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SLENDER BODY WITH TIME-VARYING MASS ELASTIC RESPONSE ESTIMATION USING A KALMAN STATE ESTIMATOR APPROACH

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ABSTRACT

Flight control systems (FCS) of flight vehicles rely on data, specifically, angular rates and accelerations, commonly measured by a strap-down inertial measurement unit (IMU). These measurements capture and reflect both the rigid body motion of the vehicle, exhibited mainly in lower frequencies, and its elastic dynamic deformations, occurring in the relatively higher frequency range. The FCS, which aims to regulate the trajectory of the vehicle, is typically designed based on rigid body dynamics, while the elastic modes are considered as unmodeled dynamics [1]. For such a control system, the presence of accelerations and angular rates due to elastic vibrations in the measurement is an undesirable feature that must be accounted for (i.e., removed from the data). The common practice in such systems is to remove the elastic motion component from the IMU data by applying a combination of low-pass and notch filters, filtering out the higher frequencies associated with the elastic motion, and retaining only the low-frequency data associated with the rigid body motion of the vehicle. The structural modes of slender aircraft, such as space launchers or missiles, vary during flight as fuel consumption changes the mass of the body, making their filtering even more complicated. To accommodate the elastic response variation uncertainty, broad stop-band filters are conventionally used, often limiting control bandwidth and degrading performance. Consequently, new adaptive methods are needed to filter out elastic responses.

This study presents a novel methodology to estimate the in-flight dynamic aeroelastic response of a slender flexible structure with time-varying mass using a Kalman State Estimation (KSE) approach. The approach utilizes a piecewise constant approximate aeroelastic model combined with multi-sensor data to estimate modal deformations, rates, and accelerations. These estimated states enable reconstruction of the structure's elastic response, and their subsequent removal from the IMU data, isolating the rigid-body response and thus circumventing the need to filter the data. The study extends former KSE approach by introducing an approximate model that includes modal accelerations as states of the system. This allows the creation of sensor configurations that make all states directly observable for better estimation. Preliminary work by the authors has showed successful estimation of a slender body's elastic response using the proposed method for a body with constant mass. The method was shown to be robust considering different process and measurement uncertainties [2].

The current study extends the method for a structure with time-varying mass, representing full flight mission of a missile. The proposed method is demonstrated with case study involving a slender missile subjected to gust load excitation. A simplified model is used to simulate the vehicle's aeroelastic response and generate IMU and other sensor data. The same model is used to create a series of aeroelastic state-space models corresponding to different flight stages, which form a piecewise constant aeroelastic database for the KSE. Numerical results show that the proposed method accurately reconstructs the elastic response and effectively removes it from the IMU measurement, acting as an adaptive filter for the elastic response of the time-varying structure. A parametric study presents the effect of time windows choice for the piecewise approximate aeroelastic model on the estimation.

1 References

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[2] Genkin, I. and Raveh, D. E. (2024). Estimation of slender body elastic rates and accelerations using a combination of measured data. In *International Forum on Aeroelasticity and Structural Dynamics, IFASD 2024*.