 \sin \alpha) + C(\omega_3 \cos \alpha - \omega_2 \sin \alpha)(\omega_2 \cos \alpha + \omega_3 \sin \alpha) + K\alpha = 0 \quad (8)$$

由角动量分量表示的附件动力学方程为

$$\ddot{\alpha} = -\frac{(A + I_1)K\alpha}{AI_1} - \frac{\dot{h}_1 - J\dot{\sigma}}{I_1} + \frac{E(A + I_1)(B - C)}{AI_1D_3^2} \quad (9)$$

E 定义如下

$$E = [(4B + 4I_2 + 4md^2)h_3 \cos \alpha - (4B + 4I_3 + 4md^2)h_2 \sin \alpha + (4B + 4I_3 + 4md^2)J\sigma_2 \sin \alpha - (4B + 4I_2 + 4md^2)J\sigma_3 \cos \alpha] \cdot [(4C + 4I_3 + 4md^2)h_2 \cos \alpha + (4C + 4I_3 + 4md^2)h_3 \sin \alpha - (4C + 4I_3 + 4md^2)J\sigma_2 \cos \alpha - (4C + 4I_3 + 4md^2)J\sigma_3 \sin \alpha] \quad (10)$$

由角动量表示的充液燃料的动力学方程为

$$\ddot{\sigma}_1 = \frac{1}{D_3} \{ [2D_1h_3\sigma_2 - 2(B - C)h_2\sigma_2 \sin 2\alpha - 2D_1J\sigma_3\sigma_2 + 2J\sigma_2^2(B - C) \sin 2\alpha] - [2D_2h_2\sigma_3 - 2(B - C)h_3\sigma_3 \sin 2\alpha - 2D_2J\sigma_3\sigma_2 + 2J\sigma_3^2(B - C) \sin 2\alpha] \} - \frac{h_1 - A\ddot{\alpha} - J\dot{\sigma}_1}{I_1 + A} - \frac{\mu\sigma_1}{J} \quad (11)$$

$$\ddot{\sigma}_2 = -\frac{1}{D_3} [2D_1h_3\sigma_1 - 2(B - C)h_2\sigma_2 \sin 2\alpha - 2D_1J\sigma_3\sigma_1 + 2J\sigma_2\sigma_1(B - C) \sin 2\alpha] + \frac{h_1 - A\dot{\alpha} - J\sigma_1}{I_1 + A} \sigma_3 - \frac{\dot{S}_1D_3 - S_1\dot{D}_3}{D_3^2} - \frac{\mu\sigma_2}{J} \quad (12)$$

$$\ddot{\sigma}_3 = -\frac{1}{D_3} [2D_2h_2\sigma_1 - 2(B - C)h_3\sigma_1 \sin 2\alpha - 2D_2J\sigma_2\sigma_1 + 2J\sigma_3\sigma_1(B - C) \sin 2\alpha] + \frac{h_1 - A\dot{\alpha} - J\sigma_1}{I_1 + A} \sigma_2 - \frac{\dot{S}_2D_3 - S_2\dot{D}_3}{D_3^2} - \frac{\mu\sigma_3}{J} \quad (13)$$

其中 μ 表示粘性边界层的阻尼效应, S_1 和 S_2 分别定义如下

$$S_1 = 2D_2h_2 - 2(B - C)h_3 \sin 2\alpha - 2D_1J\sigma_2 + 2J\sigma_3(B - C) \sin 2\alpha \quad (14)$$

$$S_2 = 2D_1h_3 - 2(B - C)h_2 \sin 2\alpha - 2D_1J\sigma_3 + 2J\sigma_2(B - C) \sin 2\alpha \quad (15)$$

