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Re-entry Vehicle State and Aerodynamic Coefficient Estimation from Dual Accelerometers

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Abstract

THE determination of the flight dynamics characteristics of spinning re-entry vehicles from onboard motion sensors has been the subject of considerable research. Typical onboard motion sensors include rate gyros and accelerometers. Measurements of vehicle motion from a combination of these sensors have been used to successfully estimate re-entry vehicle states and aerodynamic coefficients. The choice of sensor systems does affect the quality of state and parameter estimates. Gupta and Hall[1] have developed an analytical method for evaluating sensor systems for state and parameter estimation. The purpose of this study is to compare, by computer simulation, the estimates of re-entry vehicle lateral states and aerodynamic coefficients from dual accelerometer observations with estimates obtained from rate gyro and single-accelerometer measurements. The accelerometers are physically separated along the longitudinal axis of the vehicle. The motivation for this analysis comes from the severe volume and power constraints placed on onboard sensors for several proposed re-entry vehicle recovery programs. Because rate gyros usually require more volume and power than accelerometers, it is proposed to carry dual accelerometers to provide onboard motion information.

The comparison is made by using SANTRAP[2] to generate a simulated trajectory and observation set which exhibit characteristics similar to those expected on a typical re-entry vehicle flight. Baseline estimates of vehicle lateral states and aerodynamic coefficients are determined from the simulated rate gyro and accelerometer observations. These estimates and their associated error covariances are used to judge the quality of state and parameter estimation from dual-accelerometer measurements. In addition, the sensitivity of estimates and error covariances to variations in accelerometer location, axis alignment, and fit time interval are considered.

Contents

The description of the nominal trajectory, re-entry vehicle, measurement models, and so forth, are contained in Ref. 3. Simulated observations are generated using a six-degree-of-freedom dynamical model. A standard four-state model[2] describing the lateral motion of a symmetrical spinning vehicle is utilized in a postflight analysis procedure to estimate vehicle states and aerodynamic coefficients. For the estimation problem, the aerodynamic coefficients are assumed to be constant over a short time interval. The four-state dynamical model requires that dynamic pressure, velocity, and spin rate be provided as known functions of time.

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The effects of observation noise are created by utilizing a pseudorandom number generator to add small perturbations to the nominal measurements. The simulated noise is generated with an approximate Gaussian distribution. The noise levels are chosen to be characteristic of actual flight test results. To broaden the scope of the simulated measurements, five corrupted observation sets are generated; each data set is created with a different random number sequence to provide five sample paths. This will allow for ensemble average estimates to be evaluated from the simulated observations.

The initial conditions of the state vector and aerodynamic coefficients are determined from the simulated measurements in a weighted least-squares batch estimation algorithm. Such a procedure provides state estimates and error covariances, which are first determined from a combination of rate gyro and forward accelerometer observations (RG-Acc). The estimation process is repeated using the forward and aft accelerometer data (2-Acc). Comparison of these results leads to a determination of the effectiveness of using dual accelerometer data in estimating re-entry vehicle states and aerodynamic coefficients.

The initial conditions of the state vector and the aerodynamic coefficients are estimated for six epoch times over an altitude range of 150,000 to 50,000. The length of the fit interval is chosen for each epoch time so that approximately 1.5 periods of slow-frequency motion are present. The ensemble average estimates of the initial conditions for the five sample paths using the RG-Acc data set are within 1% of the nominal values at each epoch time. Furthermore, the differences between the average estimates and the nominal values are less than the square root of the corresponding average error covariance. This result is expected and confirms the capability of estimating initial conditions from gyro and accelerometer measurements. If the estimates of the initial conditions from the 2-Acc data set are compared with estimates from the RG-Acc data set, the percent differences are less than 3%. The dual-accelerometer estimates differ from the gyro-accelerometer estimates by less

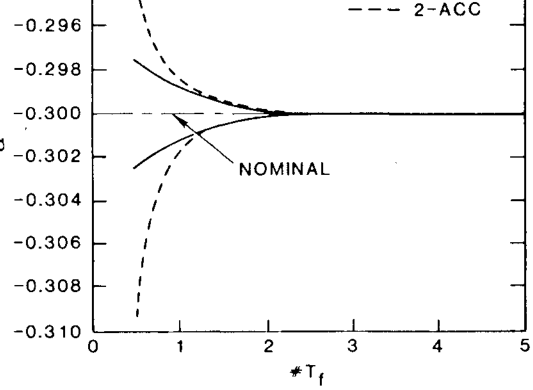

Fig. 1 C_{m_α} cycle convergence.

