

大型翼伞归航控制航迹仿真分析

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摘要: 为了对翼伞归航算法的航迹控制有效性进行验证, 可以采用空投试验或仿真分析 2 种方法. 空投试验获取航迹数据准确性高, 但存在人员和物资投入成本高、协调工作量大的缺点. 而仿真分析具有成本低、易实现的优点, 但由于气象条件和翼伞本身气动特性的不确定性, 仿真结果与真实空投数据会有差异. 如果在仿真分析的过程中采用真实空投获取的翼伞关键参数建立翼伞模型, 则仿真方法的准确性会得到很大的提升, 是一种低成本验证归航控制算法航迹准确性的优选方案. 对大型翼伞归航控制航迹仿真分析方法进行了研究, 并通过其仿真数据与真实空投数据的比较说明了该仿真方法的有效性和可行性. 通过对风的仿真说明了风速和风向对翼伞飞行航迹的影响. 结果表明, 该方法可以辅助优化翼伞归航控制算法设计, 是一种低成本易实施的验证方式, 可为控制算法的验证、分析和改进工作提供良好的参考依据.

关键词: 航天器; 返回; 可控翼伞; 控制; 航迹

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Large Parafoil Guidance Navigation & Control Algorithm Simulation

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Abstract: There are two ways to verify the flying path of parafoil using certain control algorithm: one is plane drop test and the other one is simulation. Using the method of drop test can fetch the precise data of flying path for parafoil, but the cost of human labor and material is very high, while the simulation has the advantages of low cost and less difficulty. But the simulation result will be different from the data fetched by real airdrop experiment because of the uncertainty of atmosphere and parafoil pneumatic characteristic. If the pneumatic model of parafoil can be established by using data fetched by real airdrop test, the accuracy of simulation result will be improved tremendously. Therefore it is an optimal method to verify the accuracy of parafoil control algorithm. The method of simulation analysis for parafoil returning control algorithm was researched in this paper, and the validity and feasibility was illustrated by comparing the simulation data and real drop test data. The wind effect on flying path of parafoil was studied by simulation with different wind directions and velocities. The result shows that the method can improve the design of parafoil for guidance and navigation algorithm. And it's a cost-effective method which is easy to apply. It can provide good reference for the validation, analysis and improvement of control algorithm.

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Key words: aircraft; return; parafoil; control; flying path

随着国民经济的建设发展,地面(海面)遍布了大量的重要工业、军事目标及城市群等,使得航天器和无人机的回收区日趋狭窄.特别是回收区的选择更加困难,很难提供一个较大的合适回收区域.目前国内航天器及无人机回收多采用普通降落伞及着陆缓冲装置,其落点散布范围大,着陆后寻找困难,且由于随风飘等特点容易对地面的人员及房屋设施造成损坏.翼伞系统的气动力特性决定了其可操纵滑翔和转弯飞行并具有自动定点精确着陆的功能,可广泛应用于航天器回收和人员、物资及救生物品定点精确空投领域^[1-7].因此,以大面积可控翼伞为研究背景,研究采用可控翼伞的航天器、运载火箭、无人机回收控制及精确空投归航控制算法,实现精确回收的需求迫切存在.在对翼伞的研究过程中,需频繁采用试验或仿真的方法对翼伞及控制系统进行验证^[8-10].地面拖曳试验、跑车试验、高塔投放试验和空投试验是常用的验证归航控制律和执行机构工作正确性的方法^[11].但是,由于高塔投放试验和高空空投试验具有成本高、风险大和周期长的缺点,在无法频繁使用的情况下对翼伞归航控制的多种工况并得不到充分的验证,极大地影响了研发工作的效率^[12].因此,在归航控制系统的研发过程中,对其航迹设计的仿真验证至关重要.本文对大中型可控翼伞归航控制算法归航轨迹验证的建模、仿真方法进行了研究,并通过仿真数据和真实空投数据的比较说明了该方法的有效性和可行性.同时还对不同风速风向对翼伞飞行轨迹的影响进行了仿真研究.