方程(1-3), (9) 和(11-13) 给出系统的全部动力学方程。

1.3 无量纲化动力学方程

特定义如下所示的尺度化无量纲量:

$$\varepsilon \triangleq \frac{md^2}{I_2}, \quad \tau = \frac{ht}{I_2}, \quad \bar{h}_i = \frac{h_i}{h}, \quad \bar{h}'_i \triangleq \frac{I_2}{h^2} \dot{h}_i$$

$$r_1 \triangleq \frac{I_3}{I_2} > 1, \quad r_2 \triangleq \frac{I_1}{I_2} < 1, \quad \tilde{\mu} \triangleq \frac{\mu}{h}, \quad \tilde{\sigma} \triangleq \frac{I_2}{h\sqrt{\varepsilon}} \sigma_i,$$

$$\begin{aligned}\tilde{\sigma}'_i &\triangleq \frac{I_2}{h^2 \sqrt{\varepsilon}} \dot{\sigma}'_i, \quad \tilde{\Omega} \triangleq \frac{\Omega I_2}{h}, \quad r_3 \triangleq \frac{A}{B}, \quad \tilde{J} \triangleq \frac{J}{I_2 \sqrt{\varepsilon}}, \\ \tilde{G}_1 &\triangleq \frac{B}{md^2}, \quad \tilde{G}_2 \triangleq \frac{C}{md^2}, \quad \tilde{K}_1 \triangleq \frac{K I_2}{h^2 \varepsilon}, \quad \frac{d}{d\tau} \triangleq \left(\frac{I_2}{h}\right) \frac{d}{dt}\end{aligned}$$

其中 $(\prime) = d(\prime)/d\tau$ 代表对无量纲时间变量 τ 的导数. 假定 $I_1 < I_2 < I_3$, 则有 $0 < r_2 < 1 < r_1$. 将以上无量纲量代入系统方程并将其关于 ε 进行泰劳级数展开可得到系统的如下无量纲耦合方程:

$$\begin{aligned}\tilde{h}'_1 &= [(1-r_1)/r_1] \tilde{h}_2 \tilde{h}_3 + \varepsilon \{ [(r_1^2-1)(G_1+G_2+2)/2r_1^2] \tilde{h}_2 \tilde{h}_3 / r_1^2 - \tilde{h}_2 \tilde{J} \tilde{\sigma}'_3 / r_1 + \tilde{J} \tilde{h}_3 \tilde{\sigma}'_2 \} + o(\varepsilon^2)\end{aligned}\quad (16)$$

$$\begin{aligned}\tilde{h}'_2 &= [(r_1-r_2)/r_1 r_2] \tilde{h}_1 \tilde{h}_3 + \varepsilon \{ [((G_1+G_2+2)(r_2^2+2r_1 r_2^2) - 2r_1^2 G_1 r_3)/2r_1^2 r_2^2] \tilde{h}_1 \tilde{h}_3 / r_1^2 - G_1 r_3 \alpha' \tilde{h}_3 + \tilde{J} \tilde{h}_1 \tilde{\sigma}'_3 / r_1 - \tilde{J} \tilde{\sigma}'_1 \tilde{h}_3 / r_2 \} + o(\varepsilon^2)\end{aligned}\quad (17)$$

$$\begin{aligned}\tilde{h}'_3 &= [(r_2-1)/r_1 r_2] \tilde{h}_1 \tilde{h}_2 + \varepsilon \{ [(2r_1^2 G_1 r_3 - (G_1+G_2+2)(r_2^2+2r_1 r_2^2))/2r_1^2 r_2^2] \tilde{h}_1 \tilde{h}_2 / r_2 + G_1 r_3 \tilde{h}_2 \alpha' / r_2 - \tilde{J} \tilde{h}_1 \tilde{\sigma}'_2 + \tilde{J} \tilde{\sigma}'_1 \tilde{h}_2 / r_2 \} + o(\varepsilon^2)\end{aligned}\quad (18)$$

$$\alpha'' = -[\tilde{K}/(G_1 r_3)] \alpha + [(r_1-1)/(r_1 r_2)] \tilde{h}_2 \tilde{h}_3 + o(\varepsilon^2)\quad (19)$$

$$\begin{aligned}(\sqrt{\varepsilon} - \varepsilon \tilde{J}/r_2) \tilde{\sigma}'_1 &= -\tilde{h}'_1 / r_2 - \tilde{\mu} \tilde{\sigma}'_1 / \tilde{J} + \sqrt{\varepsilon} \tilde{h}_3 \tilde{\sigma}'_2 / r_2 + \varepsilon [G_1 r_3 \alpha'' / r_2 - G_1 r_3 \tilde{h}'_1 / r_2] + o(\varepsilon^2)\end{aligned}\quad (20)$$

