Applicability of Loads Estimation Techniques using Sparse Acceleration Sensor Data to Spacecraft Structural Health Monitoring

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ABSTRACT

The use of structural health monitoring systems on spacecraft structures can play a crucial role in ensuring the safety, reliability, and longevity of the structure by gathering and analyzing onboard sensor data. Of specific importance is monitoring for excessive loading at critical interfaces as any off-nominal structural excitations experienced by spacecraft structures can cause early unpredicted high structural life consumption or damage. The availability and cost of flight-certified sensors along with the size of spacecraft structures and allowable payload mass drives the need for a method to estimate loads using sparsely-located sensors. Numerous approaches such as physics-based, statistical learning, and physics-enhanced statistical learning algorithms have gained popularity among structural prognostics applications. However, developing noise-robust prediction models to assess loads and structural life predictions from a sparse multi-sensor data acquisition system can be a challenging task. This paper discusses the evaluation of physics-based versus machine-learning algorithms for predicting loads and structural life at mission critical locations on the spacecraft structure using a finite element loads analysis with the application of simulated noise and noise reduction techniques. To estimate the loads from accelerations, the physics-based algorithm leverages a loads transformation matrix from a Craig-Bampton reduced finite element model. A System Equivalent Reduction Expansion Process (SEREP) and a pseudo-inverse approach are considered to expand from the onboard sensor degrees of freedom to the Craig-Bampton model degrees of freedom. The machine learning algorithm provides a data driven solution/mapping of the sensor accelerations to the loads at the mission critical locations using a high dimensionality analysis. Although these strategies produce comparable loads prediction without noise, the limitations of these strategies with incorporating simulated noise and noise reduction techniques with low signal to noise ratio signals are evaluated. The study demonstrates the immense potential of statistical learning algorithms for sparse structural prognostic models and enhancing signal denoising techniques. These findings also highlight the need for noise-resilient prognostic models and low-noise data acquisition systems onboard spacecraft structures.

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