1 动力翼伞的控制模型

与普通降落伞只产生拉力相比,翼伞会同时产生升力,因此翼伞具有较高的滑翔能力.高性能的翼伞可产生3.0以上的滑翔比.大部分翼伞的滑翔比在2.0~3.0.本文描述了一个六自由度翼伞运动模型.该模型从将伞衣和载荷视为一个整体和将伞衣和载荷分别视为独立体2种情况描述了翼伞在未操纵的状态下的受力情况^[13-14].其中,伞衣和载荷整体的受力情况如图1所示,力和力矩可表示为式(1)~(3).当伞衣和载荷分别视为独立体时,作用于其上的受力情况见图2.伞衣及载荷上的力和力矩由式(4)~(9)描述.

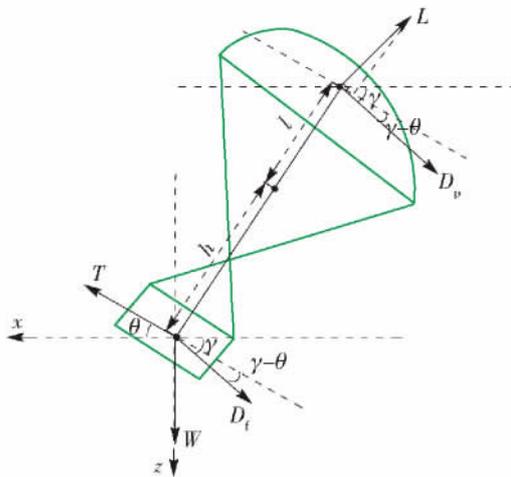


图1 伞衣和载荷为一个整体时翼伞运动模型

Fig. 1 Parafoil motion model when parachute clothes and payload are macrocosm

$$\sum F_x = T \cos \theta - [D_f + D_p] \cos \gamma - L \cos \theta = m \ddot{x} \quad (1)$$

$$\sum F_z = W + [D_f + D_p] \sin \gamma - T \sin \theta - L \cos \gamma = m \ddot{z} \quad (2)$$

$$\sum M_{eg} = h [T - W \sin \theta] - D_f \cos(\gamma - \theta) + l D_p \cos(\gamma - \theta) + L \sin(\gamma - \theta) = I_{eg} \ddot{\theta} \quad (3)$$

式中: T 为推力; D_f 为载荷阻力; D_p 为伞衣阻力; L 为伞衣升力; W 为重力; θ 为 T 与 x 轴夹角.

$$\sum F_{px} = -F_1 + D_p \cos \gamma + L_p \sin \gamma \quad (4)$$

$$\sum F_{py} = -F_2 + D_p \sin \gamma + L_p \cos \gamma - W_p \quad (5)$$

$$\sum M_p = -M_{Ac} + L_p (LA_c) \cos \gamma - D_p LA_d \cos \gamma + L_p LA_d \sin \gamma - D_p LA_c \sin \gamma - LA_c W_p \quad (6)$$

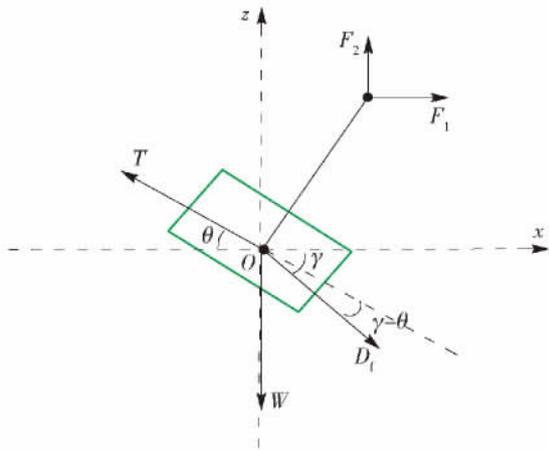
$$\sum F_{Bx} = F_1 - T \cos \theta + D_f \cos \gamma \quad (7)$$

$$\sum F_{By} = F_2 + T \sin \theta - D_f \sin \gamma - W \quad (8)$$

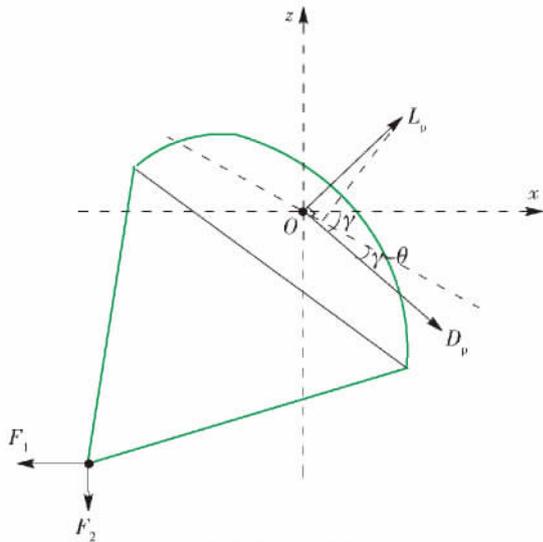
$$\sum M_B = M_B + LA_g + D_f LA_f \cos \gamma + D_f LA_g \sin \gamma - T LA_j \cos \theta - T LA_j \sin \theta \quad (9)$$