$$\begin{aligned}(\sqrt{\varepsilon} - \varepsilon \tilde{J}/r_1) \tilde{\sigma}'_2 &= -\tilde{h}'_2 - \tilde{\mu} \tilde{\sigma}'_2 / \tilde{J} + \sqrt{\varepsilon} [-\tilde{h}_3 \tilde{\sigma}'_1 / r_1 + \tilde{h}'_1 \tilde{\sigma}'_3 / r_2] + \varepsilon [(G_1+G_2+2) \tilde{h}'_2 / 2] - \sqrt{\varepsilon} (r_3 G_1 \alpha' + \tilde{J} \tilde{\sigma}'_1) \tilde{\sigma}'_3 / r_2 + o(\varepsilon^2)\end{aligned}\quad (21)$$

$$\begin{aligned}(\sqrt{\varepsilon} - \varepsilon \tilde{J}/r_1) \tilde{\sigma}'_3 &= -\tilde{h}'_3 / r_1 - \tilde{\mu} \tilde{\sigma}'_3 / \tilde{J} - \sqrt{\varepsilon} [\tilde{h}_2 \tilde{\sigma}'_1 + \tilde{h}'_1 \tilde{\sigma}'_2 / r_2] - \varepsilon [(G_1+G_2+2) \tilde{h}'_3 / 2r_1^2] + \sqrt{\varepsilon} (r_3 G_1 \alpha' + \tilde{J} \tilde{\sigma}'_1) \tilde{\sigma}'_2 / r_2 + o(\varepsilon^2)\end{aligned}\quad (22)$$

由 $\varepsilon=0$ 可得出与方程体系(16-22)相应的无扰系统的状态方程. 由此可将系统的两个子系统(16-18)和(19-22)解耦, 得到与方程(16-18)对应的无扰系统

$$\tilde{h}'_1 = \frac{1-r_1}{r_1} \tilde{h}_2 \tilde{h}_3 \quad (23)$$

$$\tilde{h}'_2 = \frac{r_1-r_2}{r_2 r_1} \tilde{h}_1 \tilde{h}_3 \quad (24)$$

$$\tilde{h}'_3 = \frac{r_2-1}{r_2} \tilde{h}_1 \tilde{h}_2 \quad (25)$$

其中无量纲随体角动量分量 \tilde{h}_1 、 \tilde{h}_2 和 \tilde{h}_3 , 构成相空间坐标架, 系统存在六个平衡点 $\{(\pm 1, 0, 0)$,

$(0, \pm 1, 0)$, $(0, 0, \pm 1)\}$; $(\pm 1, 0, 0)$ 和 $(0, 0, \pm 1)$ 分别为对应小惯量轴和最大惯量轴的稳定中心平衡点; $(0, \pm 1, 0)$ 为对应于中间惯量轴的不稳定双曲鞍点. 图2-4为在取不同初始条件下所进行的

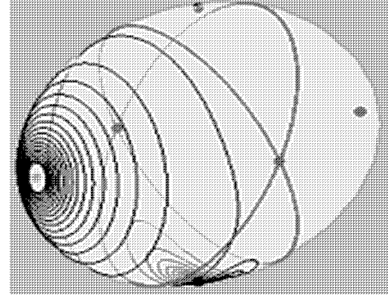


图2 随体坐标系中角动量向量从绕正向最小动量主轴机动到最大负向动量主轴
Fig.2 The path of the angular momentum vector in body coordinates starts with a positive minor axis spin and finishes with negative major axis spin

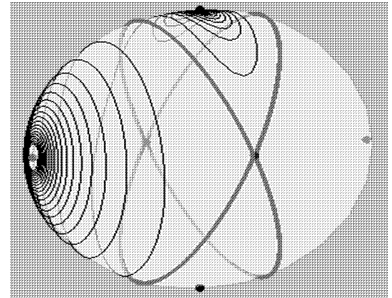


图3 随体坐标系中角动量向量从绕正向最小动量主轴机动到最大正向动量主轴
Fig.3 The path of the angular momentum vector in body coordinates starts with a positive minor axis spin and finishes with positive major axis spin