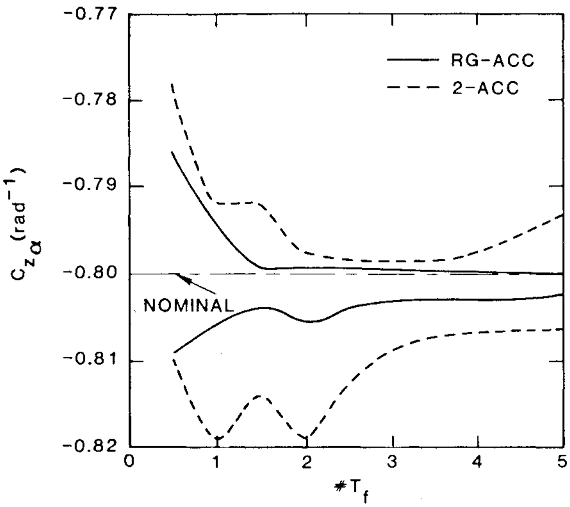

Fig. 2 C_{z_α} cycle convergence.

than 0.1% for C_{m_α} and 1% for C_{z_α}. These results indicate that 2-Acc estimates are nearly as accurate as RG-Acc estimates. However, the average error covariances for the C_{m_α} and C_{z_α} estimates are 1 to 3 times larger for the 2-Acc data set than for the RG-Acc data set. Thus, the precision of the 2-Acc estimates is less (error covariance is larger) than the precision of the RG-Acc estimates. Despite the loss in precision for the 2-Acc estimates, the square root of the error variances for the C_{m_α} and C_{z_α} estimates are equal, at worst, to 3% of the nominal values.

Also of interest in the estimation process is the number of cycles of vehicle motion required in the fit interval to obtain a reasonably accurate estimate. A solution to a restricted form of the state equations reveals that a fast and slow frequency are present in the vehicle lateral motion. Associated with each frequency is a slow (T_s) and fast (T_f) period.

Figures 1 and 2 show the estimates of C_{m_α} and C_{z_α} for the 2-Acc and RG-Acc data sets as a function of T_f. The lines in the figures represent an envelope of the minimum and maximum estimates for the five sample paths. In terms of percent differences from the nominal, the estimates of C_{m_α} are closer to the nominal than are estimates for C_{z_α}. In all cases, the envelope of estimates for the RG-Acc data set is closer to the nominal than the 2-Acc data set. Estimates of C_{m_α} reach a steady value in less cycles of motion than do C_{z_α} estimates. Also, it requires slightly more cycles of motion to reach a consistent estimate for the 2-Acc data set as compared to the RG-Acc data set. Although not shown in the figures, the scatter in the C_{z_α} and C_{m_α} estimates are equivalent to the error covariance values. After an appropriate number of cycles of motion, the estimates of C_{m_α} and C_{z_α} are bounded within $\pm 5\%$ of the nominal value.

The preceding results are based on the assumption that the accelerometers are attached to the vehicle at the correct location with respect to the vehicle center of mass and that the sensor axes are properly aligned with the vehicle-fixed, body-axis coordinate system. The effect of accelerometer longitudinal location errors on the estimation of C_{z_α} is also considered. In this analysis, the aft longitudinal accelerometer location is moved forward and aft in a range corresponding to a $\pm 10\%$ variation in the nominal axial separation distance between the dual accelerometers. The results indicate that the C_{z_α} estimate varies linearly with perturbations in separation distance. The C_{z_α} error covariance also varies linearly with separation distance. More precise estimates of C_{z_α} are obtained as the aft accelerometer moves toward the center of mass. A typical sensor width is approximately 3% of the separation distance between forward and aft accelerometers for the proposed RV recovery program. It seems reasonable, therefore, to expect that C_{z_α} estimates will differ from the nominal by nearly $\pm 3\%$ as a result of location errors. The effect of separation distance errors on C_{m_α} estimates is negligible for the range of errors considered.

The problem of sensor axis misalignment on C_{z_α} and C_{m_α} estimation is studied by systematically varying the orientation of the aft accelerometer input axes with respect to the vehicle body-axis coordinate system. The C_{z_α} estimate differs from the nominal value by less than 10% for alignment angle errors of less than 5 deg. The C_{m_α} estimates are less sensitive to angle errors. An upper bound for sensor axis misalignment is projected to be 1 deg; therefore, it is not expected that estimation errors due to sensor alignment errors will be a limiting factor in the final results.

The results briefly described herein indicate that re-entry vehicle lateral states and aerodynamic coefficients can be accurately estimated from dual-accelerometer observations when compared with estimates from gyro/accelerometer measurements. The mathematical expression for the acceleration at a location other than at the center of mass of the vehicle involves the separation distance of the instruments from the center of mass and the angular acceleration of the vehicle. Thus, dual accelerometers utilize angular motion information indirectly rather than directly, as is the case when gyro data is available. The precision of the estimates, as indicated by the error covariance, is less for the dual accelerometer data set than for the gyro/accelerometer data set. The sensitivity of state and parameter estimates to errors in accelerometer axial location is predictable and, considering the physical dimensions of the vehicle and sensor, the range of possible estimation errors is small. The effect of sensor axis misalignment in C_{z_α} and C_{m_α} estimates is negligible for angle offsets less than 1 deg.

Acknowledgment

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References

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[3]McDowell, J.L. and Williamson, W.E., "Reentry Vehicle State and Aerodynamic Coefficient Estimation from Dual Accelerometers," AIAA Paper 80-1605, Aug. 11-13, 1980.