Optimal Design of Aero-Assisted Plane-Change Orbital Transfer for Multi-Debris Removal (Postprint)

Authors: Yan Ruidong, Wang Ronglan, Liu Siqing, Shi Liqin, Gong Jiancun

Date: 2017-01-22T00:00:00+00:00

Abstract

Orbital plane change maneuvers for debris removal spacecraft entail substantial fuel consumption. This study investigates the fuel savings achieved by optimized aerodynamic-assisted orbital plane change relative to two-impulse Hohmann orbital transfer, based on the optimization design of aerodynamic-assisted plane change and analysis of design parameter impacts on transfer performance. The effects of implementing aerodynamic-assisted orbital transfer between orbits with varying altitude differentials on fuel savings are analyzed. For aerodynamic-assisted orbital transfer between Geostationary Earth Orbit (GEO) and Low Earth Orbit (LEO), the optimized velocity increment is approximately 1.55 km/s, the mass-to-area ratio is 172 kg/m², the specific impulse is 310 s, and the fuel savings rate is approximately 45% when the orbital inclination change is 16°. A comparative study is performed on fuel savings from aerodynamic-assisted orbital transfer between LEO orbits with different altitude differentials. Results demonstrate that optimization efficiency of aerodynamic assistance decreases progressively with increasing orbital altitude; for plane change maneuvers between orbits at identical altitudes, the fuel savings rate of aerodynamic-assisted orbital transfer increases with orbital inclination; when orbital inclination is less than 5°, fuel consumption for aerodynamic-assisted orbital transfer equals that of two-impulse orbital transfer.

Full Text

Optimal Impulsive Design for Aeroassisted Orbit Transfer in Noncoplanar Orbit Debris Removal

YAN Ruidong, WANG Ronglan, LIU Siqing, SHI Liqin, GONG Jiancun

(National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China)

Abstract: The problem of minimum-fuel aeroassisted orbital transfer of a high lift-to-drag ratio vehicle from Low Earth Orbit (LEO) or Geostationary Earth Orbit (GEO) to low-Earth orbit with an inclination change is considered. Assuming impulsive thrust, the trajectory design is described in detail and the aeroassisted orbital transfer is posed as a nonlinear optimal control problem. Through comparison of the double-impulsive orbit transfer and aeroassisted orbit transfer in noncoplanar orbit, we concluded the influence of altitude difference from two noncoplanar orbits and the perigee choice of the middle transition orbit. The main problem that aeroassisted orbital transfer may face is hypersonic flight in the upper atmosphere. In the end the technology used in X-37B flight was concluded.

Key words: multi-debris removal; aeroassisted orbital transfer; optimal impulsive design

Introduction

With the annual increase in spacecraft launches and the conduct of anti-satellite tests, Earth orbits—particularly special sun-synchronous low Earth orbits—have become limited natural resources. The increasing number of space objects has raised the probability of collisions between them, as exemplified by the collision of Iridium 33 and Cosmos 2251 in February 2009. The Kessler cascading effect demonstrates that collisions generate new debris, thereby increasing the probability of future collisions. Even if humanity ceased launching new spacecraft, the debris population would continue to grow.

NASA research indicates that collisions will be the primary cause of future debris growth. Debris mitigation measures and spacecraft maneuvering for collision avoidance cannot stabilize the debris environment; even after mitigation efforts, 8-9 catastrophic collisions are expected within the next 40 years. To control the growth of cataloged objects and limit space collision events, active debris removal strategies must be implemented.

The most critical issue for operational spacecraft is fuel consumption, which is even more pronounced for debris removal vehicles. Traversing a sequence of debris targets requires a series of orbital maneuvers. Since space debris is not concentrated in a single region, both in-plane and out-of-plane maneuvers are necessary, consuming substantial amounts of fuel. On March 30, 2015, China launched the new-generation upper stage Yuanzheng-1, which possesses autonomous orbital maneuvering capability, long on-orbit operation time, and multiple restart capability to meet diverse mission requirements, delivering one or multiple payloads to designated orbits. Spacecraft like Yuanzheng-1 are called Orbit Transfer Vehicles (OTV). OTVs operate primarily within Earth' s atmosphere, suggesting the possibility of using aerodynamic forces to accomplish part of the orbital transfer task—this is the Aeroassisted Orbit Transfer Vehicle (AOTV). Although AOTVs require additional mass for aerodynamic assist wings and thermal protection materials, propellant consumption is significantly reduced compared to Hohmann transfers, thereby increasing payload mass. This paper proposes applying aeroassisted orbit transfer technology to noncoplanar debris removal missions, which would save substantial fuel during debris removal operations and offers high practical value.