2 归航控制算法航迹仿真方法

翼伞的运动可分为滑翔和转弯2种飞行状态,主要依靠下拉伞翼后缘改变翼伞的气动力特性从而改变其飞行状态.当无操纵时,翼伞处于稳态滑翔状态.而单侧下拉时,则产生单侧转弯飞行^[15-17].



(a) 翼伞载荷体运动模型



(b) 翼伞伞衣运动模型

图2 将伞衣和载荷分别视为独立体时翼伞运动模型
Fig. 2 Parachute motion model when parachute clothes and payload are independent

两边同时下拉时可以操纵翼伞俯降或改变翼伞的滑翔速度和滑翔比。但由于翼伞双侧同时下拉的运动情况比较复杂且可能造成翼伞失速,目前尚未在空投试验中验证。本文只讨论翼伞单侧操纵或无操纵的情况,双侧下拉的情况暂不讨论。取一地面坐标系 Oxy , 该坐标系与地球固连, 原点 O 为目标点; Ox 轴指向正东, Oy 轴指向正北。风矢量 W 在某一高度层为常量。任一时刻翼伞系统的质心星下点在坐标系 Oxy 内的坐标为 (x, y) , 速度矢量在 x 轴的投影是 V_x , 在 y 轴的投影是 V_y , x, y, V_x, V_y 是当前时间周期值; x', y', V_x', V_y' 是下一个时间周期值。 τ 为时间周期。则在翼伞转弯运动的情况下, 每一个时间周期 τ 后的位置和速度可按递推公式 (10) ~ (13) 计算^[18]。其转弯过程的飞行关系见图 3、4。其中 r 为

转弯半径; V 为水平速度; θ 为 τ 时间内转过的圆弧角; 式中 $r = \frac{V\tau}{\theta}$ 。若向左转, $a = 1$; 若向右转, 则取 $a = -1$ 。

$$x' = x + \frac{2r}{V} \sin \frac{\theta}{2} \left(V_x \cos \frac{\theta}{2} - aV_y \sin \frac{\theta}{2} \right) + W_x \tau \tag{10}$$

$$y' = y + \frac{2r}{V} \sin \frac{\theta}{2} \left(V_y \cos \frac{\theta}{2} + aV_x \sin \frac{\theta}{2} \right) + W_y \tau \tag{11}$$

$$V_x' = V_x - 2 \sin \frac{\theta}{2} \left(V_x \sin \frac{\theta}{2} + aV_y \cos \frac{\theta}{2} \right) \tag{12}$$

$$V_y' = V_y + 2 \sin \frac{\theta}{2} \left(aV_x \cos \frac{\theta}{2} - V_y \sin \frac{\theta}{2} \right) \tag{13}$$

