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绳系卫星编队动力学及控制研究进展*

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摘要 对空间绳系卫星编队构形进行了分类,阐述了编队构形的稳定性特征. 对系统自旋运动、系绳振动及 L_2 平动点附近周期运动进行分析,指出系统展开/回收过程、卫星刚体姿态的动力学行为及控制方法. 最后,对绳系卫星编队系统的研究及发展进行概括和总结.

关键词 绳系卫星, 编队构形, 稳定性, 动力学行为, 控制

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引言

绳系系统作为空间探索的一种新型飞行器,在深空探测、样本采集、软攻防等领域具有广阔的应用前景[1-4]. 多体绳系卫星编队是绳系系统技术的重要扩展,由于具有可靠性强、稳定性高、成本低、易于重构等特征[5-7],使其在空间运输、极光观测、三维探察及干涉测量等方面被广泛重视[8-11].

多体绳系卫星编队是由两体绳系卫星系统演化而来,通常由多个卫星或航天器在空间范围内相对静止地组成某种特定的构形,同时星体间通过特制系绳连接,如图 1 所示. 一般地,多体绳系卫星是进入预定空间轨道后再按照一定的任务要求展开成相应的编队构形,此外,还可以根据任务需求及变化进行编队重构.

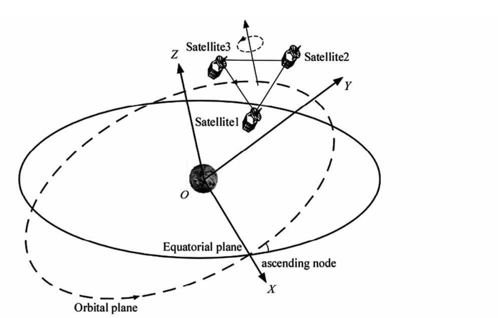

图 1 多体绳系卫星编队系统

Fig. 1 The multi-tethered satellite formation system

绳系卫星编队所处空间环境特殊、自身构形种类繁多、柔性系绳动力学特性复杂,需要对编队构形及稳定性、周期运动、展开/回收动力学及控制、卫星刚体姿态的影响等开展研究.

1 编队构形及稳定性

空间多体绳系卫星系统以一定的编队构形在轨飞行,按照编队所占据的空间维度,系统构形可分为一维、二维及三维构形. 一维构形,即编队系统中所有卫星都分布在一条直线上[12],如图 2 所示;二维构形,是指系统中全部卫星皆处于同一平面内,研究较多的构形有环形[13]、开轴-辐形[14]、闭轴-辐形[15]及 TetraStar 构形[16]等,如图 3 所示;三维构形,指的是系统中所有卫星不在同一平面内,此类构形较为复杂,典型的有四面体形[17]、双四面体形[18]、双金字塔形[19]等,如图 4 所示. 此外,还有一些其它构形也同样受到关注[20-24].

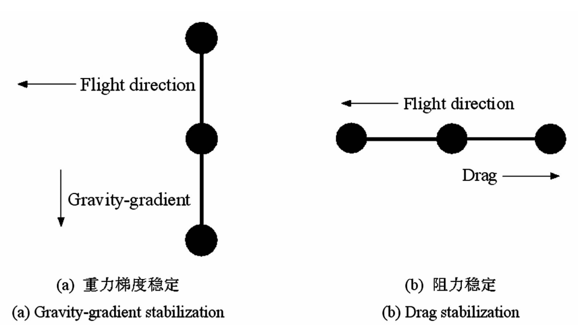

图 2 一维构形

Fig. 2 One-dimensional configuration

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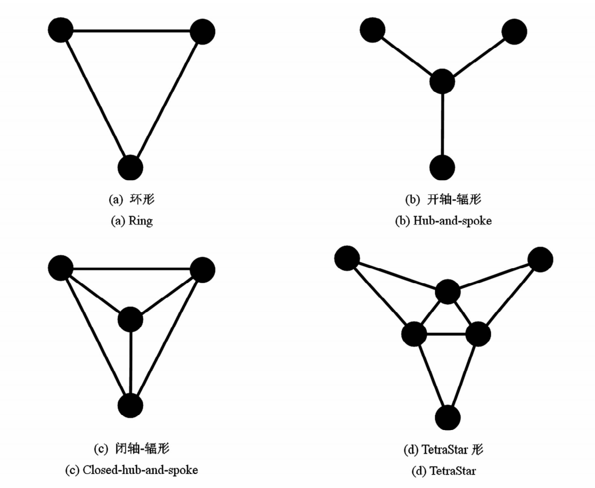
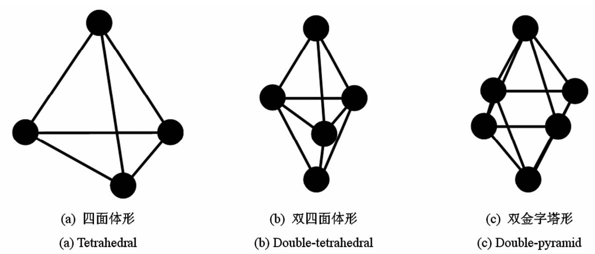