Indirect and direct methods are the two primary approaches for aeroassisted orbit transfer optimization. Direct methods employ parameterization to transform the continuous optimal control problem into a Nonlinear Programming (NLP) problem, obtaining optimal trajectories through numerical solution of the NLP problem. Direct methods are more widely applied than indirect methods and exist in many variants. Based on different parameterization approaches, direct methods fall into two basic categories: (1) discretizing control variables while obtaining state variables through numerical integration; and (2) simultaneously discretizing both control and state variables, using polynomials to represent the time variation of state variables between nodes, thereby converting continuous dynamic differential equation constraints into algebraic constraints. This paper employs the Gauss pseudospectral method and nonlinear programming to optimize aeroassisted noncoplanar orbit transfer trajectories.

1.1 Aeroassisted Orbit Transfer Description

Assuming both the initial and target orbits are circular with radii r_1 and r_2 respectively, and the atmospheric radius is $r_b = 6498$ km, the vehicle enters the atmosphere from the initial orbit, utilizes aerodynamic gliding assist to change orbital inclination, then exits the atmosphere to enter the target orbit. As shown in [Figure 1: see original paper], the process consists of three phases:

1) **Initial de-orbit segment**, from r_1 to r_b:

The velocity increment and flight path angle are given by:

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}} - \sqrt{\mu\left(\frac{2}{r_1} - \frac{1}{a_1}\right)}$$

$$\gamma_1 = \arccos\left(\frac{r_p}{r_b}\frac{v_p^2}{\mu}\right)$$

where v_p and r_p represent the velocity and radial distance at atmospheric entry, and a_1 is the semi-major axis of the transfer orbit.

2) **Atmospheric motion equations**:

$$\begin{aligned}
\frac{d\theta}{dt} &= \frac{v\cos\gamma\cos\psi}{r\cos\phi} \\
\frac{d\phi}{dt} &= \frac{v\cos\gamma\sin\psi}{r} \\
\frac{dr}{dt} &= v\sin\gamma \\
\frac{dv}{dt} &= -\frac{D}{m} - \frac{\mu\sin\gamma}{r^2} \\
\frac{d\gamma}{dt} &= \frac{L\cos\sigma}{mv} - \frac{\mu\cos\gamma}{r^2 v} + \frac{v\cos\gamma}{r} \\
\frac{d\psi}{dt} &= -\frac{L\sin\sigma}{mv\cos\gamma} - \frac{v\cos\gamma\sin\psi\tan\phi}{r}
\end{aligned}$$

Here, m is the satellite mass; θ and ϕ are longitude and latitude; r is the geocentric distance; γ is the flight path angle; ψ is the heading angle; and σ is the bank angle. The atmospheric density model adopts the NRLMSISE-2000 model. C_D and C_L are the drag and lift coefficients of the spacecraft, which follow a quadratic polar relationship:

$$\begin{aligned}
C_D &= C_{D0} + KC_L^2 \\
C_L &= C_{L\alpha}\alpha
\end{aligned}$$

where C_{D0} is the zero-lift drag coefficient, K is the induced drag factor, $C_{L\alpha}$ is the lift curve slope, and α is the angle of attack. For small angle-of-attack flight, we have $C_L = C_{L\alpha}\alpha$.

3) **Post-atmospheric ascent segment**: The velocity increment required to circularize at the target orbit is:

$$\Delta v_3 = \sqrt{\frac{\mu}{r_2}} - \sqrt{\mu\left(\frac{2}{r_2} - \frac{1}{a_2}\right)}$$

where a_2 is the semi-major axis of the exit orbit.