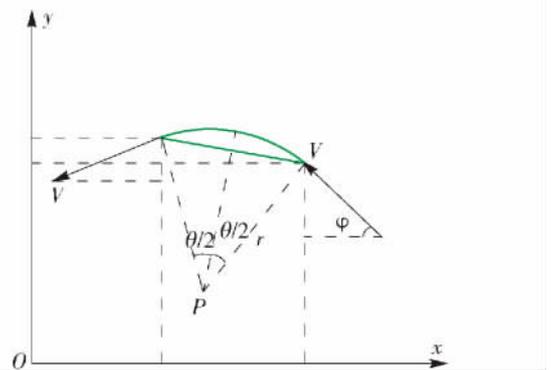


图3 左转弯飞行关系图

Fig. 3 Left-hand bend flying relationship graphic

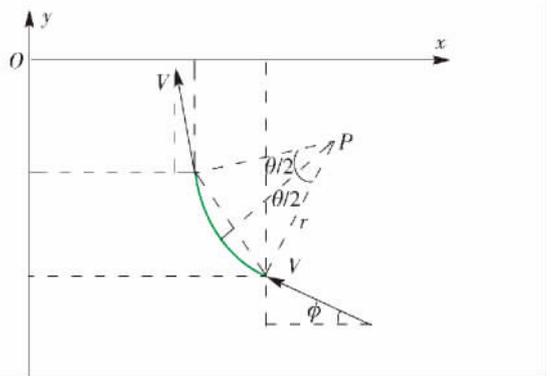


图4 右转弯飞行关系图

Fig. 4 Right-hand bend flying relationship graphic

当翼伞处于滑翔即直线运动状态时, 假设翼伞直线运动比转弯运动水平速度大 ΔV , 则其航迹仿真运动状态可使用递推公式 (14) ~ (18) 计算。其中 V^* 是翼伞系统沿直线运动情况下的水平速度; V 是翼伞系统转弯运动情况下的水平速度; ΔV 是直线运动时的水平速度与转弯运动时的水平速度之差。 ϕ 是水平速度 V 逆时针方向转动到 Ox 轴的负方向

角 $\rho < \Phi \leq 2\pi$. 如果 $\Delta V = 0$, 则使用式(19) ~ (22) 即可. 翼伞处于直线飞行状态时其飞行关系如图5所示.

$$x' = x + (V_x - \Delta V \cos \Phi + W_x) \tau \quad (14)$$

$$y' = y + (V_y + \Delta V \sin \Phi + W_y) \tau \quad (15)$$

$$V'_x = V_x \quad (16)$$

$$V'_y = V_y \quad (17)$$

$$\Delta V = V^* - V \quad (18)$$

$$x' = x + (V_x + W_x) \tau \quad (19)$$

$$y' = y + (V_y + W_y) \tau \quad (20)$$

$$V'_x = V_x \quad (21)$$

$$V'_y = V_y \quad (22)$$

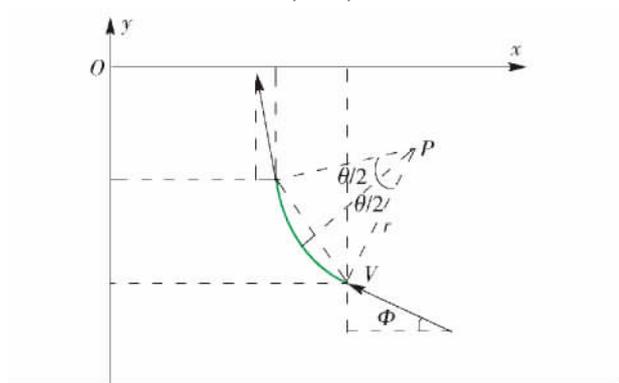


图5 直线飞行关系图

Fig.5 Beeline flying relationship graphic

3 真实空投的航迹数据与仿真分析航迹数据结果比较

笔者所在研究机构针对翼伞归航控制系统的验证进行了一系列空投试验. 试验包括气球空投和飞机空投2种方式. 其中,翼伞归航控制律选用了分段归航的控制算法,主要分为定向归航、盘旋削高、逆风控制、强制最终着陆4个阶段,其控制过程如图6所示^[19-20]. 空投试验翼伞投放和转弯飞行照片见图7、8. 本文分别以飞机空投和气球空投试验数据作为翼伞仿真分析的初始条件及运动模型参考对翼伞分段自动归航控制律进行了航迹仿真.

仿真首先在无风的条件下进行. 飞机空投某架次水平和垂直速度数据曲线如图9所示. 真实和仿真航迹数据分别如图10、11所示. 气球空投某架次真实空投速度、航迹和仿真航迹数据分析如图12~14所示. 由真实航迹和仿真航迹可以看出,翼伞均按归航控制律设计的航迹完成了4个阶段的飞行任务,但真实航迹到最后接近地面阶段水平速度会增

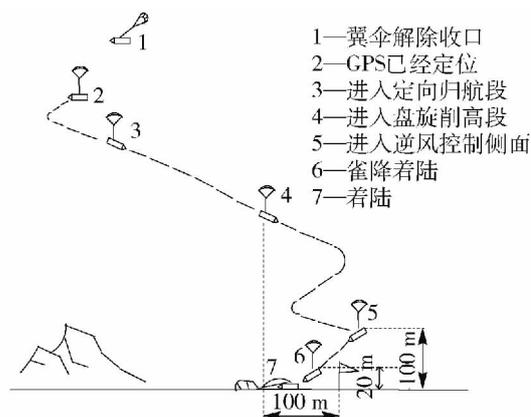


图6 翼伞分段归航控制过程示意图

Fig.6 Parafoil multi-segment return navigation control process graphic



图7 翼伞气球空投试验

Fig.7 Parafoil balloon airdrop experiment



图8 空投试验中翼伞在空中转弯飞行

Fig.8 Parafoil turning process during airdrop

大,导致转弯半径增大. 在飞机空投的水平速度数据曲线中显示更为明显.