(a) 环形 (a) Ring　(b) 开轴-辐形 (b) Hub-and-spoke
(c) 闭轴-辐形 (c) Closed-hub-and-spoke　(d) TetraStar 形 (d) TetraStar

图3　二维构形

Fig. 3　Two-dimensional configuration

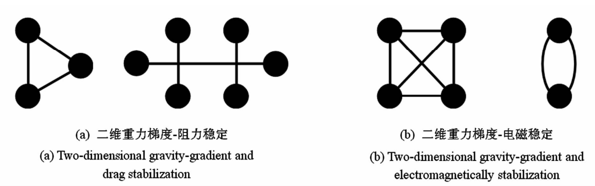


(a) 四面体形 (a) Tetrahedral　(b) 双四面体形 (b) Double-tetrahedral　(c) 双金字塔形 (c) Double-pyramid

图4　三维构形

Fig. 4　Three-dimensional configuration

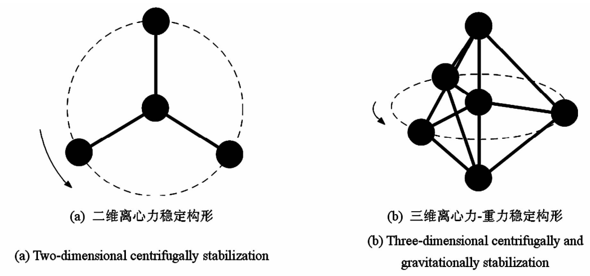
若按照绳系卫星编队的稳定飞行形式,系统还可分为静态构形和动态构形[25]. 对于静态构形,系统编队与轨道坐标系保持相对静止. 静态构形主要包括一维重力梯度稳定构形,如图2(a)所示;一维阻力稳定构形,如图2(b)所示;二维重力梯度-阻力稳定构形,如图5(a)所示;二维重力梯度-电磁力稳定构形,如图5(b)所示. 而对于动态构形,系统编队相对于轨道坐标系旋转,即飞行编队是通过系统自旋从而使系绳拉紧以达到稳定的目的. 动态构形主要包括二维离心力稳定构形,如图6(a)所示;三维离心力-重力稳定构形,如图6(b)所示. 需指出的是,以上提及的动态平衡构形其旋转轴通常都是指向地球表面或垂直于轨道平面.



(a) 二维重力梯度-阻力稳定 (a) Two-dimensional gravity-gradient and drag stabilization
(b) 二维重力梯度-电磁稳定 (b) Two-dimensional gravity-gradient and electromagnetically stabilization

图5　静态构形

Fig. 5　Static configuration

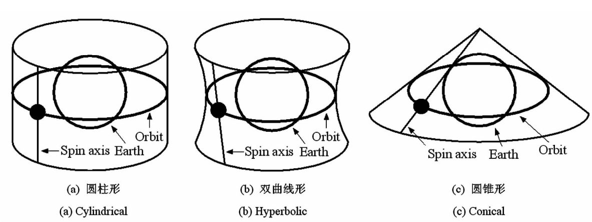


(a) 二维离心力稳定构形 (a) Two-dimensional centrifugally stabilization
(b) 三维离心力-重力稳定构形 (b) Three-dimensional centrifugally and gravitationally stabilization

图6　动态构形

Fig. 6　Dynamic configuration

除此以外,还存在一类较为特殊的相对平衡构形,即以 Likins-Pringle 相对平衡为基线的编队构形[26,27]. Likins-Pringle 平衡又可分为三种相对平衡状态,即编队构形分别呈圆柱形、双曲线形及圆锥形. 这三种构形的旋转轴相对于轨道坐标系保持固定,且角速率与轨道平均角速率相同,其中,圆柱形的旋转轴垂直于轨道平面,如图7(a)所示;双曲线形的旋转轴垂直于当地垂线,如图7(b)所示;圆锥形的旋转轴垂直于轨道切线,如图7(c)所示.



