Theoretical analysis on zero propellant maneuver existence conditions

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Zero-propellant maneuver (ZPM) is an advanced concept of attitude control using only control moment gyroscopes (CMGs). The concept of ZPM is first proposed by Bedrossian at 1996. The core idea is to establish the frame of optimal control of attitude maneuver, and plan maneuver path by making full use of environment torques. Then the spacecraft maneuvers along the planned path using CMGs only, without any fuel consumption. On November 5, 2006, ZPM was first demonstrated on the International Space Station (ISS) [1]. The ISS rotated 90 °without consuming any propellant in 7200s. On March 3, 2007, a ZPM of 180 ° rotation was achieved again, saving 50.76kg propellant at an estimated cost of US$1,100,000 [2].

Compared with traditional attitude-control thrusters, by using CMGs, mount of propellant can be saved, which directly cut down the money spent on the attitude maintain and maneuver. At the same time, CMGs and attitude-control thrusters can also be a backup for each other. Moreover, gas contamination caused by thrusters on the solar panel and other exposed device could be avoided. As can be seen above, the technology of ZPM will increase orbiting lifetime of spacecraft, and guarantee the maneuver security and reliability effectively.

However, the interchange ability of angular momentum that the CMGs can provide is limited, and when the threshold is reached, the CMGs saturated. Saturation precludes CMGs from generating torques in certain direction, and may lead to the loss of attitude-control ability. Once the CMGs saturate, thrusters need to work instead of CMGs. So whether the attitude maneuver mission can be achieved without CMG saturated is a judging condition for ZPM. To deal with the saturation problem, various approached have been explored so far. On the one hand, attitude controller and the control law of CMGs are designed to avoid the happening of saturation. On the other hand, many previous studies concentrated on the attitude maneuver path planning. However, researchers seldom considered the existence of unsaturated path for a given maneuver mission. Until now, only Zhao et al. [3] give a preliminary analysis based on the conservation of angular momentum. But the existence conditions proposed by Zhao can be appropriate only for attitude maneuvers between torque equilibrate attitudes, and the initial momentum of CMG is assumed to be zero, which limit the application to a great extent.

The existence conditions proposed in this paper can be applied to any angle maneuver mission, and there is no limitation to the momentum of CMGs. The main contributions of this paper are four folds: 1) Establish the projection function of angular momentum in the orbit frame of a spacecraft with CMGs as the only actor. 2) The ZPM existence condition is proposed ignoring the effects of environment, which can be applied to small spacecraft especially when they carry on a fast attitude maneuver mission. 3) The ZPM existence condition is proposed considering the effects of gravity. It is discovered that in the orbit frame, the Y-direction momentum of the spacecraft is independent of the other two directions, while the X-direction and the Z-direction momentum are intercoupling. Thus, two existence conditions are proposed respectively.

References

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