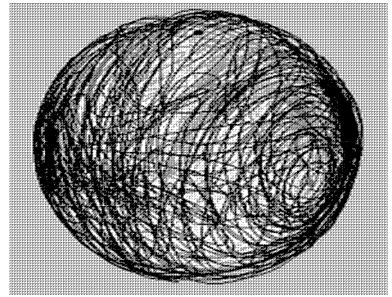


图4 随体坐标系中角动量向量从绕正向最小动量主轴机动而产生混沌姿态
Fig.4 The path of the angular momentum vector in body coordinates starts with a positive minor axis spin and finishes with chaotic spin

数值仿真结果, 结果清楚表明航天器姿态最终极性对初值的敏感性. 图中显示出在角动量相空间 \tilde{h}_1

$-\tilde{h}_2 - \tilde{h}_3$ 中的位于角动量球上的本体轨迹, 连接 \tilde{h}_2 上两鞍点轴的两个大圆表示无扰情形下的异宿环. 图 2 表示航天器由正向最小角动量坐标轴自旋最终定向于负向最大角动量坐标轴. 图 3 表示航天器由正向最小角动量坐标轴自旋最终定向于正向最大角动量坐标轴. 图 4 则表示航天器在姿态转换中出现混沌姿态, 而不能确定航天器的最终旋转极性.

2 航天器姿态再定向控制策略及实现

为了实现航天器预期的最终姿态定向, 设定以下的控制策略. 起初, 假设航天器姿态运动为以小章动角绕小角动量轴旋转. 由于存在能量耗散及扰动, 航天器姿态运动逐渐进入水平螺旋状态. 当本体轨迹穿越分支线时, 可根据最小角动量的符号对航天器旋转极性进行判断. 如果航天器姿态定向符合要求, 则不实施控制. 如果航天器姿态定向不符合要求, 则实施控制. 首先第一次脉冲推进使本体轨迹穿越分支线, 经过短暂过渡, 实施第二次的反方向脉冲推进使本体轨迹再次穿越分支线并达到所期望的姿态定向从而完成航天器姿态的再定向. 脉冲推进量可按以下公式计算^[11, 12], 其中为了方便起见已省略了代表无量纲量的符号“~”:

$$i_1 = -h_1 + \text{sgn}(h_1) \sqrt{h_1^2 - \frac{I_1 h^2 (1-K)}{I_1 - KI_2}} \quad (26)$$

$$K = \frac{1 + \Delta t \left[(1/T) \left(\frac{\partial T}{\partial t} \right)_{\text{separatrix}} \right]}{1 - 3\Delta t \left[(1/T) \left(\frac{\partial T}{\partial t} \right)_{\text{separatrix}} \right]} \quad (27)$$