(a) 圆柱形 (a) Cylindrical　(b) 双曲线形 (b) Hyperbolic　(c) 圆锥形 (c) Conical

图7　相对平衡

Fig. 7　Relative equilibrium

对于以上三种相对平衡构形,若采用三维环形绳系卫星编队,圆柱形和双曲线形的自旋轴将垂直于天底方向,故编队在地球上的投影是一条线,这不适合编队系统进行地球观测;而圆锥形绳系卫星编队的自旋轴则是垂直于轨道切线的,在地球表面的投影是一个椭圆形,这可以增大对地观测范围,所以此圆锥形相对平衡构形被较多采用[28].

由于绳系卫星编队构形较为复杂,人们对系统稳定性的研究虽然取得了一些进展,但仍存在不小的局限性. 如学者们仅从数值角度论证了,除直线形构形外绝大多数空间编队是自旋稳定的;当自旋平面与轨道平面重合或垂直时,不同卫星数目的开(闭)轴-辐形编队在一定自旋角速率下都可以实现自旋稳定,但此自旋角速率阀值与卫星数目、自旋倾角等重要的系统参数关系尚不明确;Likins-Pringle 相对平衡构形并非是 Lyapunov 意义下的稳定

等. 常见绳系卫星编队构形及稳定性如表 1 所示.

表 1　常见绳系卫星编队构形及稳定性

Table 1　Formation configuration and stability of tethered satellite

Configuration	Dimension	Stability	Figure
Linear array	1	static stable[25], spinning stable[29]	Fig. 2
Trianglar(in orbital plane)	2	spinning stable[30]	Fig. 3(a)
Y-configuration (hub-and-spoke)	2	spinning stable[7]	Fig. 3(b)
Cross(hub-and-spoke)	2	unstable[7]	Fig. 8(a)
Cross (closed-hub-and-spoke)	2	spinning stable[7]	Fig. 8(b)
Pentagon (closed-hub-and-spoke)	2	spinning stable[7]	Fig. 8(c)
TetraStar	2	unstable[16]	Fig. 3(d)
Double-tetrahedral	3	unstable[18]	Fig. 4(b)
Double-pyramid (Earth-oriented)	3	spinning stable[15]	Fig. 4(c)
Likins-Pringle equilibrium	3	spinning stable[18]	Fig. 7

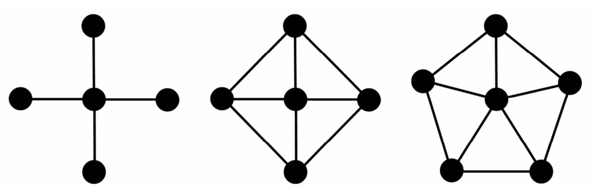


图 8　轴-辐形构形

Fig. 8　Hub-and-spoke configuration

2　动力学与控制

绳系卫星编队系统的动力学与控制研究成果丰富，不过在系统基础方程的建立上还是相对统一的. 譬如，系统模型构建及动力学响应研究通常使用第二类 Lagrange 方程或 Newton 第二定律[31-32]；讨论卫星刚体姿态问题时经常涉及动量矩定理[33]等. 最近，有学者提出利用图论方法研究系统编队的复杂构形[34].

2.1　周期运动

空间多体绳系卫星编队系统存在着丰富的动力学行为，主要有两类运动颇受学者们关注，即围绕系统质心的自旋运动和类似单摆的系绳振荡. 关于系统自旋运动稳定性的主要研究成果已列于表 1，其中 Pizarro-Chong 等在数值研究中发现，对运行于圆周轨道的开(闭)轴-辐形绳系卫星编队，若卫星体数目不小于 4，自旋编队构形通常是稳定的[7]. Kumar等在对三角形绳系卫星编队进行数值仿真时发现，此类编队的自旋速率必须大于轨道速率的0.58倍才能保持系统在轨道平面内自旋稳定[30]. 此外，Williams 分别对三维三体和双金字塔形两类绳系卫星编队进行了讨论，通过利用系绳拉伸进行最优控制实现了系统转轴朝地的周期自旋运动[35-36].