[Figure 1: see original paper] illustrates the complete aeroassisted orbit transfer scenario. The vehicle applies an impulsive burn Δv_1 at point a to enter an elliptical orbit with apogee r_1 and perigee r_p. It enters the atmosphere at point b along this elliptical orbit, utilizes aerodynamic forces to change orbital inclination within the atmosphere, exits at point c while applying velocity impulse Δv_2 to position the apogee at the target orbit, and finally applies impulse Δv_3 at point d to enter the circular target orbit of radius r_2.

The fuel consumption formula is:

$$m_{prop} = m_0\left(1 - \exp\left(-\frac{\Delta v}{g_0 I_{sp}}\right)\right)$$

where I_{sp} is the specific impulse. Different fuel types correspond to different I_{sp} values; for example, cold gas thrusters (N and NH) have I_{sp} of 10–80 s, while liquid propellant rockets (N H) have I_{sp} of 200–300 s.

2 Optimization Performance of Aeroassisted Noncoplanar Orbit Transfer Between Different Altitude Orbits

2.1.1 16° Inclination Optimization First, we consider an aeroassisted orbit transfer from Geostationary Earth Orbit (GEO) with a 16° inclination change to a 300 km Low Earth Orbit (LEO). We analyze the fuel savings rate by comparing the double-impulse Hohmann transfer with the aeroassisted noncoplanar transfer. The initial orbital elements are: $a_0 = 42164$ km, $e_0 = 0$, $i_0 = 16°$, $\Omega_0 = 0°$, $\omega_0 = 0°$, $M_0 = 0°$.

The dynamic parameters, mass-to-area ratio, and specific impulse parameters are shown in . The optimized velocity increment is 1.551 km/s, with liquid rocket fuel consumption of approximately 687.7 kg. The Hohmann double-impulse transfer requires a velocity increment of 4.018 km/s, with fuel consumption of approximately 1,261.7 kg. The orbital parameter variations within the atmosphere are shown in [Figure 2: see original paper] and [Figure 3: see original paper].

For a mass-to-area ratio of 300 kg/m² (other parameters unchanged), the optimized velocity increment is 1.556 km/s, with fuel consumption of 1,202.4 kg, compared to 2,201.2 kg for the Hohmann transfer. Atmospheric parameter variations are shown in [Figure 3: see original paper].

2.1.2 30° Inclination Optimization For a 30° inclination change from GEO, with the same initial orbital elements as Section 2.1.1, the dynamic parameters are shown in . The optimized velocity increment is 1.552 km/s, with fuel consumption of approximately 688 kg, while the Hohmann transfer requires 4.29 km/s and 1,301 kg of fuel. Atmospheric parameter variations are shown in [Figure 4: see original paper].

With a mass-to-area ratio of 300 kg/m², the optimized velocity increment is 1.553 km/s, with fuel consumption of approximately 1,201 kg, compared to 2,269.1 kg for the Hohmann transfer. Atmospheric parameter variations are shown in [Figure 5: see original paper].

2.2.1 Effect of Orbital Altitude Difference on Aeroassisted Transfer Optimization Efficiency

To analyze the fuel optimization efficiency for noncoplanar transfers between different orbital altitudes, we selected seven circular orbits from 900–1,500 km altitude. Aeroassisted optimization was performed for 16° inclination transfers from each orbit to a 300 km target orbit. The results are presented in and [Figure 6: see original paper].

The results show that the fuel savings percentage from aeroassisted transfer increases with the altitude difference between the transfer and target orbits. However, when the transfer orbit altitude exceeds 1,400 km, the optimized velocity impulse gradually stabilizes with increasing altitude. As shown in Section 2.1, when the orbital altitude reaches 36,000 km, the optimized impulse value is 1.55 km/s, indicating only a 0.15 km/s variation in optimized velocity impulse across the 1,400–36,000 km altitude range. Since fuel consumption for impulsive transfers increases with altitude, the overall fuel savings percentage from aeroassisted noncoplanar transfer increases with altitude difference.

2.2.2 Comparison of Aeroassisted Transfer Optimization at Same Altitude

This section analyzes 30° aeroassisted noncoplanar optimization transfers between orbits of the same altitude. Seven orbital groups in the 180–450 km altitude range were selected to compare optimization efficiency between double-impulse and aeroassisted transfers. The results are shown in and [Figure 7: see original paper].

