Coupled Attitude and Orbit Dynamics and Control in Formation Flying Systems

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Statement of Problem

Formation flying systems can range from global constellations offering extended service coverage to clusters of highly coordinated vehicles that perform distributed sensing [1]. Recently, the use of groups of micro-satellites in the areas of near Earth explorations, deep space explorations, and military applications has received considerable attention by researchers and practitioners.

To date, most proposed control strategies are based on linear models (e.g., Hill-Clohessy-Wiltshire equations) [2-8] or nonlinear models that are restricted to circular reference orbits [9,10]. Also, all models in the literature are uncoupled between relative position and relative attitude.

In this paper, a generalized dynamic model is proposed. The reference orbit is not restricted to the circular case like Refs [2-11]. In this formulation, the leader or follower satellite can be in either a circular or an elliptic orbit. In addition to maintaining a specified relative position, the satellites are also required to maintain specified relative attitudes. Thus the model presented couples vehicle attitude and orbit requirements. Orbit perturbations are also included. In particular, the J_2 effects are accounted in the model. Finally, a sliding mode controller is developed and used to control the relative attitude of the formation and the simulation results are presented.

Scope and Method of Approach

The generalized equations of motion for a leader/follower satellite case are derived. Extensions to multiple follower systems are discussed. In order to consider non-circular orbits, the governing equations are regularized, resulting in a true anomaly dependence. In addition, the vehicles are considered to have finite dimensions, so their attitude dynamics are coupled to the orbit mechanics. Since, for the cases considered, singularities of Euler angles would not be encountered, this attitude representation was chosen. For completeness, the Euler parameters are also discussed. Finally, an attitude controller was implemented to control the attitude of the follower relative to the leader. In the open loop scenario, each satellite's z-axis points to its own nadir position (i.e. the vehicles are assumed to be gravity gradient stabilized). For the closed-loop scenario, both vehicles are required to point to the same position on the surface of the earth (i.e., the nadir of the leader).

Statement of Data Used/Summary of Important Conclusions

The developed equations are validated by considering a leader-follower satellite system. The leader is in an equatorial orbit with eccentricity to be 0.5 and periapsis altitude is $500\,km$. The follower satellite is in a 5^{o} inclined orbit plane with eccentricity of 0.75 and periapsis altitude of $520\,km$. At epoch, the true longitude of the leader (u_{oL}) is 0^o and that of the follower (u_{oF}) is -5^o. The difference between the developed model and the classical Keplerian orbit model are shown in Figure 1-1. It is seen that the model error is in the order of $O(10^{-4})$.

The second example considers the relative attitude problem. The leader is in a $500\,km$ altitude, circular equatorial orbit. The follower is also in a $500\,km$ circular orbit with 0.1^o inclination. Initially, $u_{oL} = 0^o$ and $u_{oF} = -0.1^o$. These conditions were chosen to keep the satellites within 20 km of each other. The nadir of the leader with respect to the follower is defined by angles θ_1 and θ_2 (see Figure 1-2). A 1 Hz. sliding mode controller is developed to maintain θ_1 and θ_2 at zero (i.e., the follower is pointing at the nadir point of the leader).

Figure 1- 3 and Figure 1- 4 shows the θ_1 and θ_2 under the case without control. As expected, θ_1 is periodic and θ_2 is a constant value. Figure 1- 5 shows the controlled response. The controller was capable of maintaining the desired point of the follower to the nadir of the leader. The error is in the order of $O(10^{-4})$. Figure 1-6 shows the output commands of the sliding mode controller.