同时，系绳振荡也受到人们的持续关注. 比如，Modi 等分别将系绳考虑为刚性杆和柔性体模型，深入研究了多体绳系卫星编队中系绳的横向与纵向、面内与面外振荡[37-39]. Arrell 等论述了对深空旋转绳系干涉仪研究的初步结果，采用偏移控制和 yo-yo 控制抑制系绳的面内和面外振荡，同时提出利用系绳动力学实现绳系干涉仪的重新定位[40]. Nakanishi 等运用 Lyapunov 指数、Poincaré 映射、van del Pol平面等多种非线性方法，分析了椭圆轨道下多体绳系卫星编队中系绳周期运动的稳定性[41]. Kojima 等提出了一种“群电动绳系卫星”系统，这种新型编队可在所谓的“磁盘”轨道上实现轨道面外飞行，也可利用电动绳实现面内运动，而且通过同步控制能够使系绳做 4p-周期的运动[42]. Fedi 等考虑重力梯度及系绳拉力的影响，数值分析了轨道面内(外)开(闭)轴-辐形及双金字塔形五种绳系卫星编队，讨论了系绳的横向周期振荡[43-45].

另外，基于限制性三体问题，在日-地系统中存在五个引力平衡点，即日-地平动点 L_1、L_2、L_3、L_4 和 L_5，如图 9 所示. 这些平动点附近没有重力梯度、残余大气、地磁场等外部摄动，为各类空间科学研究的展开提供了良好条件. 其中 L_1 与 L_2 两点距地球最近，且位于 L_2 平动点附近的航天器能够始终背向太阳和地球，易于保护和校准，故更适合于放置空间天文设备. 因此，绳系卫星编队在 L_2 平动点附近的力学问题也吸引了不少学者的目光，如 Wong 等重点研究了开轴-辐形绳系卫星编队在 L_2 平动点附近的动力学行为，利用线性二次型控制器对系绳的面内、面外天平摆动进行了有效抑制，还设计了一套线性反馈控制器通过调节系绳长度及角位移实现系统的螺旋展开[46-48]. 蔡志勤团队建立了三维绳系卫星编队在 L_2 平动点附近 halo 轨道的非线性多体耦合动力学方程，对系统的周期轨道运动、自旋及非自旋稳定性、面内(外)系绳振动、最优轨迹控制等诸多力学问题进行了深入探究[49-54]. 最近，他们考虑轨-姿耦合，研究了 L_2 平动点附近旋转三角形绳系卫星编队的运动稳定性，数值结果表

明自旋速率及运行轨道对系统的稳定性影响很大[55-57].

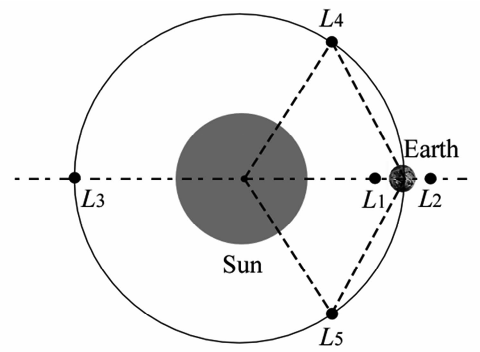


图9 日-地平动点

Fig. 9 Sun-Earth libration points

2.2 展开与回收

对于空间多体绳系卫星系统,其稳定展开直接关系到系统后期能否正常工作,另一方面,稳定回收与系统安全也是息息相关的,目前此方面也已产生较多的研究成果. 譬如,Nakaya 等基于虚拟结构法,分别利用角动量和系绳拉力生成系绳释放控制命令实现了三体环形绳系卫星编队展开,最后通过数值和地面仿真实验验证了此编队展开控制策略[58]. Kumar 等在研究轨道面内三角形及直线形绳系卫星编队的平衡条件时,也提出了一套系统展开控制策略,通过不断变化自旋速率,系统能够以一个较小的系绳释放速率稳定展开[29-30]. 此外,Kumar 等还设计了一套绳长控制律,使三体串形绳系卫星编队可以沿水平方向稳定展开/回收[59]. Williams 等基于系绳拉力控制,研究了三体环形绳系卫星编队的自旋展开问题,通过构造最优展开/回收轨迹函数以在最优机动时间下完成构形变化[60-61]. Kim 等设计了一套自适应输出反馈控制器,实现了 TetraStar 形绳系卫星编队的渐近稳定展开[62]. 刘丽丽等讨论了一类面内三体绳系卫星编队系统的最优回收控制问题,针对不同回收初值及回收初值受扰情况,数值研究了此类绳系编队的最优控制张力及飞行轨迹[63]. 基于时变的离散系绳单元,可以通过仅改变离系绳收放点最近单元的属性来仿真系绳的收放过程,并于适当时刻在离散单元链的最前端加入/移除一个单元,从而实现多体柔性绳系卫星编队展开/回收过程的数值模拟[64]. McKenzie 分析了在动量交换绳作用下空间多体绳系系统展开过程的动力学特性,讨论了轨道偏心率、系绳制动、绳长控制律等对释放过程的影响[65]. 蔡志勤等在讨论 L_2 平动点附近非自旋绳系卫星编队时发现,系绳在释放阶段的天平振动比回收时稳定得多[52]. 同时,他们采用线性系绳收放控制律,数值分析了 L_2 平动点附近三角形绳系卫星编队展开/回收过程的稳定性,同时讨论了初始旋转速率及耦合的轨道振幅对收放过程的影响[66].

