Large translation-rotation dynamics of spacecraft with nonlinear combined slosh under propellant consumption

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Abstract. The 3DOF-rigid-pendulum slosh model has been previously proposed and verified for describing nonlinear liquid motion in partially-filled spherical tanks, including large-amplitude lateral sloshing, rotary sloshing, liquid spinning motion, as well as large over-all rigid motion respect to the tanks in spacecraft. This paper subsequently focuses on the dynamics of a spacecraft with nonlinear slosh in multi-tank, simultaneously considering the effect of propellant consumption. The translation-rotation dynamics of a spacecraft with nonlinear combined slosh in 2-tank is established by using the Lagrangian formulation, whereby the propellant slosh dynamics is equivalently accommodated by using an improved parameter-variable composite 3DOF-rigid-pendulum model. Then, the dynamic responses of the spacecraft with nonlinear combined sloshing coupled are simulated by given large-angle three-axis stabilized maneuvering cases.

Introduction

A new generation of spacecraft usually carry significant amounts of liquid propellant for long-life-span tasks, station keeping, large maneuvers, etc. Especially for three-axis-stabilized liquid-filled spacecraft, the attitude control should adapt to the requirements of high stability and high precision. However, the liquid in the propellant tanks tends to experience nonlinear sloshing motion (mainly including the large-amplitude lateral sloshing, the nonplanar sloshing, the rotary sloshing, as well as the over-all rigid motion respect to the tank) when the spacecraft executing large and rapid maneuvers [1-3]. Then, to evaluate in real-time the generated slosh force and slosh torque acting on the rigid hub of spacecraft will be a very tricky problem in the aerospace engineering practice, and the disturbance of liquid slosh may cause the attitude motion of spacecraft responses with violent jitter [3]. A famous example is the failure in the second flight of the SpaceX "Falcon-1" in 2007, and the cause was recognized to be the propellant sloshing in the LOX tank increasing the circular coning oscillation in the rolling motion of the rocket.

Results and discussion

Figures 1a and 1b show the physical model of the focused spacecraft and the composite 3DOF-rigid-pendulum model, respectively. The translation-rotation dynamics equations of spacecraft, coupled with the nonlinear sloshing dynamics with propellant consumption in 2-tank, are derived by using the Lagrangian formulation. The responses of the attitude quaternions show that the linear PD controller is capable of bringing the attitude to the desired orientation and keeping the liquid-filled spacecraft triaxially stable, although the angular velocity of spacecraft is disturbed by the propellant slosh with obvious jitter in some directions (Figs. 1c and 1d). Figs. 1e and 1f show the responses of the translation position of the spacecraft during the attitude maneuvering, considering the consumption case and the non-consumption case, which indicates that the propellant consumption will cause the position deviation of the spacecraft increase continuously. Figs. 1g and 1h illustrate the motion trajectory on the $B-\boldsymbol{b}_1\boldsymbol{b}_2$ plane of the lumped mass of the pendulum, which indicate that the liquids in 2-tank experience not only a large over-all rigid motion, but also lateral and rotary sloshing motion when the spacecraft executes three-axial stabilized attitude maneuvers.

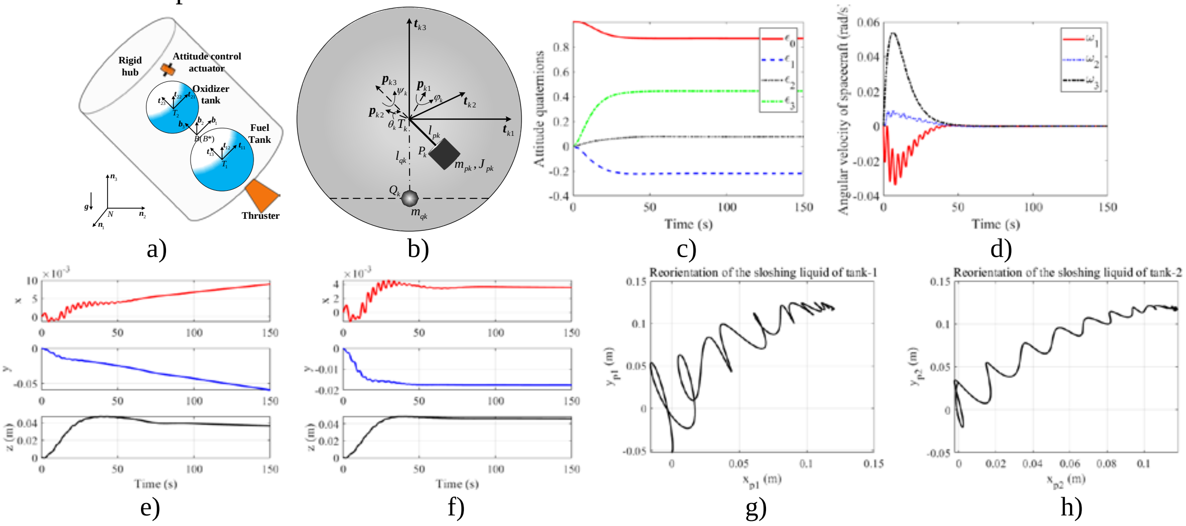

Figure 1 models and results

References

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