What does Fault Detection and Isolation have to offer for Precision Motion Systems?

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Abstract

The productivity and economic value of high-tech production equipment is largely tied to the reliability, as unexpected breakdowns can lead to major losses. These malfunctions typically result from defects, aging, and wear of system components. To minimize the downtime of production equipment and maximize productivity, early detection of faults and pinpointing their origin is essential to initiate targeted repairs and mitigate further issues, which is known as the process of Fault Detection and Isolation [1]. To design a fault detection and isolation system that is computationally attractive for real-time implementation we build upon two paradigms: a parametric modal model and the nullspace-based fault detection and isolation approach.

The nullspace-based approach enables the synthesis of a minimal-order, linear time-invariant filter that processes the system's input-output data in real-time, and generates a structured set of residuals [2]. This structured residual approach allows for robust and precise fault isolation, as each unique fault triggers a specific residual pattern, facilitating clear identification and fault localization. Despite the attractive properties of the nullspace-based approach, the effectiveness of the resulting filter hinges upon the accuracy and order of the parametric system model, as inaccuracies or unnecessarily high model order propagate directly into the residual generator, potentially reducing fault detection precision and computational efficiency.

To address these challenges, a modal modelling framework is adopted to describe the dynamical behaviour of mechanical motion systems with a minimal number of parameters [3]. These models, or the data to generate these models, are often already available prior to commissioning a machine. Recent advancements have enabled effective estimation of modal structures in multi-input multi-output systems, where the identified parameters have a direct interpretation of physical quantities, including resonance frequencies, mode shapes, and damping ratios.

In this work, a fault diagnosis system is presented to detect and isolate a large number of potential fault scenarios, based on these accurate low-order modal models, and synthesized by means of the nullspace-based fault detection and isolation approach. The developed methodology is experimentally validated on a next-generation wafer stage setup, see Figure 1, which features four sensors and thirteen actuators in the out-of-plane direction, all supposed to be prone to faults [4]. The residual signals, see Figure 2, enable to isolate seventeen distinct fault scenarios. The proposed approach is applicable to a large range of systems, including production machines and scientific instruments.

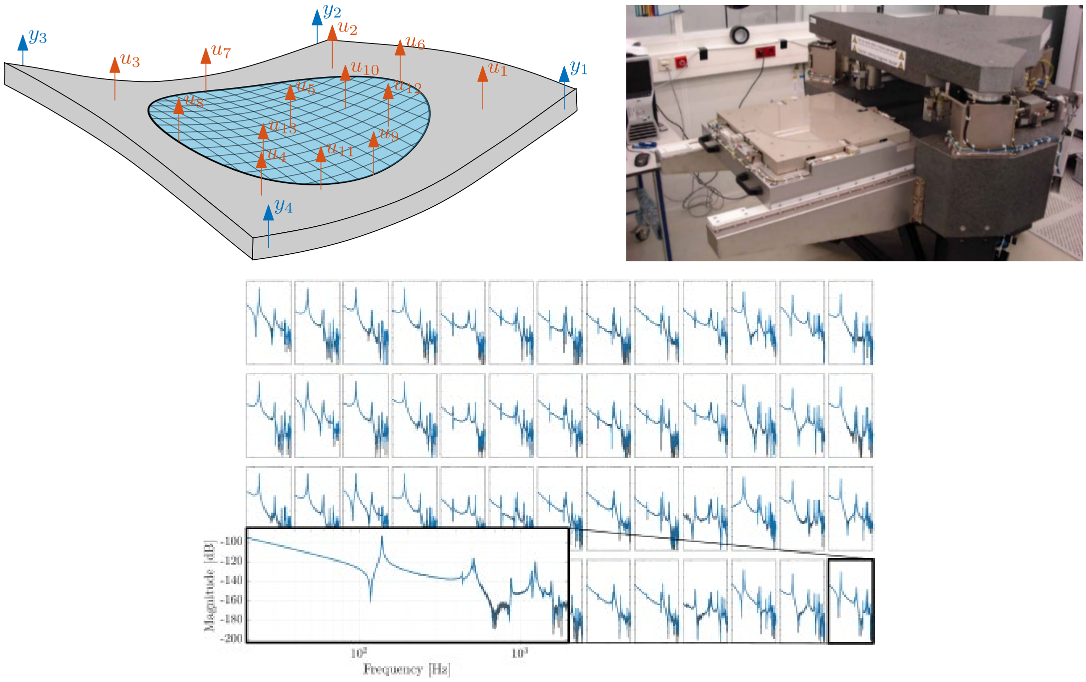

Figure 1: Schematic overview (left) and photo (right) of the prototype wafer stage. The actuators u_i and sensors z_i are assumed to be prone to faults. The identified parametric modal model (——) and the frequency-response measurement (——) from the 13 actuators u_i to the four sensors z_i serves as a basis to synthesize the fault diagnosis system.

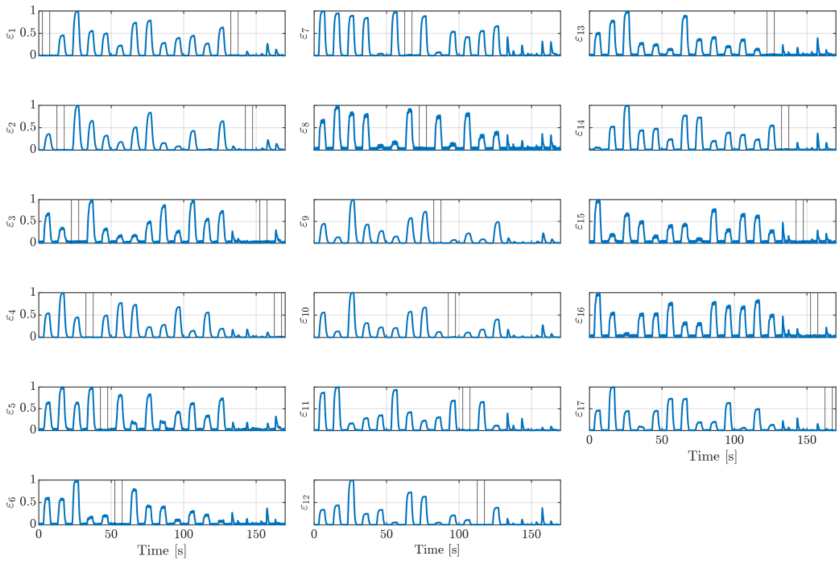

Figure 2: Residual signals used for fault detection and isolation (——). The faults can easily be localized by comparing the fired residual signals to the pre-imposed fault signatures. For instance, all residual signals fired except for ε_1 indicates a fault in actuator 1, see the residuals between 2.5s and 7.5s.

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