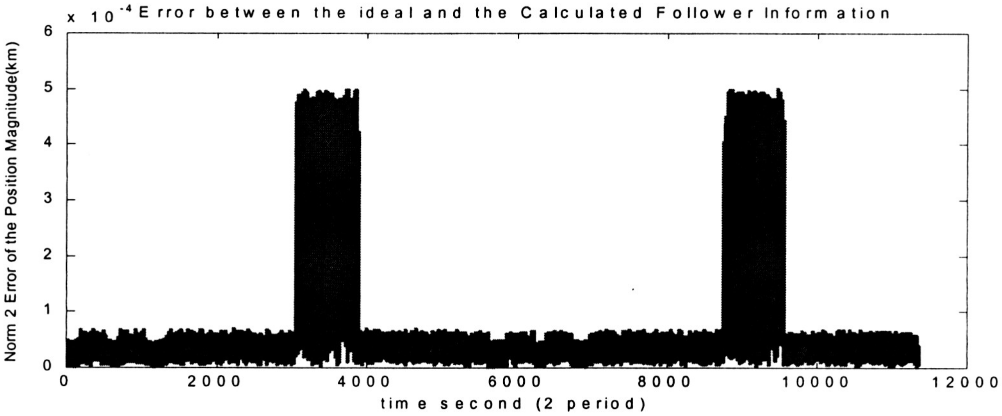


Figure 1- 1 Error of the Relative Position Models

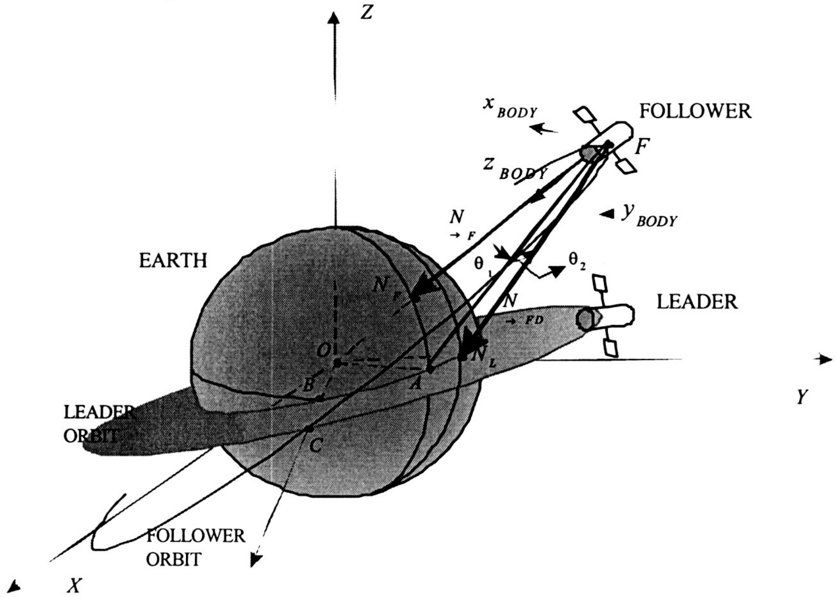


Figure 1- 2 Definition of relative attitude pointing θ_1 and θ_2

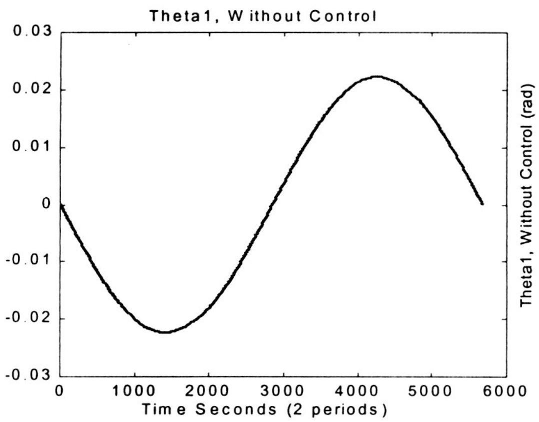


Figure 1- 3 Torque free attitude - θ_1

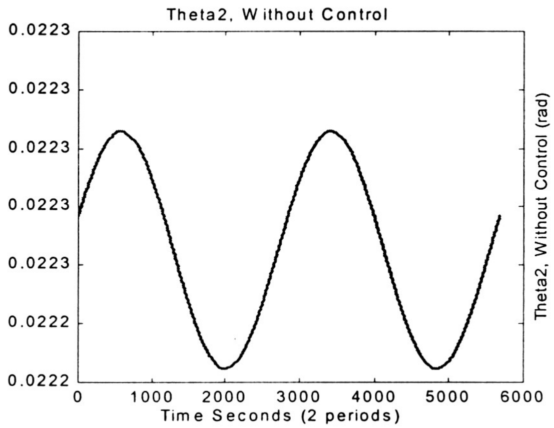