数值仿真结果如图 5-8 所示. 图 5 表示再定向控制策略实施前航天器主角动量变化的时间历程, 图 6 表示再定向控制策略实施后航天器主角动

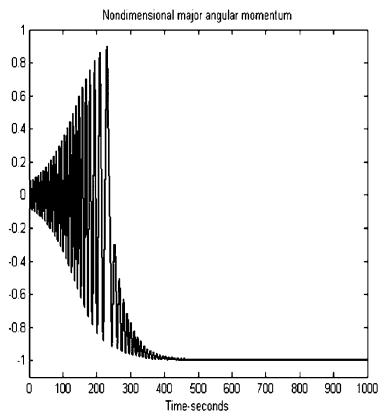


图 5 不加控制时主角动量主轴时间相应历程

Fig. 5 Uncontrolled time response of major angular momentum

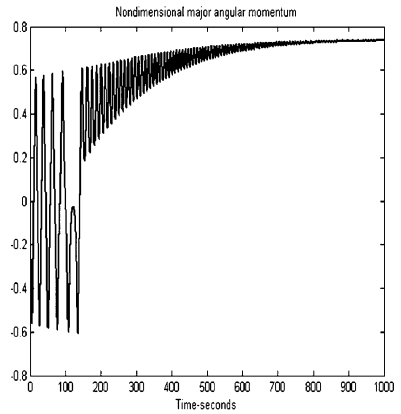


图 6 加控制时主角动量主轴时间相应历程

Fig. 6 Controlled time response of major angular momentum

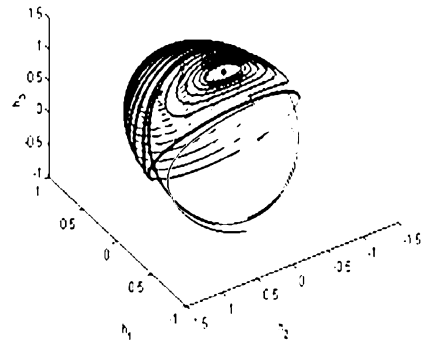


图 7 考虑自旋极性时的本体迹模拟图

Fig. 7 Polhode path simulation with spin polarity control

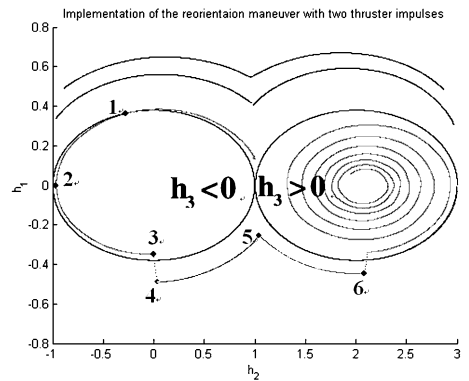


图 8 考虑自旋极性时的本体迹模拟图;

本体迹图投影到平面中以显示自旋正负极性区域

Fig. 8 Polhode path simulation with spin polarity control.

The polhode plot is projected on a plane showing both the positive and negative final polarity regions

量变化的时间历程; 图 7 表示再定向控制策略实施后航天器姿态运动在相空间 $h_1 - h_2 - h_3$ 中动量球上本体轨迹, 其中的两个大圆表示异宿环; 图 8 表示受控本体轨迹的投影图, 图中显示, 本体轨迹在标号为“1”的点第一次穿越分支线, 当 h_1 在标号为“2”的点为零时, h_3 的值将由正值变为负值. 当 h_2 在标号为“3”的点达到零值时, 第一次脉冲推进使

得本体轨迹在标号为“4”的点穿出分支线. 随后, h_3 在标号为“5”的点达到零, 预示第一次穿越分支线成功. 在标号为“6”的点, h_2 达到零值, 第二次脉冲推进使得本体轨迹传入分支线从而达到预期的姿态定向.

3 结论

本文首先采用 Lagrange 方法推导了全充液带柔性附件航天器姿态动力学方程, 然后对系统方程无量纲化并在相空间对耦合系统动力学进行了研究. 数值结果表明, 充液柔性航天器姿态运动具有对初值的敏感性, 系统动力学特性具有随机、非周期及混沌等非线性动力学特征. 结果表明: 通过互为反向的双脉冲推进控制策略可保证航天器姿态运动完成所期望的再定向控制. 确立了根据速率符号变化确定实施脉冲推进并完成本体轨迹穿越分支线的航天器姿态再定向机动控制策略. 给出了基于航天器能量耗散理论为基础, 计算脉冲推进大小的计算公式. 对控制前后的姿态本体轨迹及主角动量分量时间响应历程进行了数值仿真.

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NONLINEAR ATTITUDE DYNAMICS AND REORIENTATION MANEUVER FOR COMPLETELY LIQUID-FILLED FLEXIBLE SPACECRAFT *

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Abstract This paper investigated the problem of chaotic attitude and reorientation maneuver for completely viscous liquid-filled spacecraft with flexible appendage. All the equations of motion were derived by using Lagrangian mechanics and transformed into the form consisting of an unperturbed part plus perturbed term in order to exploit the system's nonlinear characteristics in phase space. We emphasize on the chaotic attitude dynamics produced from certain sets of the physical parameter values of the spacecraft when energy dissipation acts to derive the body from minor to major axis spin. The orientation of the spacecraft relative to the inertially fixed angular momentum vector is unpredictable because of the occurrence of chaotic dynamics during spin-axis transition. This paper demonstrated that the desired reorientation maneuver was guaranteed by using a pair of thruster impulses. The control strategy for reorientation maneuver was designed, and the numerical simulation results were presented for both the uncontrolled and controlled spins transition.

Key words nonlinear attitude dynamics, attitude reorientation maneuver, control strategy, liquid-filled spacecraft