4 风场影响仿真轨迹分析

本文采用空投初始条件数据作为输入,针对不同方向与大小的风场,对翼伞的飞行航迹进行了一系列仿真分析. 其中3个架次无风、逆风、顺风3种典型工况的翼伞仿真飞行轨迹如图15~17所示. 从无风、逆风、顺风的仿真轨迹比较情况可以看出,

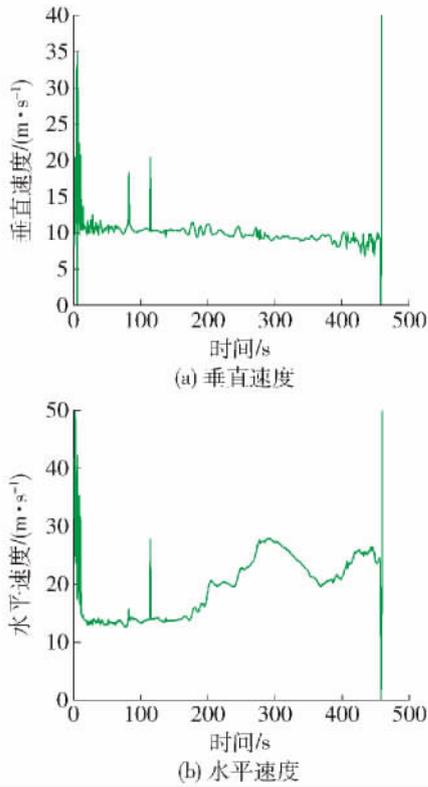


图9 飞机空投速度曲线

Fig. 9 Plane airdrop velocity curve graphic

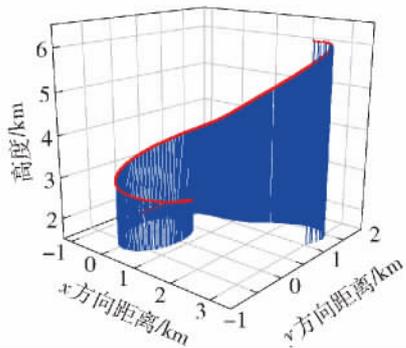


图10 飞机空投真实航迹数据曲线

Fig. 10 Plane airdrop real flight path graphic

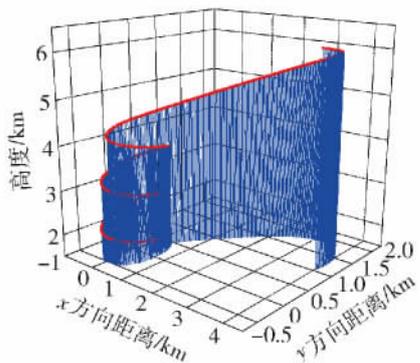


图11 飞机空投仿真航迹数据曲线

Fig. 11 Plane airdrop simulation flight path graphic

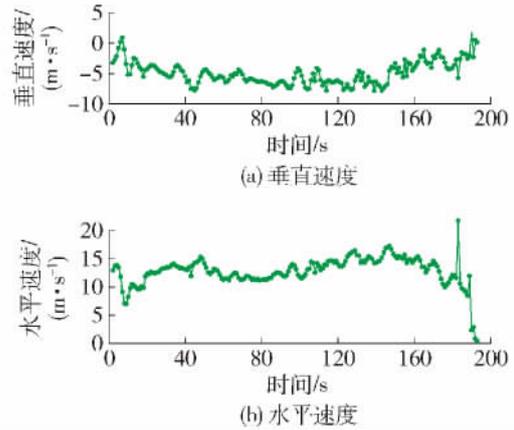


图12 气球空投速度曲线

Fig. 12 Balloon airdrop velocity curve graphic

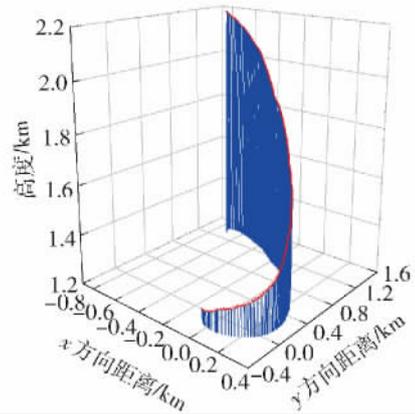


图13 气球空投真实航迹数据曲线

Fig. 13 Balloon airdrop real flight path graphic

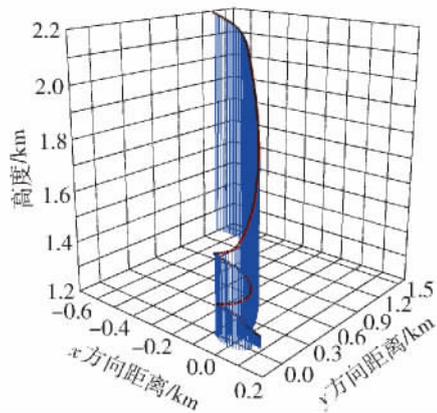


图14 气球空投仿真航迹数据曲线

Fig. 14 Balloon airdrop simulation flight path graphic

风向主要影响翼伞的滑翔比. 顺风时翼伞的水平速度增大, 飞行机动性强, 归航精度提高. 逆风时翼伞滑翔比和机动能力均降低, 因此归航精度也相应降低. 无风的情况介于两者之间.