Figure 1- 4 Torque free attitude - θ_2

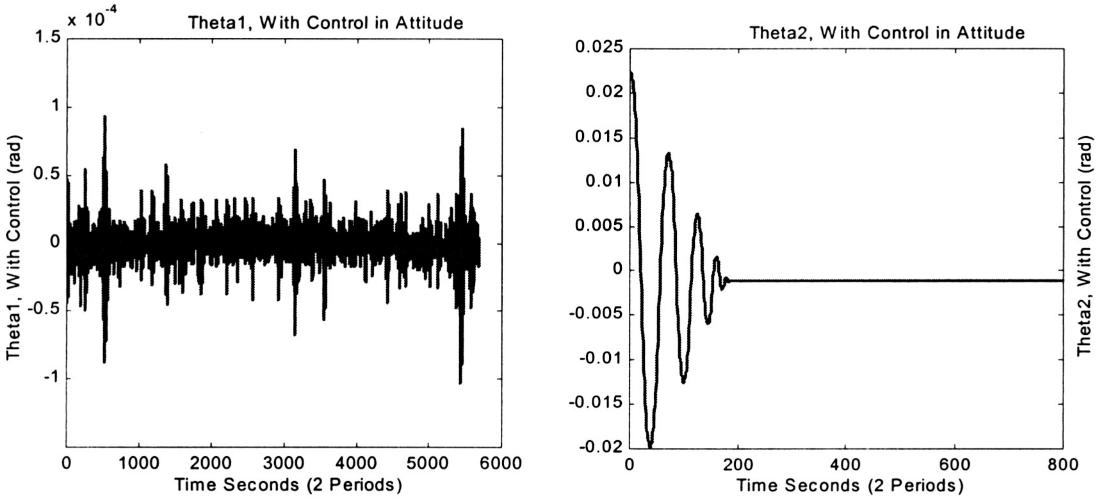
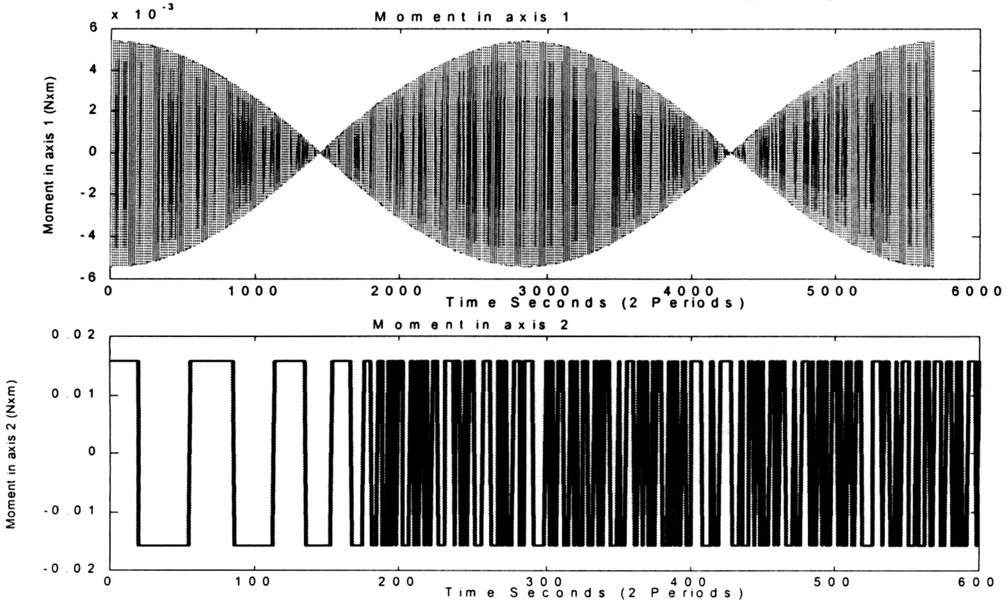


Figure 1- 5 Error in controlled attitude - θ_1 and θ_2



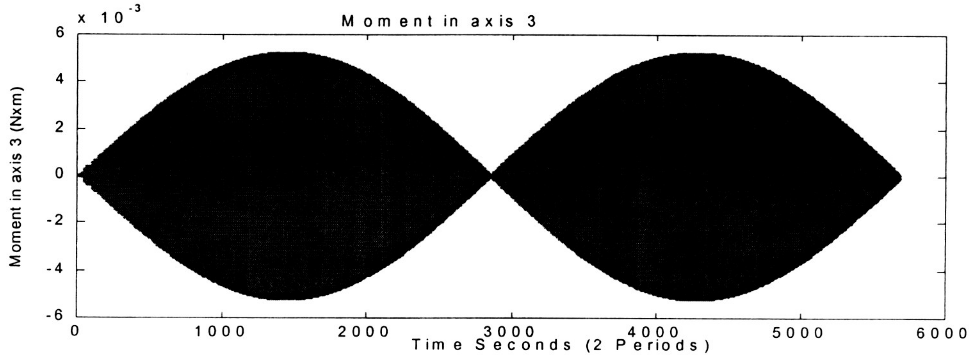


Figure 1- 6

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