2.3 刚体姿态控制

对于空间飞行的绳系卫星编队,由于内部安装有大量精密仪器或在观测时的精度要求,卫星本体的刚体姿态往往不能忽略. 如 Modi 等讨论了一类空间绳系卫星编队-平台系统的刚体动力学问题,通过 Lyapunov 方法将刚体平台控制到平衡位置[67]. 同时,他们还研究了运行于三维空间的多体绳系卫星编队,考虑柔性系绳横向及纵向振动对卫星刚体的影响,提出利用线性反馈技术和线性二次高斯/回路转换复原法对卫星刚体天平动及系绳振荡进行抑制[68]. Takeichi 等数值分析了椭圆轨道下多体绳系卫星编队的子星姿态动力学,通过 Poincaré 映射发现大气阻尼及重力梯度变化会导致处于周期运动的子星失稳[69]. Nakaya 等计入卫星姿态,使用虚拟结构法实现了自旋绳系卫星编队的构形机动[70]. Vogel 以空间遥感任务为背景,在其博士学位论文中详细描述了各类构形的多体绳系卫星编队,通过推进力、预调卷轴及拉力卷轴等完成对卫星刚体的姿态控制[71]. Chung 等先后采用线性控制、非线性控制、分散控制、同步控制,讨论了多体绳系卫星的卫星刚体姿态控制问题;此外,还介绍了已开展的空间绳系卫星编队实验器件及实施方法,展示了测试平台及初步的实验结果[11,72-76]. 文浩等通过气浮实验装置对空间绳系卫星的编队构形、收放控制、位移测量及刚体姿态进行了二维物理仿真[77],如图10所示. Chang 等采用状态相关 Riccati 法控制器对卫星刚体姿态进行误差调节,实现了三维三体绳系卫星编队的全局渐近稳定控制[78]. 黄静等考虑一类直线形三体旋转绳系卫星的参数不确定性及未知有界干扰,设计了一套分布式鲁棒最优控制器,对卫星刚体进行姿态跟踪控制[79];同时,又针对此类系统的外部有界干扰和控制饱和问题,提出一套分布式欠驱动非线性控制器,仅通过力矩作用便能使该欠驱动系统的卫星刚体姿态能够以较高的精度跟踪并达到期望状态[80].

图 10　绳系卫星编队仿真器

Fig. 10　Simulators for tethered satellite formation

3　展望

不难看出，绳系卫星编队构形及稳定性、自旋运动、系绳振动、L_2 平动点附近周期运动、系统展开/回收、卫星刚体姿态的动力学及控制研究已取得不少进展，而且空间多体绳系卫星编队因其潜在的应用前景也必将会受到更多学者的密切关注. 但是，在取得丰硕成果的同时仍有许多不足，基于以上论述，我们可将今后的研究放眼于以下几方面：

（1）高维多自由度绳系卫星编队飞行的理论分析. 目前绳系卫星编队构形的稳定性、动力学行为、控制方法等大多使用数值方法.

（2）多物理场耦合因素对系统的影响研究. 诸如 J_2 摄动、空间碎片冲击、热交变、太阳光压等空间环境对系统扰动的影响研究尚不充分.

（3）编队构形地面实验研究. 目前地面实验研究仅局限于简单绳系卫星编队，复杂编队尤其是三维空间编队构形实验无人尝试.

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ADVANCES INDYNAMICS AND CONTROL OF TETHERED SATELLITE FORMATIONS *

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Abstract The paper gives a brief summarization on the research of tethered satellite formation, starting with formation configurations and their stabilities. The dynamical behavior such as spinning motion, tether vibration, and periodic motion in the vicinity of L_2 libration point are summarized. The dynamics and control concerned on the deployment/retrieval of system and the rigid attitude of satellites are presented. Finally, future development issues of tethered satellite formation are put forward.

Key words tethered satellite system, formation configuration, stability, dynamical behavior, control

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