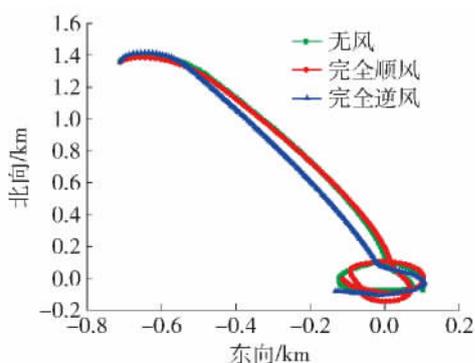


图15 第1架次无风、顺风、逆风情况下的仿真轨迹

Fig. 15 First flight trajectory simulation result with no wind , identical direction wind and opposite direction wind

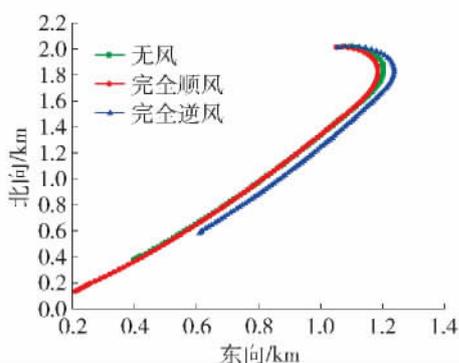


图16 第2架次无风、顺风、逆风情况下的仿真轨迹

Fig. 16 Second flight trajectory simulation with no wind , identical direction wind and opposite direction wind

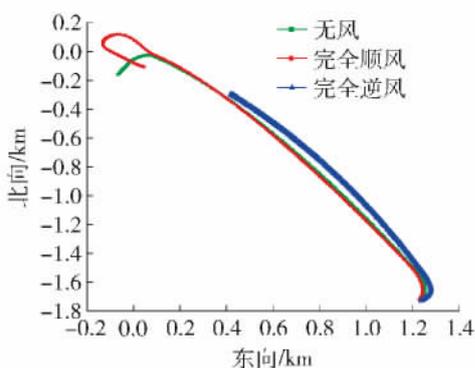


图17 第3架次无风、顺风、逆风情况下的仿真轨迹

Fig. 17 Third flight trajectory simulation result with no wind , identical direction wind and opposite direction wind

5 结论

1) 由于真实环境的气象复杂性及每一个翼伞气动特性的个体差异,仿真分析只能起到初步验证的目的,和真实空投结果具有一定的差异。

2) 通过真实空投数据优化翼伞运动模型,再利

用优化后的翼伞运动模型通过仿真分析的方法得到的翼伞航迹可以辅助优化归航控制算法设计,是一种低成本易实施的验证方式,可为控制算法的验证、分析和改进工作提供良好的参考依据。

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