The results demonstrate that aeroassisted optimization efficiency decreases with increasing orbital altitude. For same-altitude noncoplanar transfers, the fuel savings percentage decreases as orbital altitude increases.

2.3 Relationship Between Inclination Change and Optimization Rate for Same-Altitude Orbits

A critical inclination value exists for aeroassisted noncoplanar transfers between same-altitude orbits. For inclinations below this critical value, impulsive transfers are preferable; above it, aeroassisted transfers are more advantageous. We analyzed fuel consumption for various inclination changes between 185 km altitude orbits, with results shown in and [Figure 8: see original paper].

[Figure 8: see original paper] shows the optimization efficiency trend for different inclination changes at 185 km altitude. Both double-impulse and aeroassisted fuel consumption increase with inclination change, but the aeroassisted consumption increases at a lower rate. Consequently, the fuel savings rate from aeroassisted transfer increases with inclination change. Additionally, when the inclination change is below approximately 5°, the fuel consumption for aeroassisted and double-impulse transfers becomes equivalent.

3 Challenges and Prospects

The primary technical challenge for aeroassisted orbit transfer is hypersonic flight technology in the upper atmosphere. On May 20, 2015, the U.S. launched the fourth X-37B experimental vehicle (OTV-4), with one of its main mission objectives being high-Mach-number flight in the near-space regime (30–100 km altitude). X-37B achieved speeds of Mach 25 in this altitude range, while the X-51A flight test only reached Mach 6 for 200 seconds before experiencing communication issues. If X-37B can achieve Mach 25 flight in the 30–100 km near-space region with repeatable performance, this capability would be revolutionary, potentially transforming U.S. space access by enabling air-launch of X-37B (or OTV) from aircraft at 20–30 km altitude, followed by propulsive ascent to low Earth orbit without relying on expendable launch vehicles. This would enable truly reusable launch systems and dramatically reduce access costs to near-Earth space.

This paper analyzed three aspects of aeroassisted noncoplanar orbit transfer: (1) optimization efficiency between different altitude orbits, (2) optimization performance between same-altitude orbits, and (3) optimization for different inclination changes at same altitude. The analysis reveals that larger altitude differences favor aeroassisted noncoplanar transfers with higher fuel savings; for same-altitude transfers, lower orbits offer higher optimization efficiency; and for same-altitude transfers, larger inclination changes yield greater fuel savings. However, aeroassisted orbit transfer still faces numerous challenges that will require continued advancement of space technology to resolve.

References

[1] DU Heng, ZHANG Wenxiang, PANG Baojun, et al. *Space Debris* [M]. Beijing: China Astronautic Publishing House, 2007.

[2] Liou J C, Johnson N L, Hill N M. Controlling the Growth of Future LEO Debris Populations with Active Debris Removal [J]. *Acta Astronautica*, 2010, (5/6): 10.1016/j.actaastro.2009.08.005.

[3] Niels van der Pas, Lousda J, Terhes C, et al. Target Selection and Comparison of Mission Design for Space Debris Removal by DLR' s Advanced Study Group [J]. *Acta Astronautica*, 2014, 102(9/10): 241-248. DOI: 10.1016/j.actaastro.2014.06.020.

[4] CUI Enhui. Long March 3C/Yuanzheng-1 Rocket Successfully Launched [N/OL]. *China Aerospace News*, (2015-04-01) http://zhuanti.spacechina.com/n881117/content.html.

[5] HU Songqi, CHEN Yu. Application Analysis of Pseudospectral Methods in Vehicle Trajectory Optimization [J]. *Journal of Rocket Propulsion*, 2014, 40(5): 61-68.

[6] HUANG Guoqiang, LU Yuping, NAN Ying. Review of Numerical Algorithms for Vehicle Trajectory Optimization [J]. *Scientia Sinica: Technologica*, 2012, 42(9): 1016-1036.

Supported by the National Natural Science Foundation of China (11403070)

Correspondence Address: National Space Science Center, No. 1 Zhongguancun South Second Street, Haidian District, Beijing
Postal Code: 100190

Phone: 18310100236
Email: yanruidong@nssc.ac.cn